Children's and Adolescent's Physical Activity and Health: The Role of Urban-Rural Living and Natural Environments

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Summary

The United Nation's Sustainable Development Goals are an urgent call to action to tackle social, ecological, and economic challenges to ensure prosperity for the people and the planet. The third goal focuses on promoting **health and well-being**. Especially **children and adolescents** are an important target group since health is not only every child's right, but since their health and well-being is crucial to achieve a sustainable development and prosperous future. To foster health and well-being as well as sustainable development, the World Health Organization (WHO) and the United Nations have recognized the importance of **physical activity, urbanization, and natural environments** (e.g., green space), emphasizing their role in preventing non-communicable diseases, reducing mortality, and improving mental health.

Physical activity has been linked to various mental, cognitive, and physical health benefits during childhood and adolescence. However, with the large majority of children and adolescents in Germany and globally failing to engage in 60 minutes moderate-to-vigorous physical activity (MVPA) on average per day, as recommended by the WHO, action is required to tackle physical inactivity. In its *Global Action Plan on Physical Activity*, the WHO suggests policy actions and strategies across four key areas. One of those areas focuses on creating and maintaining **active environments** that facilitate physical activity across age groups. This includes transport and planning policies emphasizing connectedness, compactness, and walking and cycling infrastructure as well as strengthening equitable access to public green space and natural environments. Beyond their importance for physical activity, the United Nation's Children's Fund emphasizes the importance of the **environment and green space for children's and adolescent's health and well-being**, with previous studies showing that exposure and access to natural environments is associated with enhanced child and adolescent health and well-being.

However, although international organizations emphasize the importance of the (natural) environment for children's and adolescent's physical activity and health, **several research and knowledge gaps** remain, which are presented in the following paragraphs. Addressing those gaps could provide valuable evidence to guide policymakers and practitioners to create physical activity- and health-promoting environments as well as provide impetus for further research.

From a theoretical perspective, the socio-ecological model of physical activity proposes that walking and cycling infrastructure, walkability, and recreational and sports facilities are inducive to physical activity. These characteristics are typically more common in urban than rural areas. Hence, one could assume that urban environments are more inducive to children's and adolescent's physical activity. However, with increasing urbanization, both urban and rural environments have experienced drastic changes both before and in the context of the Covid-19 pandemic and it is **unclear how urban and rural areas relate to children's and adolescent's physical activity**, especially in Germany.

With natural environments and green space experiencing increasing interest from different academic disciplines, policymakers, and practitioners in the context of climate change and urbanization, it is important to understand how green space relates to children's and adolescent's physical activity behavior and well-being. From a theoretical perspective, natural environments enhance well-being via improved air quality, enhanced physical activity and social contacts, and stress reduction. Focusing on natural environments and physical activity, affordances theory emphasizes the potential of natural environments offering more variability in physical activity opportunities compared to manufactured environments. To objectively assess the natural environment, utilizing existing datasets with a spatial reference (e.g., digital land cover data) and analyzing those with geographic information systems (GIS) is considered state-of-the-art, especially when individuals are dispersed across large spatial areas. However, from a methodological point of view, it is **unclear how natural environments should be operationalized with GIS** for physical activity and health research with children and adolescents. Also, most research has so far focused on green space in the urban context, and it is **unclear how green space relates to children's and adolescent's physical activity across urban and rural areas**. While natural environments and health have been extensively investigated during normal circumstances across age and population groups, the Covid-19 pandemic led to major changes in daily life, affecting well-being and health behaviors. Covid-19 can be considered as a natural experiment and can serve as an example of a societal crisis, providing a learning opportunity regarding the role of green space to build resilience and empower people to promote their health and health behaviors during a crisis. However, **a comprehensive synthesis of the available research on nature, well-being, and health behaviors in the context of the Covid-19 pandemic is missing**.

While the natural environment and physical activity have been mostly considered as independent context and behavioral factors of health, based upon affordances theory, it is also possible that engaging in physical activity in a natural environment, i.e., nature-based physical activity, may yield enhanced health effects compared to physical activity in non-natural environments. This is based on the assumption that natural environments allow for more intense physical and cognitive experiences during physical activity and demand creative movement solutions due to the natural environment's diverse information and variability. However, although emerging evidence in adults points towards enhanced mental health benefits of nature-based physical activity, it is **unclear if nature-based physical activity has enhanced health effects for children and adolescents**.

While the environment has been predominantly conceptualized as an antecedent of physical activity, the interest about physical activity being an antecedent of a healthy environment and sustainable development has only surged interest recently So far, the connection between physical activity and sustainable development has been primarily established at a political and structural level in the context of climate change. However, there is currently **no conceptualization of physical activity as a behavior that can influence other sustainable behaviors**, allowing individuals to contribute to the fulfillment of sustainability goals **beyond climate-relevant behavior**.

Based upon these theoretical considerations and research gaps and taking into account the Covid-19 pandemic, the **main objective of this dissertation was to investigate the role of urban and rural living as well as natural environments for children's and adolescent's physical activity and health**. More detailed, the objective were to 1) investigate urban-rural differences in children's and adolescent's physical activity; 2) explore how the GIS-based configuration of the natural environment impacts associations with children's and adolescent's physical activity and health; 3) investigate associations between green space and children's and adolescent's physical activity across urban and rural areas; 4) summarize the evidence on the health effects of nature-based physical activity in children and adolescents; 5) summarize the research on natural environments, well-being during, and health behaviors during Covid-19, and 6) conceptualize the potential of physical activity for individual-level sustainable behavior.

The empirical investigations in this dissertation have been conducted using data from the representative population-based **Motorik-Modul (MoMo) Study** in Germany, which started out as an in-depth study within the German Health Interview and Examination Survey for Children and Adolescents (KIGGS) in 2003 with the baseline assessment The MoMo Study investigates physical activity, physical fitness, and health together with its determinants in children and adolescents between four and 17 years. Across the last two decades, the MoMo Study has followed up with participants in three measurement waves and recruited a representative sample of children and adolescents again at each measurement occasion.

The **first article** investigates children's and adolescent's physical activity and screen time trends in Germany across urban and rural areas between 2003 and 2017, using weighted data from three repeated cross-sectional assessments with a total of 12,161 children and adolescents of the MoMo Study. Self-reported physical activity was assessed during leisure, school, and in sports clubs, and self-reported screen time was assessed for TV watching and computer and gaming time. Urbanicity was assessed using the political system for community sizes in Germany with four levels based upon population size (rural, small town, medium-sized town, city). The results revealed a downward trend in total physical activity for children and adolescents in rural areas, a trend that was not observed for any other urbanicity level. Outdoor play and leisure-time physical activity decreased across all urbanicity levels, with the strongest decline observed in rural areas. Sports club physical activity increased only in cities. School-based physical activity showed increases across all four urbanicity levels. Computer and gaming time increased across all levels except for cities, with the steepest increase in rural areas. Outdoor play declines and computer and gaming time increases were primarily driven by adolescents. Girls exhibited greater increases in computer and gaming time than boys. These findings indicate that detrimental physical activity and screen time trends occur at a higher rate in rural compared to urban areas.

The **second article** complements the first article, using accelerometers for device-based physical activity assessment instead of self-report. Also, in addition to the urbanicity assessment of the first article, a more sophisticated urbanicity approach was applied using the three-level European Degree of Urbanization (cities, towns/suburbs, and rural areas). This degree considers not only population size, but also population density in conjunction with spatial contiguity. Data was again utilized from the MoMo Study, using the two repeated cross-sectional timepoints with accelerometer data (discovery study: 2015-2017; replication study: 2018-2020 prior Covid-19) with a total of 3,930 participants between six and 17 years. In both studies, children and adolescents living in cities engaged in more MVPA and were more likely to comply with the WHO's physical activity recommendations. There were no interactions between urbanicity and gender or age for MVPA, meaning that the associations are generalizable across age groups and gender. Regarding WHO physical activity guideline compliance, stratified analysis revealed that especially girls as well as children (six to ten years) and older adolescents (14-17 years) benefited from city living. This complements the finding from the first article, with positive implication of urbanization for children's and adolescent's physical activity, while indicating that rural areas should be specifically targeted for physical activity promotion.

The **third article** focuses on natural environments and investigates how the geospatial and conceptual configuration of the natural environment impacts the association with children's and adolescent's physical activity and health, using data from the MoMo Study between 2018 and 2020 pre-Covid-19. A total of 2,843 children and adolescents between four and 17 years were included. More specifically, participant's residential address was geocoded, and using GIS, land cover, and land use data, nature was operationalized in three different ways (green and water-based space; only green space; only green space without agricultural areas). For each of the nature operationalizations, circular buffers using distances from 100m to 1000m and street-network buffers using distances from 1000m-5000m were created around the residential addresses. When investigating associations with mental health, muscular fitness, and accelerometer-assessed MVPA, results revealed considerable heterogeneity in the association with natural environments based upon nature operationalization, buffer type, and buffer size. Furthermore, the results differed by socio-economic status. These findings were used to develop a conceptual framework and guiding questions combining geospatial and conceptual considerations that can be used to decide for a natural environment measure in health research studies. This framework was also used to decide for the natural environment measure in the fourth article.

The **fourth article** investigated associations between green space and MVPA across urban and rural areas using data from the MoMo Study between 2018 and 2020 pre-Covid-19 with a total of 1,211 children and adolescents between six and 17 years. Based upon the third article, the natural environment was operationalized as the percentage of green space within a 1000m street-network buffer and divided

into quartiles. MVPA was assessed using accelerometers, and urbanicity using the European Degree of Urbanization (cities, towns/suburbs, and rural areas). For rural areas, results showed that compared to children and adolescents with the least green space (bottom quartile), those within the middle (2^{nd}) and upper (3^{rd}) green quartile engaged in less MVPA. This finding did not transfer to towns and cities. In cities, boys and younger children (six to ten years) in the middle (2^{nd}) green quartile engaged in more MVPA than those in the bottom quartile. However, at the same time, city children and adolescents with a low socio-economic status engaged in less MVPA in the upper (3^{rd}) compared to the bottom green quartile. These results indicate that green space in cities may facilitate physical activity for some child and adolescent sub-groups, but may constitute a barrier to physical activity in rural areas.

The **fifth article** moves beyond natural environments as a correlate for physical activity and health, but investigates natural environments as a context factor that may modify and strengthen the health effects of physical activity. Hence, using a systematic literature review, the available evidence regarding the relationship between nature-based physical activity and psychosocial and physiological health parameters in children and adolescents was synthesized. Four relevant databases were systematically searched, and study quality was rated using the Effective Public Health Practice Project (EPHPP) tool. Fourteen studies were included in the review, reporting six different physiological and 15 different psychosocial health outcomes. For the large majority of studies, health outcomes following nature- and non-nature based physical activity did not differ. Study quality was consistently rated weak. Based upon the available literature, there is little evidence that nature-based physical activity has enhanced health effects compared to physical activity in non-natural settings for children and adolescents. However, major study limitations in the synthesized literature hinder definite conclusions.

Moving into pandemic times, the **sixth article** investigates how urban and rural living predict children's and adolescent's physical activity changes during Covid-19 using longitudinal data from the MoMo Study collected pre- and during the first Covid-19 lockdown. This study is an extension of previous findings of the MoMo Study, which showed that overall, physical activity increased during the first Covid-19 lockdown. Urbanicity was assessed via population density, with more densely populated areas representing more urban areas. The number of active days (≥ 60 minutes physical activity) as well as engagement in sports-related (e.g., leisure sports) and daily life physical activity (e.g., outdoor play, gardening) were self-reported before and during Covid-19. Results showed that higher population density predicted less positive changes regarding the number of active days per week and daily life physical activity. Changes in sports-related physical activity were unrelated to population density. Contrasting findings from prior Covid-19, rural living was beneficial for children and adolescents in terms of physical activity during the lockdown, while physical activity increases diminished with increasing population density.

The **seventh article** summarizes the scientific literature regarding natural environments, health, and health behaviors in the Covid-19 pandemic. Using a comprehensive scoping review in conjunction with a thematic analysis, this work investigated which health behaviors and psychosocial health outcomes were explored in relation to natural environments across all age groups during Covid-19. A total of 188 articles were included. Overall, the results indicate that natural environments have the potential to mitigate the negative impact of a public health crisis on psychological health and physical activity. The focus on psychological health and physical activity as health topics in the context of natural environments was similar to pre-Covid-19 studies. Simultaneously, the pandemic seems to have intensified research on specific aspects of the nature–health relationship, including intensified research about the role of private green space in form of gardens, the potential of digital nature, as well as the role of nature for social health. Based upon this, several avenues for future research regarding the nature-health relationship in the Covid-19 context and beyond were identified, including a) exploring health-

promoting nature characteristics, b) investigating the potential of virtual and digital nature, c) investigating nature's potential for health promotion and resilience rather than health risks, d) investigating health-promoting behaviors other than physical activity, e) exploring underlying mechanisms regarding heterogeneity in the nature–health relationship based on human, nature, and geographic characteristics, and f) focusing on vulnerable groups, including children and adolescents.

The final **eighth article** reversed the perspective, not investigating the environment as a correlate of physical activity and health, but physical activity as a behavior that can contribute to creating and maintaining healthy natural and social environments for a sustainable development. More specifically, physical activity was conceptualized as a sustainable behavior that, based upon multiple (health) behavior change theory, has the potential to impact other behaviors that contribute to achieving the sustainable development goals (SDGs) on the individual level. Within this conceptualization, different physical activity types were considered to have the potential to promote behaviors for social sustainability, including tackling malnutrition (SDG 2), promoting health behaviors to prevent non-communicable diseases for health and well-being (SDG 3), promoting skills and competences for education (SDG 4), promoting social behaviors to reduce inequalities (SDG 10), and promoting cultural practices and identities for sustainable communities (SDG 11). Different physical activity types were also considered to have the potential to promote behaviors for ecological sustainability, including bike and car sharing for responsible consumption (SDG 12) and active transport to reduce greenhouse gases to combat climate change and air pollution (SDG 13). At the same time, it must be acknowledged that physical activity also has the potential to contribute and reinforce behaviors counteracting a sustainable development. Hence, a research agenda is suggested to investigate a) physical activity as a socially and ecologically sustainable behavior, b) sustainable physical activity promotion, c) sustainable physical activity measurement, d) psychological constructs that can promote physical activity and sustainable behaviors, and e) technology's role to promote and assess sustainable physical activity.

Based upon the current state of knowledge, the findings of this dissertation **contribute to the field of urbanicity, green space, and children's and adolescent's physical activity and health** in several ways. First, in line with the socio-ecological model of physical activity, city living is beneficial for children's and adolescent's physical activity. In contrast, rural living is detrimental to children's and adolescent's physical activity. Second, green space benefits for physical activity are only present for child and adolescent sub-groups in urban, but not rural areas. Third, in contrast to adults, there is very limited evidence of enhanced health effects for children and adolescents engaging in nature-based physical activity compared to physical activity in non-natural environments.

Considering the findings of this dissertation in the context of current knowledge allows for both **research and practical recommendations**. On the research side, future studies should investigate environmental correlates of children's and adolescent's physical activity types across urban and rural areas to derive urban-rural specific planning recommendations. Furthermore, child and adolescent physical activity should be monitored across urban and rural areas to monitor current trends. Regarding natural environments, reaching consensus on how to geospatially assess green space in physical activity and health studies would be helpful to enhance study comparability and data harmonization. Beyond, combining global positioning systems (GPS) and accelerometers is a promising approach for determining physical activity intensities and locations device-based. Furthermore, conducting quasi-experimental or health impact assessment studies on natural environments and physical activity would strengthen the evidence base and allow more specific practical recommendations. When investigating health effects of nature-based physical activity, randomized controlled trials should be rigorously designed, guided by suitable theoretical considerations, and conducted in real-world settings. These trials should include adolescents and clinical populations as target groups.

Practically speaking, rural areas should be specifically targeted to tackle physical inactivity, using multi-level interventions across physical activity domains and settings. When planning or implementing greening interventions, green space should be designed equitably, addressing the needs of groups with different socio-demographic characteristics, including gender, age, and socio-economic status.

Zusammenfassung

Die Nachhaltigkeitsziele der Vereinten Nationen sind ein dringender Aufruf zum Handeln, um soziale, ökologische und wirtschaftliche Herausforderungen anzugehen und Wohlstand für Mensch und Erde zu gewährleisten. Das dritte Nachhaltigkeitsziel widmet sich der Förderung von **Gesundheit und Wohlbefinden**. **Kinder und Jugendliche** sind in diesem Zusammenhang besonders wichtig, da Gesundheit nicht nur ein Recht jedes Kindes ist, sondern da ihre Gesundheit auch entscheidend ist, um eine nachhaltige Entwicklung und prosperierende Zukunft zu gewährleisten. Um Gesundheit, Wohlbefinden und nachhaltige Entwicklung zu fördern, haben die Weltgesundheitsorganisation (WHO) und die Vereinten Nationen die Bedeutung von **körperlicher Aktivität, Urbanisierung und Natur (z.B. Grünflächen)** sowie deren Rolle bei der Prävention chronischer Krankheiten, Reduktion der Sterblichkeit, und Verbesserung des Wohlbefindens erkannt.

Körperliche Aktivität ist mit positiven mentalen, kognitiven und physischen Gesundheitsparametern bei Kindern und Jugendlichen assoziiert. Die große Mehrheit der Kinder und Jugendlichen in Deutschland und weltweit schafft es jedoch nicht durchschnittlich 60 Minuten pro Tag mit moderater bis anstrengender Intensität körperlich aktiv zu sein wie von der WHO empfohlen. In ihrem *Globalen Aktionsplan für körperliche Aktivität* schlägt die WHO politische Maßnahmen und Strategien in vier Kernbereichen vor, um körperliche Aktivität zu fördern. Einer dieser Bereiche konzentriert sich auf die Schaffung und Erhaltung **aktiver Umgebungen**, die körperliche Aktivität in allen Altersgruppen fördern. Dies beinhaltet Verkehrs- und Planungsstrategien, die Vernetzung, Bewohner:innen-Dichte und Infrastruktur für Fußgänger:innen und Radfahrer:innen, sowie auch die Stärkung des Zugangs zu öffentlichen Grünflächen und natürlichen Umgebungen betonen. Jenseits ihrer Bedeutung für körperliche Aktivität hebt das Kinderhilfswerk der Vereinten Nationen die Bedeutung der **Umwelt und von Grünflächen für die Gesundheit und das Wohlbefinden von Kindern und Jugendlichen** hervor. Frühere Studien haben gezeigt, dass Zugang zu und Exposition gegenüber Natur mit verbesserter Gesundheit und Wohlbefinden assoziiert sind.

Obwohl internationale Organisationen die Bedeutung der (natürlichen) Umgebung für die körperliche Aktivität und Gesundheit von Kindern und Jugendlichen betonen, bestehen mehrere **Forschungs- und Wissenslücken**, auf die in den folgenden Absätzen kurz eingegangen wird. Das Schließen dieser Lücken könnte wertvolle Hinweise für politische Entscheidungsträger:innen und Praktiker:innen liefern, um gesundheits- und aktivitätsfördernde Umgebungen zu schaffen und einen Anstoß für weitere Forschung geben.

Aus theoretischer Sicht betont das sozial-ökologische Modell körperlicher Aktivität, dass Infrastruktur für Fußgänger und Radfahrer, Begehbarkeit, sowie Freizeit- und Sporteinrichtungen zur körperlichen Aktivität anregen. Diese Merkmale sind in der Regel stärker in städtischen als ländlichen Gebieten ausgeprägt. Daher ist anzunehmen, dass städtische Umgebungen die körperliche Aktivität von Kindern und Jugendlichen besser fördern als auf dem Land. Allerdings haben mit zunehmender Urbanisierung sowohl städtische als auch ländliche Umgebungen drastische Veränderungen erfahren, sowohl vor als auch während Covid-19 Pandemie und es ist **unklar, wie städtische und ländliche Gebiete mit der körperlichen Aktivität von Kindern und Jugendlichen zusammenhängen**.

Im Kontext von Klimawandel und Urbanisierung gewinnen insbesondere Grünflächen und Natur sowohl aus wissenschaftlicher als auch politischer Sicht immer mehr an Bedeutung. Daher ist es wichtig zu verstehen, welche Rolle die Natur für die körperliche Aktivität von Kindern und Jugendlichen und das Wohlbefinden spielen. Aus theoretischer Sicht verbessert die Natur das Wohlbefinden durch verbesserte Luftqualität, gesteigerte körperliche Aktivität und soziale Kontakte, sowie Stressabbau. Mit Blick auf Natur und körperlicher Aktivität betont die Affordanz-Theorie das Potenzial natürlicher Umgebungen, die mehr Variabilität und damit mehr Handlungsmöglichkeiten für körperliche Aktivität

als künstlich gebaute Umgebungen bieten. Für die objektive Erfassung der Natur wird die Nutzung vorhandener Datensätze mit räumlichem Bezug (z. B. digitale Landbedeckungsdaten) und deren Analyse mit geografischen Informationssystemen (GIS) als State-of-the-Art angesehen, insbesondere wenn Personen über große räumliche Gebiete verteilt sind. Allerdings ist aus methodischer Sicht **unklar, wie Natur mittels GIS für die Forschung zur körperlichen Aktivität und Gesundheit bei Kindern und Jugendlichen operationalisiert** werden sollte. Zudem hat die bisherige Forschung hauptsächlich Natur und Grünflächen im städtischen Kontext untersucht, und es ist **unklar, welche Zusammenhänge Grünflächen mit körperlicher Aktivität von Kindern und Jugendlichen über städtische Gebiete hinaus in ländlichen Gebieten aufweisen**. Während Natur und Gesundheit während normaler Umstände umfassend in verschiedenen Alters- und Bevölkerungsgruppen untersucht wurden, führte die Covid-19-Pandemie zu erheblichen Veränderungen im täglichen Leben, die sich auf das Wohlbefinden und Gesundheitsverhalten ausgewirkt haben. Covid-19 kann als Beispiel für eine gesellschaftliche Krise dienen und bietet eine Möglichkeit zu lernen, wie Grünflächen zum Aufbau von Resilienz beitragen und Menschen während einer Krise dazu befähigen, ihre Gesundheit und Gesundheitsverhalten zu fördern. Allerdings **fehlt bisher eine umfassende Synthese der verfügbaren Forschung zu Natur, Wohlbefinden und Gesundheitsverhalten im Kontext der Covid-19-Pandemie**.

Während Natur und körperliche Aktivität bisher in erster Linie als unabhängige Kontext- und Verhaltensfaktoren der Gesundheit betrachtet wurden, ist es basierend auf der Affordanz-Theorie auch möglich, dass körperliche Aktivität in der Natur, d.h. naturbasierte körperliche Aktivität, verstärkte Gesundheitseffekte im Vergleich zu körperlicher Aktivität in nicht-natürlichen Umgebungen aufweist. Dies basiert auf der Annahme, dass natürliche Umgebungen aufgrund der vielfältigen Informationen und erhöhten Variabilität eine intensivere körperliche und kognitive Erfahrung während der körperlichen Aktivität erlauben sowie kreative Bewegungslösungen fordern. Während Forschungsergebnisse bei Erwachsenen auf verstärkte psychologische Gesundheitsvorteile von naturbasierter körperlicher Aktivität hindeuten, ist **unklar, ob naturbasierte körperliche Aktivität verstärkte gesundheitliche Vorteile für Kinder und Jugendliche bringt**.

Während die Umgebung bisher überwiegend als Prädiktor körperlicher Aktivität konzeptualisiert wurde, hat in den letzten Jahren das Interesse daran zugenommen, wie körperliche Aktivität zu einer gesunden Umgebung und nachhaltigen Entwicklung beitragen kann. Die Verbindung von körperlicher Aktivität und nachhaltiger Entwicklung erfolgte bisher jedoch in erster Linie auf einer politischen, strukturellen Ebene im Kontext des Klimawandels. Bisher gibt es jedoch **keine Konzeptualisierung von körperlicher Aktivität als Verhalten, das andere nachhaltige Verhaltensweisen beeinflussen kann**, die es der individuellen Person **über Klima-relevantes Verhalten hinaus** erlauben zur Erfüllung der Nachhaltigkeitsziele beizutragen.

Basierend auf diesen theoretischen Überlegungen und Forschungslücken und unter Berücksichtigung der Covid-19-Pandemie waren die **Hauptziele dieser Dissertation** 1) Stadt-Land Unterschiede in der körperlichen Aktivität von Kindern und Jugendlichen zu untersuchen; 2) zu untersuchen wie die GIS-basierte Operationalisierung der Natur die Zusammenhänge mit körperlichen Aktivität und Gesundheitsparametern von Kindern und Jugendlichen beeinflusst; 3) zu untersuchen, wie Grünflächen und körperlichen Aktivität von Kindern und Jugendlichen in städtischen und ländlichen Gebieten zusammenhängen; 4) einen Überblick über die Evidenzlage hinsichtlich der gesundheitlichen Auswirkungen naturbasierter körperlicher Aktivität bei Kindern und Jugendlichen zu schaffen; 5) die Forschung zu Natur, Wohlbefinden und Gesundheitsverhalten während der Covid-19 Pandemie zusammenzufassen; und 6) das Potential körperlicher Aktivität für individuelles, nachhaltiges Verhalten zu konzeptualisieren.

Die empirischen Untersuchungen in dieser Dissertation wurden mit Daten aus der repräsentativen bevölkerungsbasierten **Motorik-Modul (MoMo) Studie** in Deutschland durchgeführt, die 2003 als Vertiefungsmodul der Studie zur Gesundheit von Kindern und Jugendlichen in Deutschland (KiGGS) mit der Basiserhebung begonnen hat. Die MoMo Studie untersucht körperliche Aktivität, körperliche Fitness und Gesundheit sowie deren Determinanten bei Kindern und Jugendlichen im Alter von vier bis 17 Jahren. Im Laufe der letzten zwei Jahrzehnte hat die MoMo Studie die Teilnehmenden der Basiserhebung in drei Folge-Erhebungen untersucht und bei jeder Erhebung zusätzlich eine repräsentative Stichprobe von Kindern und Jugendlichen rekrutiert.

Der **erste Artikel** untersucht Stadt-Land Trends der körperlichen Aktivität und Bildschirmzeit bei Kindern und Jugendlichen in Deutschland zwischen 2003 und 2017 unter Verwendung gewichteter Daten aus drei Querschnitts-Erhebungen mit insgesamt 12 161 Kindern und Jugendlichen der MoMo-Studie. Mittels Fragebogen wurden körperliche Aktivität während der Freizeit, in der Schule und in Sportvereinen erfasst, sowie auch die Bildschirmzeit, aufgeteilt nach Fernsehen und Computer- und Konsolen-Spielen. Die Urbanität wurde anhand des politischen Systems für Gemeindegrößen auf Grundlage der Bevölkerungsgröße ermittelt (ländlich, Kleinstadt, mittelgroße Stadt, Großstadt). Die Ergebnisse zeigen einen abnehmenden Trend für die körperliche Aktivität von Kindern und Jugendlichen in ländlichen Gebieten. Dieser Trend war in keinem der Stadtgebiete zu sehen. Spielen im Freien und körperliche Aktivität in der Freizeit sind in allen Gebieten zurückgegangen, der stärkste Rückgang war jedoch in ländlichen Gebieten zu verzeichnen. Die sportliche Aktivität in Vereinen nahm nur in Großstädten zu. Körperliche Aktivität in der Schule ist in allen Gebieten angestiegen. Computer- und Konsolen-Spielen ist in allen Gebieten außer in der Stadt angestiegen, wobei die stärkste Zunahme in ländlichen Gebieten zu verzeichnen war. Rückgänge beim Spielen im Freien und Zuwächse beim Computer- und Konsolen-Spielen waren vor allem auf Jugendliche zurückzuführen. Mädchen verzeichneten größere Zuwächse beim Computer- und Konsolen-Spielen als Jungen. Diese Ergebnisse deuten darauf hin, dass nachteilige Trends der körperlichen Aktivität und der Bildschirmzeit insbesondere im ländlichen Raum zu beobachten sind.

Der **zweite Artikel** ergänzt den ersten Artikel durch die Verwendung von Akzelerometern (Beschleunigungsmessern) zur Geräte-basierten Erfassung der körperlichen Aktivität anstelle von Selbstbericht durch Fragebögen. Darüber hinaus wurde über die Urbanitäts-Erfassung im ersten Artikel hinaus der dreistufige Europäische Verstädterungsgrad verwendet (Großstädte, Kleinstädte und suburbaner Raum, ländliche Gebiete). Dieser Grad berücksichtigt nicht nur die Bevölkerungsgröße, sondern auch die Bevölkerungsdichte in Verbindung mit räumlicher Kontinuität. Die Daten stammen erneut aus der MoMo Studie und den Erhebungswellen, bei denen Akzelerometrie eingesetzt wurde (Studie 1: 2015-2017; Studie 2: 2018-2020 vor Covid-19) mit insgesamt 3930 Teilnehmern im Alter von sechs bis 17 Jahren. In beiden Studien verzeichnen Kinder und Jugendliche in Großstädten ein höheres Maß an moderater-bis-anstrengender körperlich Aktivität als Kinder und Jugendliche in ländlichen Gebieten. Es gab keine Interaktion zwischen Urbanität und Geschlecht oder Alter, was bedeutet, dass die positiven Assoziationen über Altersgruppen und Geschlechter hinweg generalisierbar sind. Ebenso haben Kinder und Jugendliche in Großstädten eine höhere Wahrscheinlich die Bewegungsempfehlungen der WHO zu erfüllen. Dies gilt insbesondere für Mädchen sowie Kinder (sechs bis zehn Jahre) und ältere Jugendliche (14-17 Jahre). Diese Ergebnisse ergänzen die Erkenntnisse aus dem ersten Artikel, mit positiven Implikationen der Urbanisierung für die körperliche Aktivität von Kindern und Jugendlichen. Gleichzeitig zeigt dies, dass körperlichen Aktivität auf dem Land spezifisch gefördert werden sollte.

Der **dritte Artikel** beschäftigt sich mit natürlichen Umgebungen und untersucht, wie die Operationalisierung der Natur mittels geographischer Informationssysteme (GIS) die Assoziation mit körperlicher Aktivität und Gesundheitsparametern von Kindern und Jugendlichen beeinflusst. Dabei wurden Daten aus der MoMo Studie zwischen 2018 und 2020 vor Covid-19 mit insgesamt 2843 Kindern und Jugendlichen im Alter von vier bis 17 Jahren verwendet. Die Wohnadresse der Teilnehmenden wurde geokodiert und unter Verwendung von GIS, Landbedeckungs- und Landnutzungsdaten wurde Natur auf drei verschiedene Arten operationalisiert (Grün- und Wasser-basierte Flächen; nur Grünflächen; nur Grünflächen ohne landwirtschaftliche Nutzung). Für jede Operationalisierung wurden kreisförmige Puffer in den Distanzen 100m-1000m und Straßennetzwerk-Puffer in den Distanzen 1000m-5000m um die Wohnadressen erstellt. Bei der Untersuchung von Zusammenhängen mit der psychischen Gesundheit, muskulären Fitness und moderater-bis-anstrengender Aktivität (MVPA) zeigen die Ergebnisse eine erhebliche Heterogenität in der Assoziation mit der Natur abhängig von der Operationalisierung, Puffer-Distanz und Puffer-Art. Darüber hinaus variieren die Ergebnisse nach sozioökonomischem Status. Diese Erkenntnisse wurden verwendet, um einen konzeptuellen Rahmen und Leitfragen zu entwickeln, welche geographische und konzeptionelle Überlegungen kombinieren und bei der Entscheidungsfindung für eine angemessene Operationalisierung der Natur in Gesundheitsstudien verwendet werden können. Dieser konzeptuelle Rahmen wurde auch für die Entscheidung bezüglich der Operationalisierung von Natur im vierten Artikel genutzt.

Der **vierte Artikel** untersuchte Assoziationen zwischen Grünflächen und MVPA in städtischen und ländlichen Gebieten unter Verwendung von Daten aus der MoMo-Studie zwischen 2018 und 2020 vor Covid-19 mit insgesamt 1211 Kindern und Jugendlichen im Alter von sechs bis 17 Jahren. Auf der Grundlage des dritten Artikels wurde die natürliche Umgebung als der Prozentsatz Grünfläche ohne landwirtschaftliche Flächen innerhalb eines 1000m Straßennetzwerk-Puffers um den Wohnort operationalisiert und in Quartils unterteilt. MVPA wurde mit Akzelerometern erfasst, sowie die Urbanität mit dem Europäischen Grad der Verstädterung (Großstädte, Kleinstädte und suburbaner Raum, ländliche Gebiete). Die Ergebnisse zeigen, dass Kinder und Jugendlichen in ländlichen Gebieten im mittleren (2.) und oberen (3.) grünen Quartil weniger MVPA verzeichnen als Kinder und Jugendliche mit dem geringsten Grünanteil (unterstes Quartil). Diese Zusammenhänge waren ausschließlich für ländliche Gebiete zu finden. In Städten zeigt sich hingegen, dass Jungen und jüngere Kinder (sechs bis zehn Jahre) im mittleren (2.) grünen Quartil aktiver sind als diejenigen mit dem geringsten Grünanteil (untersten Quartil). Gleichzeitig sind Kinder und Jugendliche mit einem niedrigen sozioökonomischen Status im oberen (3.) Grünquartil weniger aktiv als solche mit dem geringsten Grünanteil (unterstes Quartil). Diese Ergebnisse deuten darauf hin, dass Grünflächen in Städten für die körperliche Aktivität von Sub-Populationen von Kindern und Jugendlichen Vorteile bringen können. Auf dem Land scheinen Grünflächen jedoch eine Barriere für die körperliche Aktivität von Kindern und Jugendlichen darzustellen.

Der **fünfte Artikel** geht über die Natur als Korrelat körperlicher Aktivität und Gesundheit hinaus, und untersucht Natur als Kontextfaktor, welcher die gesundheitlichen Auswirkungen von körperlicher Aktivität modifizieren und stärken kann. Daher wurde mittels einer systematischen Literaturübersichts-Arbeit die Studienlage hinsichtlich naturbasierter körperlicher Aktivität und psychosozialer und physiologischer Gesundheitsparameter bei Kindern und Jugendlichen zusammengefasst. Vier Datenbanken wurden systematisch durchsucht und die Studienqualität wurde mit dem Effective Public Health Practice Project (EPHPP) bewertet. Vierzehn Studien wurden einbezogen, die sechs verschiedene physiologische und 15 verschiedene psychosoziale Gesundheitsparameter berichten. Bei der überwiegenden Mehrheit der Studien gab es keine Unterschiede hinsichtlich der gesundheitlichen Auswirkungen zwischen natur- und nicht-naturbasierter körperlicher Aktivität. Die Studienqualität wurde durchgehend als schwach bewertet. Basierend auf der aktuellen Studienlage gibt es kaum Evidenz, dass naturbasierte körperliche Aktivität im Vergleich zu körperlicher Aktivität in nicht-natürlichen Umgebungen bessere gesundheitliche Auswirkungen bei Kindern und Jugendlichen hat. Allerdings erlaubt die schwache Studienqualität keine endgültigen Schlussfolgerungen.

Im Kontext der Covid-19 Pandemie untersucht der **sechste Artikel**, wie Stadt- und Land-Leben Veränderungen in der körperlichen Aktivität von Kindern und Jugendlichen während Covid-19 prädizieren. Hierfür wurden Längsschnittdaten aus der MoMo Studie verwendet, die vor und während des ersten Covid-19-Lockdowns gesammelt wurden. Diese Studie baut auf den vorherigen Erkenntnissen der MoMo Studie auf, dass körperliche Aktivität während des ersten Covid-19-Lockdowns insgesamt zugenommen hat. Die Urbanität wurde anhand der Bevölkerungsdichte bewertet, wobei dichter besiedelte Gebiete mehr städtische Gebiete repräsentierten. Die Anzahl der aktiven Tage (≥ 60 Minuten körperliche Aktivität) sowie die Beteiligung an sportlichen Aktivitäten (z. B. Freizeitsport) und körperliche Aktivität im Alltag (z.B. Spielen im Freien, Gartenarbeit) wurden vor und während Covid-19 durch Fragebögen erfasst. Die Ergebnisse zeigen, dass eine höhere Bevölkerungsdichte weniger positive Veränderungen bei der Anzahl der aktiven Tage pro Woche und körperliche Alltagsaktivität prädiziert hat. Veränderungen der sportbezogenen körperlichen Aktivität zeigen keinen Zusammenhang mit der Bevölkerungsdichte. Im Gegensatz zu Ergebnissen vor der Covid-19 Pandemie war das Leben auf dem Land während des Lockdowns vorteilhaft für die körperliche Aktivität von Kindern und Jugendlichen, während Zuwächse bei der körperlichen Aktivität mit zunehmender Bevölkerungsdichte abgenommen haben.

Der **siebte Artikel** fasst die wissenschaftliche Literatur über Natur, Gesundheit und Gesundheitsverhalten während der Covid-19-Pandemie zusammen. Mittels eines umfassenden Scoping-Reviews in Verbindung mit einer thematischen Analyse wurde der Frage nachgegangen, welche Gesundheitsverhaltensweisen und psychosozialen Gesundheitsparameter im Zusammenhang mit Natur während Covid-19 untersucht wurden. Insgesamt wurden 188 Artikel einbezogen. Die Ergebnisse deuten darauf hin, dass natürliche Umgebungen das Potenzial haben die negativen Auswirkungen einer öffentlichen (Gesundheits-)Krise auf die psychische Gesundheit und die körperliche Aktivität abzumildern. Der Fokus auf psychische Gesundheit und körperliche Aktivität als Gesundheitsthemen im Kontext von Natur ist vergleichbar mit den Studien vor Covid-19. Gleichzeitig scheint die Pandemie die Forschung zu spezifischen Aspekten der Beziehung zwischen Natur und Gesundheit intensiviert zu haben. Hierzu zählen die Rolle privater Grünflächen in Form von Gärten, das Potential digitaler Natur, sowie die Rolle der Natur für die soziale Gesundheit. Auf dieser Basis wurden mehrere Themen für die zukünftiger Forschung im Bereich Natur und Gesundheit identifiziert, einschließlich a) Identifizierung gesundheitsfördernder Naturmerkmale, b) Untersuchung des Potenzials virtueller und digitaler Natur, c) Untersuchung des Potenzials für Gesundheitsförderung und Resilienz anstelle von Gesundheitsrisiken, d) Untersuchung weiter gesundheitsfördernden Verhaltensweisen über körperlicher Aktivität hinaus, e) Erforschung zugrunde liegender Mechanismen, welche für die Heterogenität in der Natur-Gesundheits-Beziehung basierend auf menschlichen, natürlichen und geographischen Merkmalen verantwortlich sind, und f) verstärkter Fokus auf vulnerable Gruppen, einschließlich Kinder und Jugendliche.

Der abschließende **achte Artikel** kehrt die Perspektive um und untersucht nicht die Umgebung als Korrelat für körperliche Aktivität und Gesundheit, sondern körperliche Aktivität als Verhalten, das zur Schaffung und Erhaltung gesunder natürlicher und sozialer Umgebungen für eine nachhaltige Entwicklung beitragen kann. Körperliche Aktivität wird hierbei als nachhaltiges Verhalten konzipiert, das auf der Grundlage der Multiplen-(Gesundheits-)Verhaltensänderungs-Theorie das Potenzial hat andere Verhaltensweisen zu beeinflussen, die zur Erreichung der Nachhaltigkeitsziele (SDGs) auf individueller Ebene beitragen. In dieser Konzeption werden verschiedene Arten körperlicher Aktivität als potenziell förderlich für Verhaltensweisen für soziale Nachhaltigkeit betrachtet, einschließlich der

Prävention von Fehlernährung (SDG 2), Förderung von Verhaltensweisen zur Prävention nicht übertragbarer Krankheiten für Gesundheit und Wohlbefinden (SDG 3), Förderung von Fähigkeiten und Kompetenzen für Bildung (SDG 4), Förderung sozialen Verhaltens zur Verringerung von Ungleichheiten (SDG 10) und Förderung von kulturellen Praktiken für nachhaltige Gemeinden (SDG 11). Verschiedene Arten körperlicher Aktivität wurden auch als potenziell förderlich für Verhaltensweisen für ökologische Nachhaltigkeit betrachtet, einschließlich Fahrrad- und Carsharing für verantwortungsvollen Konsum (SDG 12) und aktivem Transport zur Reduktion von Treibhausgasen zur Bekämpfung des Klimawandels und Luftverschmutzung (SDG 13). Gleichzeitig ist es wichtig zu beachten, dass körperliche Aktivität auch das Potenzial hat Verhaltensweisen zu fördern und zu verstärken, die einer nachhaltigen Entwicklung entgegenwirken. Daher wird eine Forschungsagenda vorgeschlagen, um a) körperliche Aktivität als sozial und ökologisch nachhaltiges Verhalten, b) Förderung nachhaltiger körperlicher Aktivität, c) Messung nachhaltiger körperlicher Aktivität, d) psychologische Konstrukte, die körperliche Aktivität und nachhaltiges Verhalten fördern können, und e) die Rolle der Technologie zur Förderung und Evaluation nachhaltiger körperlicher Aktivität, zu untersuchen.

Die Ergebnisse dieser Dissertation tragen in mehrfacher Hinsicht zum **Erkenntnisstand im Bereich Urbanität, Grünflächen und körperliche Aktivität sowie Gesundheit von Kindern und Jugendlichen** bei: 1) Im Einklang mit dem sozial-ökologischen Modell körperlicher Aktivität ist das Leben in der Stadt vorteilhaft für die körperliche Aktivität von Kindern und Jugendlichen. Im Gegensatz dazu ist das Leben auf dem Land nachteilig für die körperliche Aktivität von Kindern und Jugendlichen. 2) Die Vorteile von Grünflächen für die körperliche Aktivität sind nur bei Sub-Populationen von Kindern und Jugendlichen in Großstädten, aber nicht in ländlichen Gebieten vorhanden. 3) Im Gegensatz zu Erwachsenen gibt es kaum Evidenz für stärkere gesundheitliche Auswirkungen naturbasierter körperlicher Aktivität auf verbesserte gesundheitliche Auswirkungen im Vergleich zu körperlicher Aktivität in nicht-natürlichen Umgebungen für Kinder und Jugendliche.

Die Ergebnisse dieser Dissertation im Kontext des aktuellen Wissensstands ermöglichen sowohl **Forschungs- als auch praktische Empfehlungen**. Bezüglich Forschung sollten zukünftige Studien Umweltkorrelate verschiedener körperlicher Aktivitäts-Arten von Kindern und Jugendlichen in städtischen und ländlichen Gebieten untersuchen, um Planungsempfehlungen spezifisch für städtische und ländliche Gebiete abzuleiten. Darüber hinaus sollte die körperliche Aktivität von Kindern und Jugendlichen in städtischen und ländlichen Gebieten beobachten werden, um die gegenwärtigen Trends weiter zu verfolgen. Im Hinblick auf die Erfassung der Natur wäre es hilfreich, einen Konsens darüber zu erzielen, wie Grünflächen in Gesundheitsstudien geografisch erfasst werden, um die Vergleichbarkeit der Studien und die Datenharmonisierung zu verbessern. Darüber hinaus ist die Kombination von globalen Positionierungssystemen (GPS) und Akzelerometern ein vielversprechender Ansatz für die Geräte-basierte Erfassung körperlicher Aktivität und relevanter Aktivitäts-Räume. Ebenso würde die Durchführung quasi-experimenteller oder Gesundheitsfolgenabschätzungs-Studien bezüglich Natur und körperliche Aktivität die Evidenzbasis stärken und spezifischere praktische Empfehlungen ermöglichen. Für die Untersuchung der gesundheitlichen Auswirkungen naturbasierter körperlicher Aktivität sollten randomisierte kontrollierte Studien unter Einbezug geeigneter theoretischen Überlegungen rigoros geplant und in realen Umgebungen durchgeführt werden. Diese Studien sollten Jugendliche und klinische Bevölkerungsgruppen als Zielgruppen einschließen.

Aus praktischer Sicht sollten spezifisch Interventionen und Maßnahmen auf mehreren Ebenen für den ländlichen Raum entwickelt werden, um körperliche Aktivität dort spezifisch zu fördern. Bei der Planung oder Umsetzung von Begrünungsmaßnahmen sollten Grünflächen so gestaltet werden, dass sie die Bedürfnisse von Personen mit unterschiedlichen soziodemografischen Merkmalen berücksichtigen, einschließlich Geschlecht, Alter und sozio-ökonomischem Status.

Table of Content

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Preface

Parts of this dissertation have been published or are under review in peer-reviewed scientific journals. Thus, the following chapters can be read independently from each other:

CHAPTER 2: Nigg C., Weber, C., Schipperijn, J., Reichert, M., Oriwol, D., Worth, A., Woll, A., & Niessner, C. (2022). Urban-Rural Differences in Children's and Adolescent's Physical Activity and Screen Time Trends Across 15 Years. *Health Behavior & Education, 49*(5), 789-800. https://doi.org/10.1177/10901981221090153

CHAPTER 3: Reichert, M.*, Nigg, C.*, Brüßler, S., Burchartz, A., Jekauc, D., Limberger, M., Fiedler, J., Krell-Rösch., J., von Haaren-Mack, B., Jekauc, D, Ebner-Priemer, U. W., Niessner, C., Schipperijn, J., & Woll, A. (submitted). City-Living Can Level Physical Activity Up: Germany's Youth City Dwellers Engage in More Moderate to Vigorous Physical Activity than Their Rural Counterparts. *Environment & Behavior. [* these authors contributed equally to this work]*

CHAPTER 4: Nigg, C., Burchartz, A., Niessner, C., Woll, A., & Schipperijn, J. (2022). The Geospatial and Conceptual Configuration of the Natural Environment Impacts the Association with Health Outcomes and Behavior in Children and Adolescents. *International Journal of Health Geographics, 21*, 9. https://doi.org/10.1186/s12942-022-00309-0

CHAPTER 5: Nigg, C., Fiedler, J., Burchartz, A., Niessner, C., Woll, A., & Schipperijn, J. (submitted). Distinct Associations between Green Space and Youth's Physical Activity in Urban and Rural Areas - Results of the MoMo Study. *Landscape & Urban Planning*.

CHAPTER 6: Mnich, C., Weyland, S., Jekauc, D., & Schipperijn, J. (2019). Psychosocial and Physiological Health Outcomes of Green Exercise in Children and Adolescents - A Systematic Review. *International Journal of Environmental Research and Public Health*, *16*(21), 4266. https://doi.org/10.3390/ijerph16214266

CHAPTER 7: Nigg, C., Oriwol, D., Wunsch, K., Burchartz, A., Kolb, S., Worth, A., Woll, A., & Niessner C. (2021). Population density predicts youth's physical activity changes during Covid-19 - Results from the MoMo study. *Health and Place, 70*, 102619. https://doi.org/10.1016/j.healthplace.2021.102619

CHAPTER 8: Nigg, C., Petersen, E., & MacIntyre, T. (2023). Natural environments, psychosocial health, and health behaviors during a crisis – A scoping review in the COVID-19 context. *Journal of Environmental Psychology*, *88*, 102009. https://doi.org/10.1016/j.jenvp.2023.102009

CHAPTER 9: Nigg, C., & Nigg, C. R. (2021). It's more than Climate Change and Active Transport - Physical Activity's Role in Sustainable Behavior. *Translational Behavioral Medicine, 11*(4), 945-953. https://doi.org/10.1093/tbm/ibaa129

CHAPTER 1

General introduction

1.1 Physical activity and the environment – crucial pillars for sustainable development

Growing social, ecological, and economic problems led to the United Nation's *Agenda for Sustainable Development* (UN, 2015). This agenda consists of 17 comprehensive, cross-sectoral sustainable development goals (SDGs). The third SDG aims at health promotion and well-being, amongst others by preventing non-communicable diseases and promoting mental health. Especially children and adolescents, describing any person younger than 18 years (UN, 1990), are an important target group: Ensuring children's and adolescent's well-being and that they can fulfill their potential and contribute to society is crucial to achieve a long-term sustainable development and a prosperous future (OECD, 2018). Considering that as of December 2021, 16.7% of Germany's population comprises children and adolescents younger than 18 years (destatis, 2022), this is also crucial for a healthy and sustainable development in Germany. At the same time, health is not only a target to be achieved through a sustainable development, but also a right that every child has according to the *United Nation's Convention on the Rights of Children* (UN, 1990).

To promote health and well-being as part of a sustainable development, the World Health Organization (WHO) has recognized the crucial role of physical activity and natural environments (WHO, 2012, 2016, 2018, 2023). More specifically, in its *Global Action Plan on Physical Activity 2018-2030*, the WHO emphasizes the role of physical activity for the SDG sub-goals preventing non-communicable diseases and premature mortality, reducing injuries and deaths from road traffic, universal health coverage, and reducing air pollution (UN, 2015; WHO, 2018). Similarly, in the light of increasing urbanization, with 68% of the population being expected to live in cities by 2050 (UN, 2018), the WHO acknowledges the importance of cities and urban environments (WHO, 2015, 2019) together with (urban) natural environments (WHO, 2012, 2016, 2023) to promote a healthy and sustainable development via facilitation of physical activity, prevention of premature mortality from non-communicable diseases, and mental health promotion.

Building upon this, this dissertation investigates the interplay between natural environments, physical activity, and children's and adolescent's health. Chapter 1 elaborates on term definitions and empirical evidence regarding associations between natural environments, physical activity, and health, before presenting theoretical and conceptual considerations that built the basis for the research presented in this dissertation. Next, for each of the research studies included in this dissertation, the background, including the empirical findings to date, and a brief summary of the main findings are provided. Chapter 2 and Chapter 3 present the results of two studies that investigated urban-rural physical activity differences in Germany's child and adolescent population. Chapter 4 and 5 present the results from two studies investigating green space from a methodological perspective in relation to children's and adolescent's physical activity and health as well as green space and physical activity across urban and rural areas. In Chapter 6, findings from a systematic review are presented regarding the health effects for children and adolescents of being physically active in natural environments. Chapter 7 and Chapter 8 take a look at urban-rural contexts and natural environments during the Covid-19 pandemic. While

Chapter 2 until Chapter 8 investigated the potential of the environment for physical activity and health, the last article presented in Chapter 9 conceptualizes how physical activity can contribute to a healthy environment and sustainable development. Chapter 10 provides a summary of the main findings and contributions of this dissertation as well as potential for future research and practical implications.

1.2 Physical activity and health in children and adolescents

To ensure a common understanding throughout this dissertation, the terms “physical activity” and “health” are first defined. Physical activity is an overarching term, referring to any movement of the body, produced by muscles and leading to energy expenditure (Caspersen et al., 1985). Physical activity can be further divided into different domains (e.g., transport and recreational physical activity; DiPietro et al. (2020)), dimensions (based upon the FITT-principle; that is frequency, intensity, time, and type), and time frames (see Figure 1; Jekauc et al., 2014). Regarding intensity levels, physical activity is commonly categorized into light, moderate, and vigorous physical activity for health recommendations (WHO, 2020) based upon the metabolic equivalent describing the ratio of energy expenditure during activities compared to resting level (Ainsworth et al., 2000; Howley, 2001; Pate et al., 1995).

Figure 1. Physical activity characteristics.

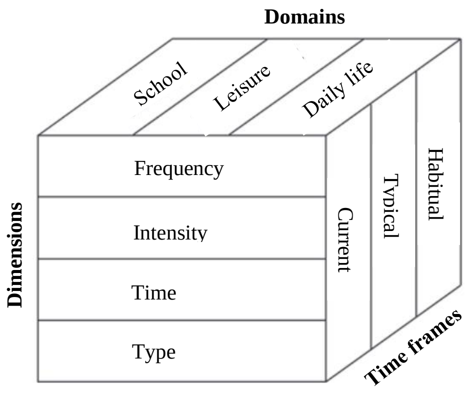
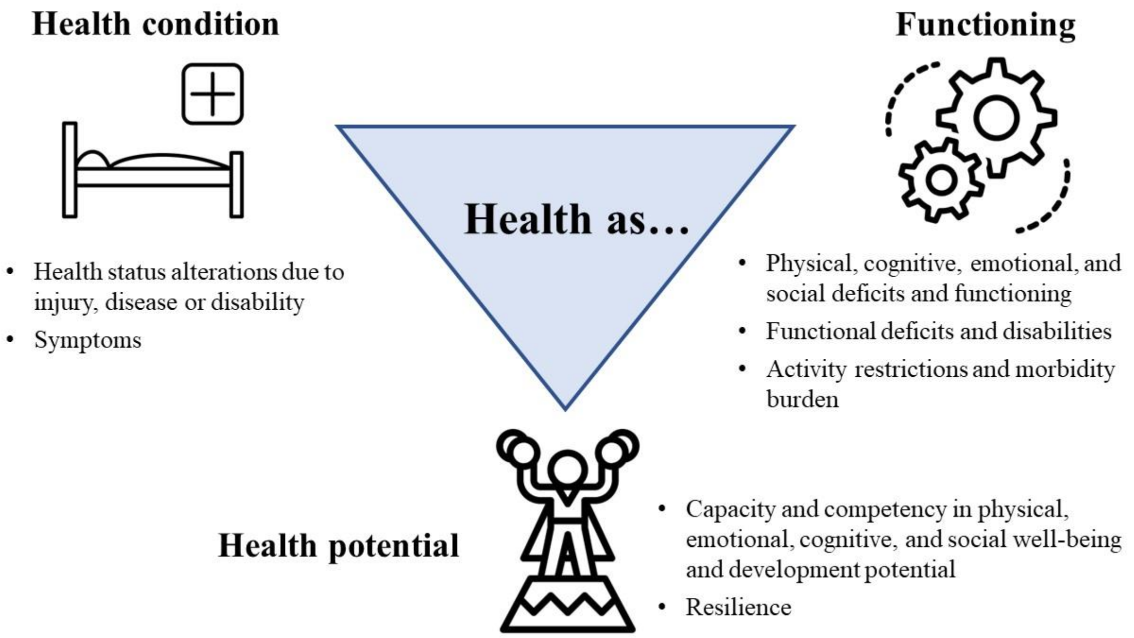


Illustration based upon based upon Jekauc et al. (2014, p. 80)

While the physical activity definition of Caspersen and colleagues (1985) is well established in the field of physical activity and health (e.g., Bull et al., 2020), there exist various concepts and definitions regarding health. According to the WHO, health is not only the absence of disease, but a state of complete mental, physical, and social well-being (WHO, 1948). Based on this definition, maintaining people’s health does not only include prevention through the reduction of risk factors, but also health promotion (WHO, 1986). Health promotion is an empowerment approach, enabling people to take over responsibility, control, and improve their health. Although the WHO health definition is still widely used, it has been criticized for several reasons, including the phrase “complete well-being” that characterizes almost everybody as unhealthy, the lack of usefulness due to operational problems, and a rise of chronic diseases together with progress in medicine that allows people to experience well-being despite being diagnosed with a disease (Huber et al., 2011; Leonardi, 2018; Saracci, 1997). Additionally, this definition is more appropriate for adults than for children as it does not consider the developmental processes, transitions, and the higher vulnerability of children compared to adults (NRC & IOM, 2004). Thus, the American National Research Council and the Institute of Medicine recommend an expanded definition that is based upon the WHO’s understanding of health promotion, but considers the characteristics of developing children: “Children’s health should be defined as the extent to which individual children or groups of children are able or enabled to (a) develop and realize their potential, (b) satisfy their needs, and (c) develop the capacities that allow them to interact successfully with their biological, physical, and social environments.” (NRC & IOM, 2004, p. 33). Based upon this definition, three health dimensions are included: health conditions, functioning, and health potential (see *Figure 2*).

Figure 2. Dimensions of children's and adolescent's health.



Health dimensions based upon NRC and IOM (2004, p. 35)

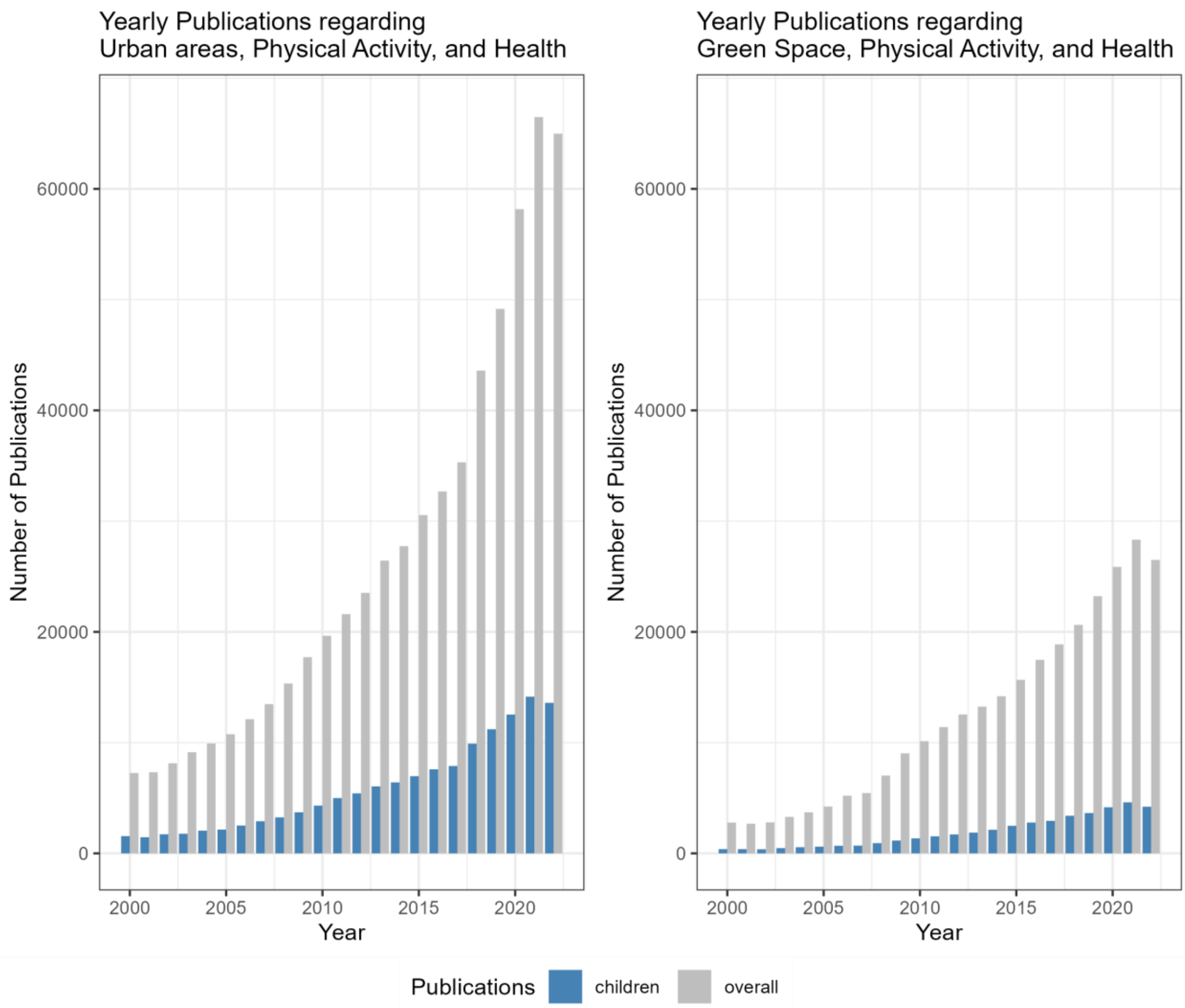
To prevent health conditions, facilitate functioning, and build the capacities and competencies of children and adolescents to fulfill their health potential, physical activity is a key lifestyle behavior. Physical activity has been associated with numerous health benefits that improve physical, emotional, and cognitive functioning, such as improved cardiorespiratory fitness and cardiometabolic health, reduced depression, and improved execute functions (Biddle et al., 2019; Chaput et al., 2020; Lubans et al., 2016; Marques et al., 2018; WHO, 2020) as well as psychosocial and physical health resources (Tittlbach et al., 2011), hence serving as an importance resource to enhance children's and adolescent's health potential. Also, since physically active children and children building physical activity as part of their identity are more likely to become physically active adults (Pongiglione et al., 2020; Smith et al., 2015), physical activity is crucial in preventing serious health conditions in adulthood, including coronary heart disease, diabetes type 2, cancer, and all-cause mortality (Biswas et al., 2022; Bull et al., 2020; Reiner et al., 2013).

Due to the numerous health benefits, the WHO recommends that children and adolescents engage in on average 60 minutes of moderate-to-vigorous physical activity (MVPA) per day (WHO, 2020). However, only about 20% of children and adolescents meet these recommendations globally and in Germany (Aubert et al., 2022), which also translates into low physical activity levels in adulthood (WHO, 2022). These high levels of physical inactivity do not only incur drastic health consequences for the individual, but lead to an estimated 500 million new cases of non-communicable diseases between 2020 and 2030, incurring estimated health care costs of US$ 27 billion annually (WHO, 2022). These numbers show that it is crucial to tackle the physical inactivity pandemic.

1.3 Environment and green space – key to physical activity and health

To tackle the physical inactivity "pandemic" (Pratt et al., 2020), the WHO (2018) published the *Global Action Plan on Physical Activity 2018-2030* (GAPPA), which suggests policy actions across four categories. This includes: 1) creating active societies through social norms and positive attitudes towards physical activity, 2) creating active people through physical activity programs and opportunities in different settings, 3) creating active systems through coordinated and effective actions leadership and multisectoral partnership, and 4) creating active environments. The latter one is especially important in the context of this work, since it aims at creating and maintaining environments that facilitate physical activity for people across all ages. More specifically, the WHO highlights five policy actions to create active environments across urban and rural areas for all age groups and with equitable access, including a) urban and transport planning policies to create compact, mixed land use, and highly connected neighborhoods that facilitate walking and cycling, b) improved walking and cycling network infrastructure, c) improved personal and road safety, d) strengthening access to public green space and natural environments, and e) strengthening design guidelines to create active settings (e.g., schools) (WHO, 2018). Although the WHO explicitly mentions that these design features concern both urban and rural areas, especially the first two policy actions – compactness and connectedness as well as network infrastructure – are commonly more typical for urban areas (Federal Ministry of Food and Agriculture, 2020; Sallis et al., 2016). Simultaneously, cities are more and more becoming the focus of physical activity research (e.g., Cerin et al., 2022; Giles-Corti et al., 2022; see also *Figure 3*) due to cities growing both in size and number, with the prospect that 68% of the world's population will be living in urban areas by 2050 (UN, 2018). These developments also apply to Germany, with an urban population of 77% in 2018, which is expected to increase to 84% by 2050 (UN, 2018).

Figure 3. Yearly publications 2000-2022 relevant study fields



Left panel: Yearly publications 2000-2022 in the field urban areas, physical activity, and health overall (grey) and for children and adolescents (blue) based upon publication numbers in Web of Science. Right panel: Yearly publications 2000-2022 in the field green space, physical activity, and health overall (grey) and for children and adolescents (blue) based upon publication numbers in Web of Science. (Search date: 8th May, 2023)

Beyond the WHO's understanding of the importance of the environment for physical activity, the United Nations Children's Fund (UNICEF, 2022) emphasizes the importance of the environment for children's health and well-being based upon direct environmental exposure (the world of the child), physical environmental aspects that children are exposed to and interact with (the world around the child), and the broader context that impacts the world around and of the child (the world at large; see also *Figure 4*). Regarding the environment as the world around the child, UNICEF emphasizes the importance of public green space as an opportunity to be physically active and play outdoors, especially for children living in densely populated areas and high-rise buildings (UNICEF, 2022).

Figure 4. The (natural) environment as an important facilitator of children's health and well-being.

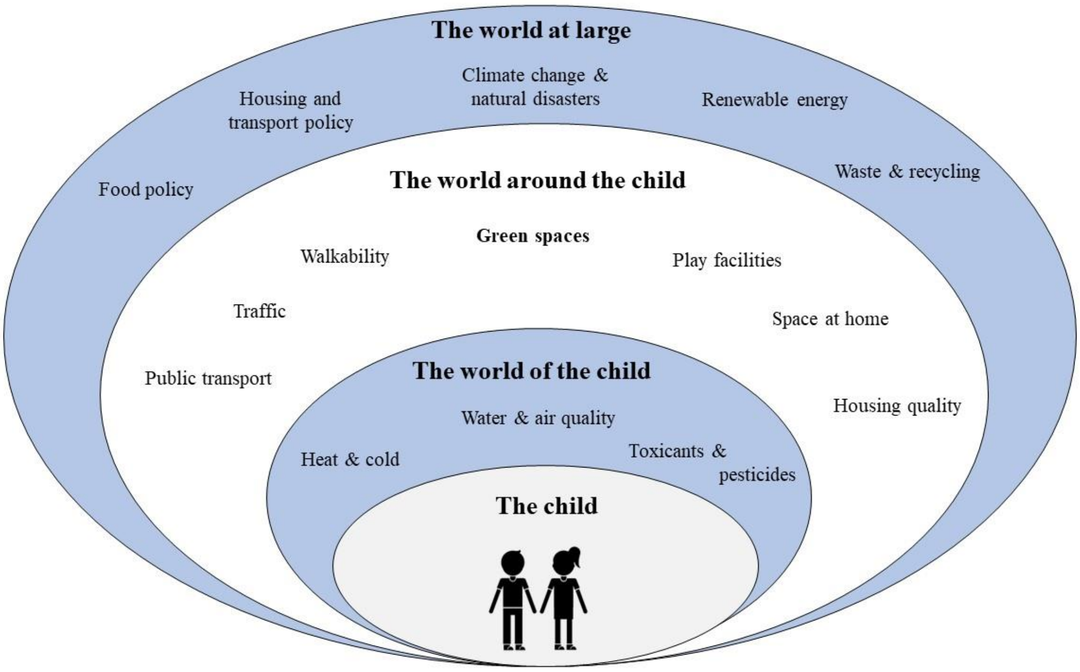


Illustration based upon UNICEF (2022)

In summary, international organizations such as the WHO and the UN highlight the importance of the environment, including urban and rural areas as well as green space, for a healthy and sustainable development and for children's health and well-being. So far, policies and perspectives have been presented. The next part presents the scientific paradigm of this work, before elaborating on the theoretical foundations and conceptual considerations that link urban and rural environments as well as green space with physical activity and health and which do not only build the basis for the reports of international organizations, but also for this dissertation.

1.4 Scientific paradigm of this work

In this dissertation, the framework of critical rationalism (Popper, 1934) serves as a guiding principle for the empirical investigations of the research topic. In its epistemology, critical rationalism emphasizes the importance of falsifiability of scientific theories. A theory is considered scientific if it can, in principle, be disproven by empirical observations (Chalmers, 2007). Following a deductive-nomological approach, research questions and hypotheses should be derived from existing theories regarding cause-effect-relationships. Scientists should actively seek to disprove theories through empirical observations or experimental investigations based upon cause-effect relationships. If hypotheses are falsified, this does not necessarily indicate that the theory or model as a whole is useless, but should be taken as a chance to modify and improve the theory or model. In its axiology, critical rationalism emphasizes the importance of objectivity when investigating cause-effect-relationships, i.e., values and attitudes of the researcher must not impact the result. If a hypothesis withstands empirical tests, it gains temporary credibility until new observations or experiments may falsify it. Since it is impossible to come to a final conclusion regarding the "truth" about a finding, critical rationalism emphasizes that research is a never-ending search for the truth (Döring & Bortz, 2016). Regarding the ontological premises, critical rationalism predominantly advocates for critical realism, although this cannot be empirically tested. According to critical realism, there exists a reality independent of human consciousness that follows certain regularities, and that is at least partially consciously accessible to humans. However, objective reality and human perceptions are not necessarily congruent due to human cognitions and information processing (Döring & Bortz, 2016). By adopting the critical rationalist approach, this dissertation seeks to contribute to the field of environment, physical activity, and health research by providing a systematic investigation based on the principles of falsifiability and critical scrutiny with the goal to offer insights into potential interventions, policies, and strategies to create environments that promote physical activity and well-being.

1.5 Theoretical foundations and conceptual considerations linking urbanicity and green space with physical activity and health

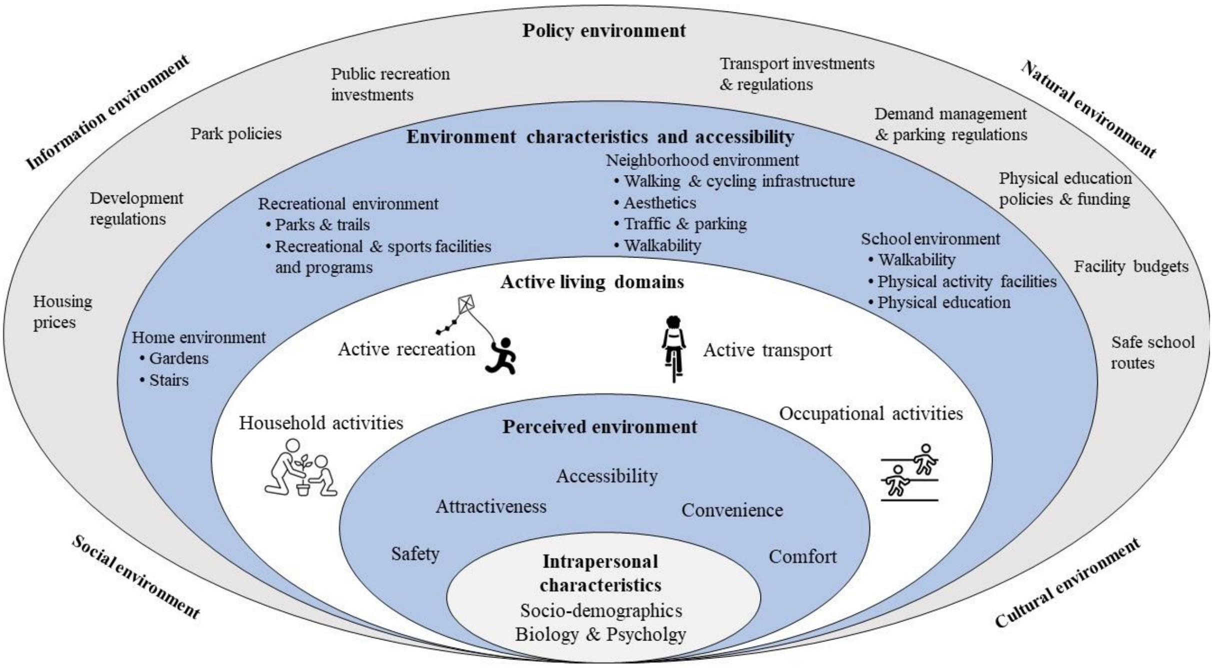
1.5.1 Socio-ecological models of health and health behaviors

Socio-ecological models are important conceptual models when investigating the environment in relation to health and physical activity. Socio-ecological models acknowledge multiple influences across different levels, ranging from intrapersonal determinants (e.g., socio-demographic characteristics and psychological constructs) over social and physical, setting-specific characteristics, to the policy level. Such models have been applied both for research and practice regarding the determinants of health (Dahlgren & Whitehead, 1991) and health behaviors, including physical activity (Sallis et al., 2006; Sallis & Owen, 2015). Socio-ecological models postulate that environmental contexts are key determinants of physical activity. Simultaneously, they consider multiple factors within and across levels that influence health and health behaviors, making multi-level interventions the most promising strategy to impact health and health behaviors on a population level (Sallis & Owen, 2015). Focusing on physical activity, Sallis et al. (2006) specified a socio-ecological model based upon empirical findings and concepts of, amongst others, behavioral science, transport and city planning, leisure science, and public health tailored to physical activity behavior. Physical activity behavior is considered as the result of person-environment interactions. The model distinguishes between four physical activity domains, namely household, recreational, active transport, and occupational physical activity, with both specific and commonalities regarding their environmental influences. (Sallis et al., 2006; see also *Figure 5*).

Socio-ecological models have their strength in considering multiple influences across different levels, providing a framework or "meta-model" to integrate multiple approaches and theories into one comprehensive approach (Sallis & Owen, 2015). Through the consideration of these multiple influences, it brings people from different sectors together (e.g., public health and transport planning) and is appreciative of the different expertise, hence supporting a multisectoral approach (Dahlgren & Whitehead, 2021), which is needed to enhance physical activity (WHO, 2018). Finally, it focuses on facilitators and determinants of health behaviors and health, instead of a medicalized approach, which focuses on specific risk factors or barriers, resulting in comprehensive strategies that target main determinants of health and health behaviors and allow (co-)benefits across multiple areas (Dahlgren & Whitehead, 2021). For example, when considering green space as one determinant, this can facilitate physical activity, enhance mental health, and help to mitigate effects of climate change, especially in cities (Bratman et al., 2019; Demuzere et al., 2014; Remme et al., 2021; Zhang et al., 2017). Finally, with the socio-ecological model's focus on the physical environment and policies, it is expected that related changes would have an impact on the whole population in the relevant area and not only on the ones deciding to participate in an individual-level program (Sallis & Owen, 2015).

At the same time, there are several limitations of socio-ecological models that should be considered. While socio-ecological models summarize relevant determinants relating for health (behaviors), such as physical activity, they are lacking specificity regarding mechanisms and hypotheses *how* the determinants relate to the specified health outcome or behavior (Sallis & Owen, 2015). Hence, based upon the critical rationalism, the model as a whole cannot be falsified, but only specific associations investigated based upon the model. While the model specifies that there are multiple influences, it is unclear how those influences interact within and across levels, which would be important to be specified to develop effective interventions. Finally, while the strength of the model is that it considers multiple influences, which have also been shown to shown stronger associations with the behavior of interest (Sallis et al., 2020), this makes it difficult to disentangle the relative importance of the single aspects and to identify the aspects that would be most crucial for health and health behaviors.

Figure 5. Socio-ecological model of physical activity



Model adapted from Sallis et al. 2006

Although socio-ecological models have not been specifically developed for the urban or rural context, several environmental determinants that have been show to facilitate physical activity in children and adolescents, such as walking and cycling infrastructure, short distance to daily facilities, mixed land use, park, and playground equipment, as well as better walkability (Nordbø et al., 2020; Smith et al., 2017), are typically more common in urban areas (Sallis et al., 2016). Hence, from a theoretical lens, it would be hypothesized that children and adolescents living in urban areas display higher levels of physical activity. While there is no consensus regarding the definition of urban or rural areas (McCormack & Mendeering, 2016), urban areas are characterized through higher population density, economic and social organization, and through a large proportion of built instead of natural environments, while rural areas refer to any place not being urban (Weeks, 2010). However, it should be acknowledged that urban and rural areas are the ends of a continuum rather than dichotomous categories (Week, 2010).

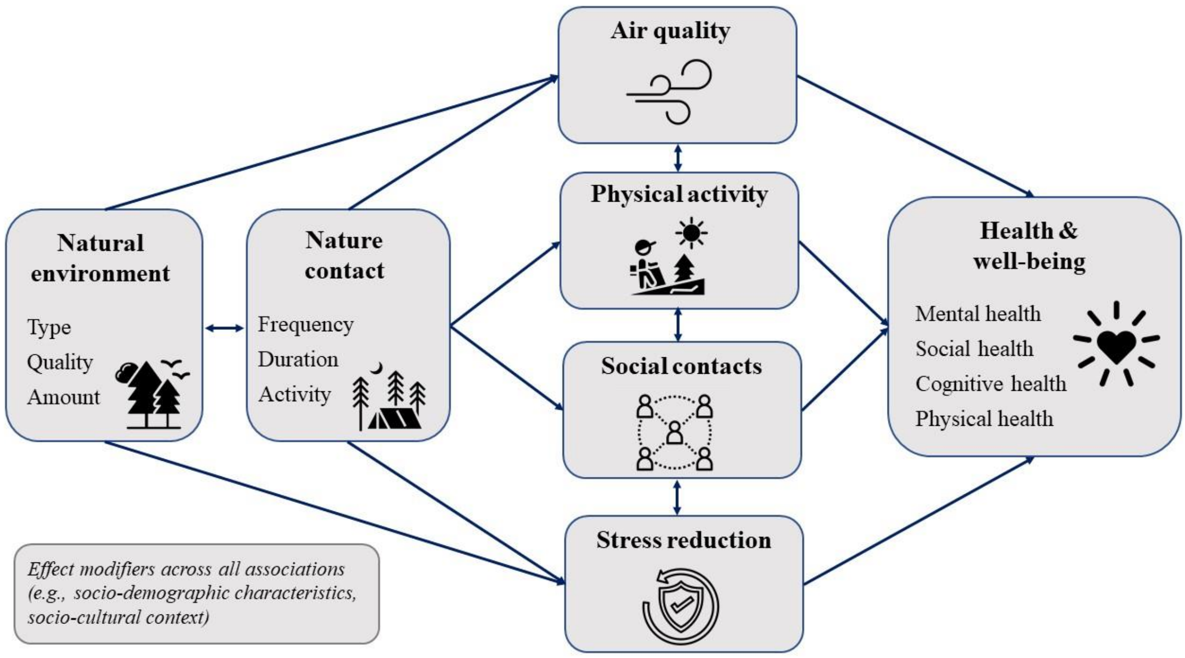
1.5.2 Pathways linking natural environments to health

As outlined in section 1.3 and presented in *Figure 3*, natural environments and green space have gained increasing interest from the research community in the health context. While there is no consensus definition regarding the natural environment, in the context of this dissertation, based upon Hartig et al. (2014), natural environments are considered as landscapes comprising physical processes and features of non-human origin which can be perceived by individuals, which includes all elements of nature, such as flora and fauna, animals, and water. In the context of this work, we consider both real-life (e.g., parks, forest) and digital (e.g., presented on a screen or via virtual reality) natural environments.

Based upon a comprehensive examination of research on the pathways between greenspace and health, Hartig et al. (2014) developed a comprehensive model that outlines the mechanisms through which natural environments unfold their positive impact on health and well-being. The authors identified four main pathways through which natural environments lead to enhanced health and well-being, including better air quality, enhanced physical activity, increased social cohesion, and stress reduction. Regarding air quality and stress reduction, the model suggests that benefits occur not only with direct exposure to the environment, but also through reducing exposure to harmful environmental conditions (e.g., reduced air pollutants; Islam et al., 2012; reduced road traffic annoyance; Schäffer et al., 2020).

For natural environments to facilitate physical activity and social contacts, this requires direct nature contact. Hartig and colleagues suggest that natural environments allow for certain activity types that are only possible in natural environments (e.g., hiking) and through the experiences it can offer. Regarding social cohesion, the model suggests that natural environments facilitate positive and friendly relationships as well as belongingness. Associations between the natural environment and nature contact as well as between nature contact, each single pathway, and the pathway and the outcome, is subject to potential effect modifiers that range from socio-demographic characteristics (e.g., gender or socio-economic status) to context perceptions (e.g., perceived safety) and socio-cultural aspects (e.g., cultural importance of nature).

Figure 6. Pathways between nature and health.



Model adapted from Hartig et al. (2014)

1.5.3 Affordances theory – linking natural environments and physical activity

The model suggested by Hartig et al. (2014) provides a useful framework to understand how nature unfolds its health benefits, including physical activity as one potential mechanism. However, the model is not very useful in explaining *why* natural environments are inducive to physical activity. For this, the theory of affordances provides a useful framework. Originating from an ecological dynamic framework, the concept of "affordances" was initially introduced by Gibson (1979) and then further developed (Heft, 1988, 1989, 2010). In this framework, humans are conceptualized as active agents that are not only passive receivers of environmental stimuli, but build a relationship with their surroundings, resulting in a dynamic person-environment system. From this understanding, any object that one perceives in the environment provides potential affordances, referring to actions or behaviors that are made possible by the environmental perception (Gibson, 1979). Hence, affordances are environmental characteristics in relation to an individual with functional meaning. Environmental function and meaning are not objective, but are qualities represented in the dynamic relationship between environmental features and individuals (Heft, 1989, 2010). For example, a bench in a park is an object that has the same measured dimensions or form for any person; however, the affordances of the park bench may differ: For an older adult taking a walk in the park, the bench may elucidate the action to sit down and take a break; for a couple with a baby, the bench may afford to change the diapers; and for an eight-year-old girl, the bench may afford to jump up on it and down again. This example demonstrates that affordances are about actions guided by environmental characteristics, about activities that someone may engage in cued by certain environmental features (Heft, 2010). Gibson (1979) also postulates that affordances can be simultaneously positive (beneficial) and negative (injurious), i.e., a tree affords climbing up on the one side, while it can also afford falling. Heft (2010) further distinguishes between potential and actualized affordances, i.e., the environment offers multiple potential affordances between and within objects, while the individual only perceives and utilizes a subset of this (actualized affordance). For example, perceiving a large rock offers multiple affordances to a child: climbing up, jumping down, running around it, sitting on it, kicking it – there would be several ways how this rock can be utilized. If the child ignores the rock and walks by, this constitutes a potential affordance, climbing up and jumping down would constitute two actualized affordances.

While affordances are in general applicable to any object in the environment that can be perceived, this provides also a useful framework regarding the physical activity-promoting potential of natural environments. Criticizing that affordances are only theoretically infinite, Costall (2012) introduced canonical affordances as a concept, considering that the use and function of many objects is socio-culturally determined (e.g., a chair is for the action sitting), thus restricting affordances. In contrast, natural environments compared to manufactured environments are less restricted by such canonical affordances, and hence provide more affordances and variability in physical activity opportunities compared to manufactured environments (Araújo et al., 2019). For example, when a child is using a pedestrian path along a busy road, the affordances along this road are probably restricted to walking, and while there may be other potential affordances (e.g., a streetlight, a fence), they are not supposed to be utilized. In contrast, if the child is walking along a path in a park, there might other environmental features (e.g., tree trunks, benches, water-based areas) that afford other activities beyond walking and with less socio-cultural restrictions regarding their use.

One of the strengths of affordance theory is the emphasis on the direct perception of opportunities for action in the environment. Gibson (1979) argued that perception is not solely based on the processing of sensory information, but is inherently linked to the possibilities for action that the environment presents. This perspective challenges traditional information-processing approaches that prioritize internal mental representations and cognitive processes. Moreover, affordance theory recognizes the inherent subjectivity of affordances. It acknowledges that affordances are not objective properties of the environment but are relational and dependent on the characteristics and goals of the perceiving individual. This perspective aligns with the idea that perception is not a passive reception of stimuli but an active engagement with the environment. It emphasizes the role of the individual's perception-action coupling, highlighting the dynamic and reciprocal nature of the relationship between individuals and their surroundings.

Simultaneously, affordances theory neglects both higher-level cognitive processes in the person- for perception and actualization of affordances, such as motivation, intention, goals, attitudes, or values. In addition, the social and cultural influences that shape affordance perception receive little attention. Since human behavior is profoundly influenced by psychological constructs, social norms, and cultural practices (Ajzen, 1991; Bandura, 1986), neglecting these aspects may limit the explanatory power of the theory and its applicability to complex human behaviors.

1.5.4 Extending affordances as a conceptual framework for nature-based physical activity

So far, models and theories how environmental features promote physical activity have been presented. Going one step further, the question arises if the built environment does not only facilitate, but may also moderate the impact of physical activity on health, especially on mental health. Within this context, the concept of nature-based physical activity, originally called “green exercise”, emerged, referring to any physical activity that is conducted while being exposed to nature (Pretty et al., 2003) and which has been hypothesized to have additive or synergistic health effects when combining natural environments and physical activity (Shanahan et al., 2016).

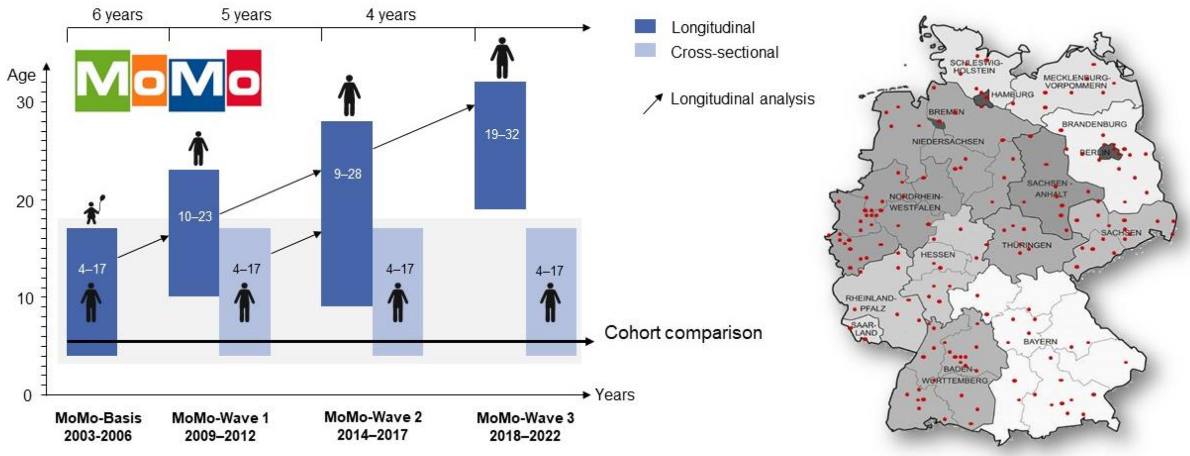
Regarding the *why* physical activity in natural environments should yield more health benefits than physical activity in manufactured environments, Araújo et al. (2019) utilize the concept of affordances and argue that distinct affordances in natural environments require more flexible movements during physical activity, so called “degeneracy”, fostering movement adaptability and creativity. This means that individuals have to come up with different movement solutions to actualize affordances in diverse, variable natural environments consisting of different textures, surfaces, ledges, and barriers compared to more uniform, manufactured environments. Furthermore, the authors argue that this variability in the natural environment requires the individual to be involved with the natural environment, thus going beyond immersion, but requiring that the individual actualizes the affordances through exploration and discovery in natural environments while exerting physical activity. This does not only require skills and mastery from a movement perspective, but also continued psychological engagement via perceiving and adapting to the natural environment while moving. This comprehensive engagement is hypothesized to lead to enhanced health and well-being benefits (Araújo et al., 2019).

1.6 The Motorik-Modul (MoMo) Study

Before presenting the articles that built upon the previously presented theoretical and conceptual considerations, a brief overview regarding the MoMo study is provided since five out of eight articles included in this dissertation utilized data from this study. The Motorik-Modul (MoMo) Study is a nationwide study in Germany (Woll et al., 2021) which started out as an in-depth study within the German Health Interview and Examination Survey for Children and Adolescents (KIGGS) conducted by Germany’s public health Robert Koch Institute (Hölling et al., 2012; Kurth et al., 2008). It has been funded by the Federal Ministry of Education and Research (funding reference number: 01ER1503) within the research program ´long-term studies` in public health research. The study uses a cohort sequence design, which means that in addition to following-up with participants since baseline, in addition to the participants examined longitudinally, a representative sample of children and adolescents between four and 17 years was recruited based on census tract data regarding age, gender, migration, and social status at each follow-up. Baseline data (MoMo Basis) was collected between 2003 and 2006 (Woll et al., 2011), with follow-ups between 2009 and 2012 (Wave 1), 2015 and 2017 (Wave 2), and

2018 and 2022 (Wave 3; Woll et al., 2021). Data collection for Wave 3 was initially planned from 2018 to 2020, but had to be interrupted due to the Covid-19 pandemic. Hence, data collected between 2018 and 2020 prior to the Covid-19 pandemic is referred to as Wave 3.1 (data collection during lockdown one: Wave 3.2, lockdown two: Wave 3.3, and after the restrictions were lifted: Wave 3.4). For this dissertation, data was mostly utilized from MoMo Basis to Wave 3.1, i.e., without the influence of the Covid-19 pandemic (Chapters 2-5), and for one work with data before and during the first lockdown (Waves 3.1 and 3.2; Chapter 7). Study participant selection was based upon a multi-stage sampling approach with two evaluation levels (Kamtsiuris et al., 2007): First, a systematic sample of 167 primary sampling units was selected from an inventory of German communities stratified according to the classification system that measures the level of urbanization and geographic distribution. Second, based on the official registers of local residents, an age-stratified sample of randomly selected children and adolescents was drawn. For measurement purposes, participants were invited to examination rooms within proximity to their homes, where they filled out a questionnaire, participated in various fitness tests, and, from T3 onwards, were asked to wear an accelerometer for the coming week. The study was conducted according to the Declaration of Helsinki. Ethics approval was obtained by the Charité Universitätsmedizin Berlin (MoMo Basis) ethics committee, by the University of Konstanz (Wave 1) and the Karlsruhe Institute of Technology (Wave 2 and Wave 3). The Federal Commissioner for data protection and freedom of information was informed about the study and approved it. Participants and their parents were informed in detail about the study and data management and provided written informed consent.

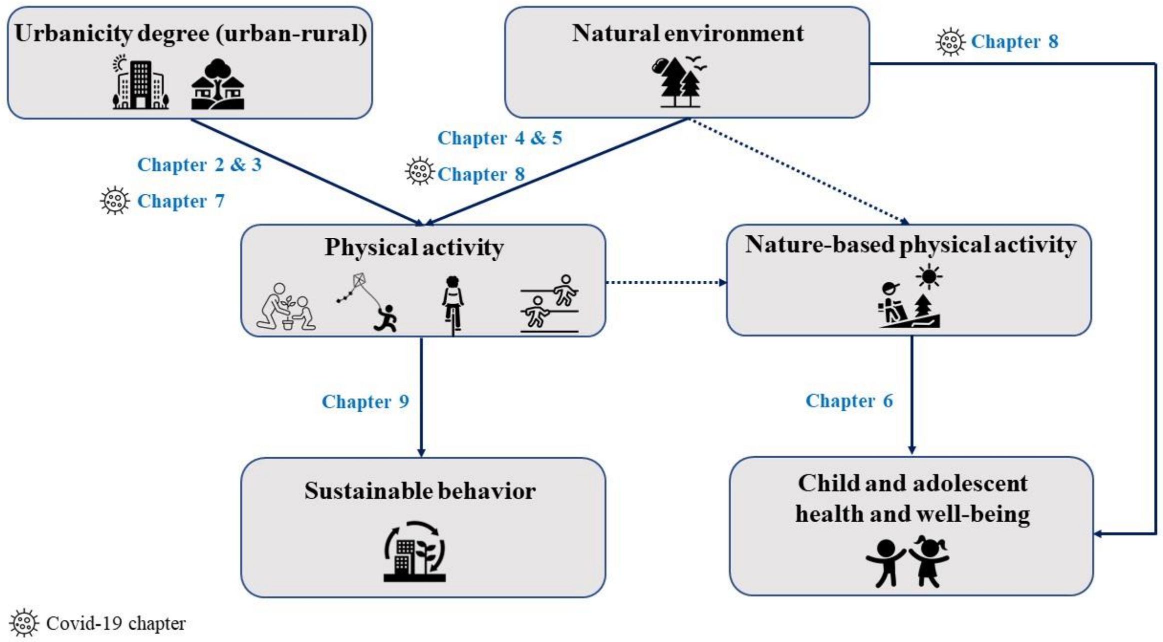
Figure 7. Study design and sampling points of the MoMo Study.



1.7 Summary and synthesis of the articles included in the dissertation

Building upon the theoretical and conceptual considerations elaborated on previously, empirical evidence and research gaps for the relevant topics of this dissertation will be presented in the next paragraphs together with the main findings of the research conducted in the context of this dissertation.

Figure 8. Structure of the dissertation



Regarding children's and adolescent's physical activity engagement, a recent meta-analysis showed that between 1995 and 2017, children's and adolescent's overall physical activity declined in developed countries (Conger et al., 2022), while trends across physical activity domains, such as organized sports or leisure physical activity, varied (Mathisen et al., 2019; Schmidt, Anedda, Burchartz, Oriwol, et al., 2020). However, these studies did not specify how physical activity developed across urban and rural areas against the background that urban and rural areas experienced drastic changes across the last two decades (Federal Ministry of Food and Agriculture, 2020; Brown & Schafft, 2019; UN, 2018): In Germany, cities are growing in number and size, while rural areas are characterized by people with higher education moving to cities, an aging population, and deteriorating infrastructure (Federal Ministry of Food and Agriculture, 2020; UN, 2018). These changes may also reflect in different physical activity trends across urban and rural areas.

Looking at **empirical evidence to date**, a systematic review about children's and adolescent's urban-rural physical activity and screen time differences in the US found that in the majority of studies, higher physical activity and higher screen time levels were more common in rural compared to urban youth (McCormack & Meendering, 2016). While these studies only looked at physical activity and screen time at one time point, studies investigating physical activity engagement in urban and rural areas across time are scarce, but show detrimental trends for physical activity and screen time for children and adolescents in rural areas (Corder et al., 2015; Cui et al., 2011). In adults across 28 countries of the European Union, physical activity declined across both urban and rural areas, but stronger declines were observed in rural areas (Moreno-Llamas et al., 2021). However, **it is unknown** if this trend is generalizable to Germany's pediatric population.

Issue 1
How has physical activity developed across urban and rural areas in Germany's child and adolescent population?

Hence, the **first article** (Nigg, Weber, et al., 2022) of this dissertation examined physical activity, and to complete the picture, screen time trends in Germany's child and adolescent population across urban and rural areas. Using weighted data from the MoMo Study between 2003 and 2017, the study revealed declining physical activity (total and leisure physical activity as well as outdoor play) and increasing screen time trends in rural areas. While some trends were also observed in urban areas (decreasing leisure physical activity and outdoor play; increasing computer and gaming time), the detrimental trends were strongest for rural areas.

These results show that rural areas are most affected by detrimental physical activity trends. The strength of this study was that it investigated physical activity and screen-time trends across different domains, providing important information regarding which physical activity domains could be intervened upon in urban and rural areas to counter declining trends and promote physical activity. However, urbanicity was categorized based upon the common German system for political community sizes (Research Information System on Mobility and Traffic, 2020; Wittwer, 2008), which is solely based on the population size. Other urbanicity assessments, such as the European Degree of Urbanisation (DEGURBA), using a combination population size, population density, and geographical contiguity (EU et al., 2021; eurostat), allow more advanced urbanicity assessments. In addition, the questionnaire-based assessment comes with some limitations, including self-report bias (Nigg et al., 2020) as well as a focus on exercise domains, neglecting other important domains such as active travel (Rainham et al., 2012; White et al., 2021).

To overcome these limitations, device-based physical activity assessment provides a valuable opportunity to determine moderate-to-vigorous physical activity (MVPA), the specified intensity for health-enhancing effects in the WHO (2020) guidelines. In addition, this methods is not prone to self-report bias, thus being a valuable addition to self-reported information across physical activity domains (Burchartz et al., 2020). Looking at **evidence to date** regarding studies with accelerometer-assessed MVPA across urban and rural areas, there were mixed findings, with some studies supporting more physical activity of children and adolescents living in rural areas (Manyanga et al., 2019), others finding no urban-rural differences (Euler et al., 2019; McCrorie et al., 2020), and others supporting more activity of children in urban areas (Machado-Rodrigues et al., 2014; Rainham et al., 2012). These heterogenous findings together with limitations regarding the geographical generalizability to Germany (e.g., studies from or Mozambique; Manyanga et al., 2019; or New Zealand; White et al., 2021) and a focus on adolescents do not allow conclusions regarding urban-rural differences of device-based physical activity in Germany's children and adolescents.

Issue 2
How do urban and rural children and adolescents differ in their device-based assessed physical activity?

Hence, the **second article** (Reichert et al., under review) investigated urban-rural differences in MVPA as well as WHO (2020) physical activity guideline compliance in Germany's youth (6-17 years) utilizing accelerometer-data of the MoMo Study. To assess urbanicity, both the urbanicity system of political community sizes and the European Degree of Urbanization were employed. The results showed that compared to rural youth, city youth demonstrate higher engagement in MVPA, with generalizable findings across age groups and gender. City youth are more inclined to adhere to the physical activity guidelines, which was especially pronounced for girls as well as younger children (six to ten years) and adolescents (14 to 17 years).

These findings complement the findings from the first article, supporting the trends reported in the first article. To understand in more detail how the surrounding environment relates to children's and adolescent's physical activity behavior and health, this dissertation investigates green space as an important environmental attribute that has gained increasing interest in the context of climate change and urbanization (Cui et al., 2021; Kabisch et al., 2017; Nassary et al., 2022; Schwaab et al., 2021). To assess green space objectively, using geographic information systems (GIS) is considered state-of-the-art methodology, especially when individuals are dispersed across a large area (Brownsown et al., 2009), such as all over Germany. GIS describes comprehensive systems to create, administer, analyze, and geographically represent various data, integrating both location data (where something is located) and descriptive characteristics (what something looks like there; esri, n.a.). Although green space has been hypothesized to be an important facilitator of children's and adolescent's physical activity and health from a theoretical perspective, empirical findings based upon different GIS-based measure of green space (e.g., distance to or type of green space, count or proportion of green space) and youth physical activity and health are highly heterogenous (Nordbø et al., 2020). These inconsistent findings could be partially due to prevailing methodological problems. In terms of methodology, there is a lack of consensus on how to evaluate the built environment using GIS in health research. Previous reviews have shown that measures derived from GIS to assess the built environment, physical activity and health vary significantly and lack clear definitions, making it difficult to compare findings across studies (Brownson et al., 2009; Nordbø et al., 2018). This also brings the problem of the modifiable areal unit problem, which means that the relationship between spatial variables and the outcome depends on the arbitrary chosen spatial aggregation size (scale problem) and the spatial aggregation level (zone problem) (Jelinski & Wu, 1996; Openshaw, 1984). Looking at the **evidence to date**, the modifiable areal unit problem has been repeatedly reported in studies examining geographical contexts, but predominantly with adults (Clark & Scott, 2014; Jakobsen, 2021; Klompmaker et al., 2018; Mavoa et al., 2019; Mitra & Buliung, 2012; Yamada et al., 2012). In addition to the lack of studies in children and adolescents, studies are missing that explored different operationalizations of natural environments in conjunction with different spatial configurations, and that investigated those associations across different health and health behaviors domains, taking the socio-demographic characteristics of the study participants into account.

Issue 3
Which impact does the geospatial and conceptual configuration of the natural environment have on the association with children's physical activity, physical fitness, and mental health?

In this **third article** (Nigg, Niessner, et al., 2022), address data from MoMo's participants was geocoded and based upon land use and land cover data, three different GIS-based concepts for the natural environment were employed. For each one, different spatial configurations consisting of circular and street-network-buffers of different sizes around participant's residential address were derived. The results showed that relationship between the natural environment and the three outcomes investigated (physical activity, physical fitness, and mental health) varied considerably depending not only on the spatial and conceptual configuration, but also on socio-demographic characteristics. Based upon these results, a conceptual framework and guiding questions were developed that combine geospatial and conceptual considerations, and which can be used to decide for a natural environment measure in future environment and health (behavior) research studies.

The results of this third article indicated that the geospatial and conceptual configuration of the natural environment should be carefully considered when deciding for an exposure measure in relation to children's and adolescent's physical activity and health. To further advance our understanding regarding green space and physical activity, it is important to understand which role the geographical green space context plays, i.e., to understand how green space relates to children's and adolescent's physical activity across urban and rural areas. However, green space research has mostly intensified in the context of cities (Zhang et al., 2020). Since green space characteristics differ between urban and rural areas (King & Clarke, 2015; Veitch et al., 2013), this may also translate to different associations with physical activity. **Evidence to date** regarding associations between green space and physical activity across urban and rural areas is scarce (Hansen et al., 2015), with the few existing studies showing that green space was positively associated with physical activity in both urban and rural areas (Babey et al., 2008; Craggs et al., 2011), while a study with older adolescents in Germany yielded inconclusive results (Markevych et al., 2016).

Issue 4
How does green space relate to children's and adolescent's physical activity across urban and rural areas in Germany?

In this **fourth article** (Nigg et al., under review), data was again utilized from the MoMo Study and based upon geospatial and conceptual considerations derived from the third article, green space was operationalized within a 1000m street-network buffer including green space without agricultural areas around participant's residential address and divided into quartiles. The results showed that associations between green space and MVPA differed across urban and rural areas: Children and adolescents in rural areas with some compared to no green space engaged in less MVPA. The opposite was observed for cities: There, boys and younger children engaged in more MVPA with some compared to no green space. However, in cities, low socio-economic status youth engaged in less MVPA with more green space.

This fourth article shows that when considering green space as a correlate of physical activity, the association depends on children's and adolescent's urbanicity status and socio-demographic characteristics. In the next step, this dissertation moves beyond the natural environment as a correlate, but as a context factor during physical activity engagement that may impact the health effects of physical activity. While both physical activity and natural environments are beneficial for children's and adolescent's health (Chaput et al., 2020; Zare Sakhvidi et al., 2023), it is unclear if combining both in the form of nature-based physical activity yields synergistic health effects (Shanahan et al., 2016). **Evidence to date** comparing nature-based physical activity to indoor physical activity or physical activity in urban environments without natural features shows that nature-based physical activity has a positive effect on a range of well-being outcomes, including higher positive and lower negative affect, decreased anxiety and depression, as well as salutogenic effects on stress-related brain regions (Coventry et al., 2021; Lahart et al., 2019; Sudimac et al., 2022; Thompson Coon et al., 2011; Wicks et al., 2022). However, these studies only investigated health outcomes in adults.

Issue 5
Is nature-based physical activity more beneficial for children's and adolescent's mental and physical health than physical activity in non-natural environments?

In this **fifth article** (Mnich et al., 2019), the available literature regarding associations between nature-based physical activity and psychosocial and physiological health parameters in children and adolescents was synthesized in a systematic literature review, including 14 studies. Based upon consistently weakly rated evidence, there were no differences between nature-based physical activity and physical activity in non-nature settings for the health outcomes under investigation.

Up to now, this dissertation investigated urban-rural areas, natural environments, and physical activity and health under normal circumstances. With the arrival of the Covid-19 pandemic in March 2020, the daily structure of most people across age groups around the world was disrupted: During the first lockdown, important institutions of children's and adolescent's life were closed, including kindergartens, schools, and leisure facilities. Based upon the structured day hypothesis (Brazendale et al., 2017), this was expected to have a negative impact on children's and adolescent's obesogenic behaviors, including physical activity, that are typically more regulated in a structured context. **Evidence to date** summarized in reviews shows that children's and adolescent's total physical activity declined during the Covid-19 lockdown, especially for MVPA (Kharel et al., 2022; Neville et al., 2022; Paterson et al., 2021; Stockwell et al., 2021). Although the negative impact was consistently found in the available literature, there was little research regarding how the geographical context, such as urban-rural living, impacted physical activity during that time (Do et al., 2022). Regarding the impact of Covid-19 on physical activity in Germany during the first lockdown, contrasting results were found compared to the international literature: Children and adolescents increased overall physical activity and daily life physical activity, but decreased sports activity (Schmidt, Anedda, Burchartz, Eichsteller, et al., 2020).

So far, this dissertation showed that urban living is beneficial for children's and adolescent's physical activity (Nigg, Weber, et al., 2022; Reichert et al., under review). However, during the lockdown phase, physical activity engagement may had been more difficult in urban compared to rural areas due elevated Covid-19 related fear in urban areas (Schweda et al., 2021), density issues in open space hampering physical distancing, as well as closed facilities and daily physical activity routines (e.g., cycling to school) (Klinker et al., 2014) that were the same for urban and rural areas, but may have had a stronger impact in urban areas.

Issue 6
How has the first Covid-19 lockdown impacted children's and adolescent's physical activity in urban and rural areas in Germany?

This **sixth article** (Nigg et al., 2021) investigated how population density predicted Covid-19 related changes in children's and adolescent's physical activity using longitudinal data from the MoMo Study collected prior the Covid-19 lockdown and during the first lockdown in April 2020. Extending previous results showing positive changes in children's and adolescent's physical activity during the lockdown (Schmidt, Anedda, Burchartz, Eichsteller, et al., 2020), the results of this work showed that these changes were predominantly due to overall and daily life physical increases of children and adolescents living in places with lower population density, while physical activity increases diminished with increasing population density.

Beyond the impact on physical activity, the Covid-19 pandemic had a tremendous effect on psychological health and well-being across all age groups, with especially psychiatric symptoms and feelings of loneliness having exacerbated during this time (Bonati et al., 2022; Lee et al., 2020; Loades et al., 2020; Vindegaard & Benros, 2020; Wunsch et al., 2021; Xiong et al., 2020). There are first indications that the pandemic's impact will be long-lasting across several domains, including lower physical activity (Koch et al., 2022; Salway et al., 2022), mental health (Iqbal et al., 2020), the development of children born during the pandemic (Wenner Moyer, 2022) as well as their future welfare (Fuchs-Schündeln et al., 2022). Although Covid-19 related restrictions in everyday life have been dropped in most places, this pandemic serves as an example of societal crisis that is relevant for global public health, and thus, learning from this crisis is critical for potential future challenges on the social level, e.g., when facing consequences of climate change (Cattaneo et al., 2019; Thiery et al., 2021), as well as when facing critical challenges on the personal level (Dohrenwend & Dohrenwend, 1974). This includes learning about environmental characteristics, including green space, that build resilience and empower people to promote their health and health behaviors during a crisis (Holmes et al., 2020; Kola et al., 2021) and beyond (WHO, 1986). **Evidence to date** shows that prior to the Covid-19 pandemic, exposure and access to nature are related to improved well-being and mental health across age groups (Barboza et al., 2021; Bratman et al., 2019; De Bell et al., 2020; Engemann et al., 2019; Jarvis et al., 2021; Kolokotsa et al., 2020; Tost et al., 2019; White et al., 2020) and are an important resource for health behaviors and buffering stressful life events (Beavers et al., 2020; Davis et al., 2011; Remme et al., 2021; Van Den Berg et al., 2010). While these studies were conducted under normal circumstances, the Covid-19 pandemic was an opportunity to conduct research on natural environments, psychosocial health, and health behaviors in a public health crisis situation.

Issue 7
What do we know about the scientific literature regarding the associations between natural environments and psychosocial health as well as health behaviors in the COVID-19 context?

Hence, this **seventh article** investigated which types of nature as well as which health behaviors and psychosocial health outcomes were explored across age groups in relation to natural environments during the Covid-19 pandemic using a comprehensive scoping review including 188 articles from studies in predominantly western countries. Overall, the findings indicate that natural environments have a large potential to buffer the impact of stressful events on mental health and physical activity. Based upon the synthesized research, this scoping review suggests future research directions to enhance our understanding of natural environments as a facilitator of health (behaviors), including a) identifying the health-promoting characteristics of natural environments, b) investigate the potential of virtual and digital nature, c) investigate their potential from a salutogenic, health promotion understanding instead of a medicalized risk factor understanding, d) investigate the underlying mechanisms for heterogenous associations in the nature-health relationship across human, nature, and geographic characteristics, and e) intensify research on vulnerable groups, including children and adolescents.

The previous seven articles investigated the environment as a key factor for physical activity and health in line with **models and frameworks to date** (Hartig et al., 2014; Sallis et al., 2006). However, only recently, there has been growing interest about physical activity as an antecedent of a healthy environment and sustainable development, predominantly in the context of climate change (Bernard et al., 2021) and active travel (Brand et al., 2021). However, physical activity has the potential for a larger impact on sustainable development that goes beyond climate change: The WHO's (2018) *Global Action Plan on Physical Activity* provides an overview how physical activity can contribute to the United Nation's Sustainable Development Goals (SDGs) (UN, 2015), with this overview focusing mostly on the structural and political level. However, to achieve sustainable developments, it is necessary to intertwine political actions and individual behavior change (IPCC, 2018; Whitmee et al., 2015; WHO, 2018). Combining concepts from multiple health behavior change (Knäuper et al., 2004; Nigg et al., 2009) and the concept of co-benefits (Paul et al., 2016), physical activity may serve as a sustainable behavior with favorable behavior changes beyond environmental aspects.

Issue 8
How can physical activity be conceptualized as a sustainable behavior in the context of the United Nation's Sustainable Development Goals?

Hence, this final **eight paper** (Nigg & Nigg, 2021) conceptualizes physical activity as an individual-level sustainable behavior that has the potential to serve as and lead to other individual-level behaviors that contribute to six predominant social sustainable development goals (SDGs 2-4, 10-11) and two predominant ecological sustainable development goals (SDGs 12-13). Simultaneously, this article acknowledges that physical activity can also contribute to and reinforce behaviors countering these goals. Hence, a research agenda is suggested to investigate a) physical activity as a social and ecological behavior, b) sustainable physical activity promotion, c) sustainable physical activity measurement, d) psychological constructs that can promote both physical activity and sustainable behaviors, and e) technology's role to promote and assess sustainable physical activity.

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CHAPTER 2

Urban-rural physical activity trends of children and adolescents in Germany

Slightly modified version of the 1st published article:

Nigg C., Weber, C., Schipperijn, J., Reichert, M., Oriwol, D., Worth, A., Woll, A., & Niessner, C. (2022). Urban-Rural Differences in Children's and Adolescent's Physical Activity and Screen Time Trends Across 15 Years. *Health Behavior & Education, 49*(5), 789-800.
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Introduction

Physical activity has numerous health benefits (Poitras et al., 2016) while sedentary behavior, specifically screen time, is related to negative health outcomes and mental health problems in children and adolescents (Boers et al., 2019; Nigg et al., 2021). However, only about 20% of youth meet the physical activity recommendations of the World Health Organization (Guthold et al., 2020) while about 88.2% of adolescents spend more than two hours on screen time every day (Ghekiere et al., 2019).

A recent study showed that physical activity assessed via pedometers and accelerometers declined across the last two decades in children and adolescents in developed countries (Conger et al., 2022). Looking at trends across physical activity domains, in Finland and Norway, both participation in organized sports and leisure-time vigorous physical activity increased between 1985 and 2014 (Mathisen et al., 2019). For organized sports participation, similar trends were observed in Germany between 2003 and 2017, but leisure-time physical activity decreased (Schmidt et al., 2020). Looking at trends across screen time domains, results from 30 countries showed that TV watching slightly decreased across most of the countries, while there was a sharp increase in computer use (Bucksch et al., 2016).

However, it is unclear how physical activity and screen time have developed in rapidly changing urban and rural areas across the last two decades (Federal Ministry of Food and Agriculture, 2020; Brown & Schafft, 2019; UN, 2018). These changes are characterized by cities growing both in number and size, with an estimated 60% of the world's population living in cities by 2030 (UN, 2018), while in Germany, especially rural areas are affected by an aging population and people with higher education moving away (Federal Ministry of Food and Agriculture, 2020). In rural areas, these demographic changes are connected to changes in the infrastructure, such as fewer public transport options, schools, shopping and leisure facilities, and education opportunities (Federal Ministry of Food and Agriculture, 2020). These structural changes may also influence children's and adolescent's physical activity: Based on ecological models of health behaviors, environmental aspects, such as traffic safety, walkability, cycling infrastructure, and parks, are crucial for physical activity (Sallis & Owen, 2015). Looking at empirical evidence of environmental correlates of physical activity, infrastructure for walking and cycling, short distances to facilities, better walkability, mixed land use, as well as park and playground equipment have been positively related to youth's physical activity (Nordbø et al., 2020; Smith et al., 2017). These features are commonly more prevalent in urban areas (Sallis et al., 2016), while those aspects may have deteriorated in Germany's rural areas due to demographic and structural changes.

Although ecological models also assume environment influences on sedentary behavior (Owen et al., 2000), less studies investigated built environment correlates of sedentary behavior and screen time in children and adolescents. In US adolescents, walkability was associated with lower total sedentary behavior and TV watching (Sallis et al., 2018). In another study in the US, physical activity promoting features, such as walking and cycling infrastructure and recreational facilities, were associated with less sedentary behavior of adolescents in boroughs or cities, but not in townships (Poulsen et al., 2018).

Regarding empirical evidence about urban-rural physical activity and screen-time differences, empirical findings are inconsistent: In a systematic review including 16 studies with youth between two and 19 years in the USA (McCormack & Meendering, 2016), nine studies indicated that rural youth are more active than urban youth, five studies did not find any differences, and one study supported more physical activity in urban youth. Three studies indicated that screen time was higher in rural populations. Yet, different operationalization and assessment methods of physical activity, a lack of device-based assessment methods, and varying definitions of the rural category limited conclusions (McCormack & Meendering, 2016). While the previous review found mostly support for rural youth being more active than urban youth, using accelerometers, Machado-Rodrigues et al. (2014) observed that urban 13-16-year old adolescents in Portugal were more physically active than their rural counterparts and spent less time in sedentary behavior. Similar results for moderate-to-vigorous physical activity were obtained in another study using accelerometer assessment in 7^{th} grade students in Canada (Rainham et al., 2012). In a more recent study in Scotland, rural youth spent 14 minutes less in sedentary behavior and 13 minutes more in light physical activity compared to urban youth while there were no differences in total and moderate-to-vigorous physical activity (McCrorie et al., 2020). However, the studies outlined above investigated physical activity at one timepoint in urban and rural areas, while little research has investigated physical activity trends in children and adolescents, and even less so in Europe (Booth et al., 2015), and across urban and rural areas. In a longitudinal study, 10-year old children in the UK were followed up over one and four years, showing that rural children had consistently lower moderate-to-vigorous physical activity levels than their urban counterparts and also experienced the strongest decline in moderate-to-vigorous physical activity (Corder et al., 2015). In a study in China, screen time trends in children between six and 18 years were investigated, with screen time increasing across both urban and rural areas, but sharper increases in rural areas (Cui et al., 2011). In Europe, we are only aware of one study in adults that investigated urban-rural differences in physical activity trajectories across 28 countries of the European Union, which showed that both in urban and rural areas physical activity decreased, but the trend was stronger for rural areas (Moreno-Llamas et al., 2021). However, it is unknown if this trend is also present in children and adolescents across the pediatric age range.

Thus, the purpose of this study was to investigate trends in physical activity and screen-time domains between urban and rural areas at three cross-sectional timepoints from 2003 to 2017 in a representative sample of children and adolescents in Germany.

Methods

Study design

Data was obtained from a cohort study in Germany (details blinded for peer-review) using a cohort-sequence-design. Hence, in addition to the longitudinal participants, at each study wave, a cross-sectional sample representative for Germany’s children and adolescent population was recruited. This study focusses on the periodic trends over time using data of the three repeated cross-sectional studies that is representative for Germany’s pediatric population at each measurement timepoint (T1: 2003-2006, T2: 2009-2012, T3: 2014-2017).

Participants were informed in detail about the study and data management and gave written consent. For participants under 18 years, parents gave written consent and for participants under the age of 15 years, the presence of a legal guardian during data collection was mandatory. For children under the age of eleven years, data was proxy-reported via the parents. The study was conducted according to the Declaration of Helsinki. Ethics approval was obtained (institution providing approval blinded for peer review).

Participants and procedures

At each measurement occasion, the aim was to select a representative sample of children and adolescents in Germany aged four to 17 years. Thus, study participants were selected based on a multi-stage sampling approach with two evaluation levels (Kamtsiuris et al., 2007): First, a systematic sample of 167 primary sampling units was selected from an inventory of German communities stratified according to the classification system that measures the level of urbanization and geographic distribution (Aschpurwis+Behrens GmBH, 2001). Second, based on the official registers of local residents, an age-stratified sample of randomly selected children and adolescents between four and 17 years was drawn. Parents and children were invited to examination rooms at central locations within proximity to their homes. The physical activity self-report questionnaire was filled out on site independently by the participants on laptops. For children younger than 11 years, parents completed the questionnaires.

To ensure the representativeness of the data, the sample was post-stratified and design weighting was applied using data from the German Micro Census 2004 (T1), 2010 (T2), and 2016 (T3) to reflect age, gender, region (Eastern/Western Germany), education level, and migration background. Longitudinal participants were not considered in the weighting process and thus excluded from our study. We decided not to use the longitudinal data as our goal was to analyze trends across cohorts at different time points to capture societal effects in a sample of children and adolescents that is representative for Germany’s pediatric population. In addition, for the longitudinal data, we have only about 500 participants that are in the age range of interest and completed all measurement timepoints, thus decreasing our sample size and mitigating the sample’s representativeness.

Measures

We assessed the level of urbanicity based on the German national categorization system for political community sizes, a categorization system that is used to investigate influences on mobility (Research Information System on Mobility and Traffic, 2020). While there is no consensus on political community sizes, the following categorization has been commonly applied in federal reports and statistics (Wittwer, 2008): 1) city (≥ 100,000 citizens); 2) medium-sized town (20,000 – 99,999); 3) small town (5,000 – 19,999), and 4) rural (< 5,000 citizens). We decided to use this system to allow for policy-relevant conclusions of our study.

A physical activity questionnaire was applied to assess physical activity during leisure, school, and in sports clubs which has demonstrated sufficient reliability and validity (ICC = 0.68, Jekauc et al., 2013). Physical activity in school was assessed with two items asking about the frequency of 45-minutes classes (that is typically the length of one school lesson in Germany) in physical education and extracurricular activities. To correct for school holidays (about 14 weeks) in which no physical education and extracurricular activities take place, total minutes were calculated with a correction factor of 8.5 divided by 12. Indices were obtained for physical education and extracurricular activities separately in minutes per week. Sports club physical activity was assessed by asking for type of sports club activity, frequency, and duration for each activity (times per week and duration per session), as well as time throughout the year the activity is conducted (months per year). All sports club activities were combined into one index representing sports club physical activity in minutes per week. Leisure-time physical activity was assessed by asking for type, duration in minutes per week, and time throughout the year the activity is conducted (months per year). All leisure-time physical activities were combined into one index representing leisure-time physical activity in minutes per week. In all indices, types of physical activity that do not lead to increased energy expenditure (Caspersen et al., 1985) (e.g., playing chess) were excluded. Total physical activity was calculated by adding up the indices sports club physical activity, physical activity in school (physical education and extracurricular activities), and leisure-time physical activity. Outdoor play was assessed by asking how often the child normally plays outside during a week, such as skipping rope or playing tag. Response options ranged from zero to seven days per week.

For screen time, participants self-reported how much time they spent on TV and video watching (hereafter called "TV watching"), using the computer and surfing the internet, as well as playing games on any device. The latter ones were summarized to one index indicating computer and gaming time. Each screen time behavior was reported in minutes per day. Similar items were used in another study, which reported acceptable reliability and validity for those items (*ICC* = 0.60-0.75; *K* = 0.54-0.69) (Cabanas-Sánchez et al., 2018).

For socio-demographic and individual characteristics, we collected data on gender, age (continuous variable), body-mass-index (BMI), and socio-economic status. Height and weight were measured by trained research staff, with this data being used to classify children according to four weight categories (underweight, healthy weight, overweight, obese) based on the cut-off points of the International Obesity Task Force [IOTF] (Cole et al., 2000; Cole et al., 2007). Socio-economic status was captured using an index that is based on information about the parents' monthly household income, job qualification and level, and education. Participants in the first quintile of the index were categorized as participants with low socio-economic status, participants in the second to the fourth quintile with middle socio-economic status, and participants in the fifth quintile as high socio-economic status (Lampert et al., 2014).

Statistical analysis

We used a multiple-group structural equation modeling framework as implemented in M*plus* 8 to simultaneously estimate linear trends over T1, T2 and T3 for each urbanicity group. We used gender, BMI, socio-economic status, age, and the squared age term (age^2)[1] as covariates to account for differences in the outcome variables which might be due to socio-demographic differences between areas. Moreover, we used a Wald-χ^2-Test to test whether linear trends differ across groups. Although a linear trend is a simple summary measure that could reduce noise (e.g. induced by sampling), it might also be biased due to constraining a nonlinear trend to be linear (Parker et al., 2018). Thus, we additionally tested whether mean changes between T1 and T2 as well as T2 and T3 differ significantly. As significant differences indicate nonlinear trends, we also report mean changes between consecutive time points if at least one area showed a non-linear trend (Diallo & Morin, 2015). To facilitate the interpretation of the trend estimates, we calculated effect size estimates (standardized mean differences *d*) which must be – in the case of linear trend models – multiplied by two to obtain the effect size for the trend between T1 and T3. For example, if the linear trend estimate is 0.1, this must be multiplied by two (i.e., $2 \times 0.1 = 0.2$). Thus, a *d*-value of 0.1 corresponds to a small effect, a value of 0.25 to a medium, and a value of 0.4 to a large effect (Cohen, 1992) across the whole period under investigation.

Due to well-known physical activity differences regarding gender and age (Konstabel et al., 2014; Schmidt et al., 2020), we investigated whether trends are moderated by age (continuous variable) and gender by including interaction terms between age and time as well as gender and time in the models. Due to the complex sampling design of the study, we adjusted standard errors for clustering. This was accomplished by using TYPE = COMPLEX and the primary sampling units (PSUs) as cluster variable.

[1] We included the age^2-term as physical activity increases around the age of 10 years before it decreases again (Schmidt et al. 2020)

TYPE = COMPLEX applies a sandwich estimator, that adjusts for biased standard errors due to clustering, provided that there are at least 25 PSUs (Huang, 2018). This requirement is met in the study. PSUs range from 57 (cities) to 87 (small towns). Missing data ranged from 0.3% (total physical activity) to 3.1% (computer and gaming time) for the outcome variables and from 0.0% (age, gender) to 15.1% (BMI) for the covariates. To appropriately deal with missing data, we used a full information maximum likelihood (FIML) estimation. Finally, most outcome variables were skewed (< 4.15) and highly kurtotic (< 24.03), amongst others, due to extreme outliers. To mitigate the impact of outliers, we excluded cases where the respective outcome variable was three standard deviations above the mean. This also reduces non-normality (skewness < 3.00 and kurtosis < 8.01). More detailed information regarding the statistical procedures can be found in the *Appendix A S1*.

Results

Descriptive results

Weighted sociodemographic individual characteristics of the samples at all three timepoints are displayed in *Table 1*. At T1, 4,528 youth participated, at T2, 3,964 youth, at T3, 3,669 youth participated. We excluded cases with values of 3 SDs or higher above the mean: total physical activity (N=193 excluded cases), sports club physical activity (N=185), leisure physical activity (N=272), physical education (N=102), extracurricular physical activity (N=244), TV and video watching (N=342), and computer and gaming time (N=260) Weighted descriptive results for physical activity and screen time domains at each time point and for each urbanicity level can be found in *Appendix A S2a*, group comparisons between the four groups at T1 and T3 in *Appendix A S2b*.

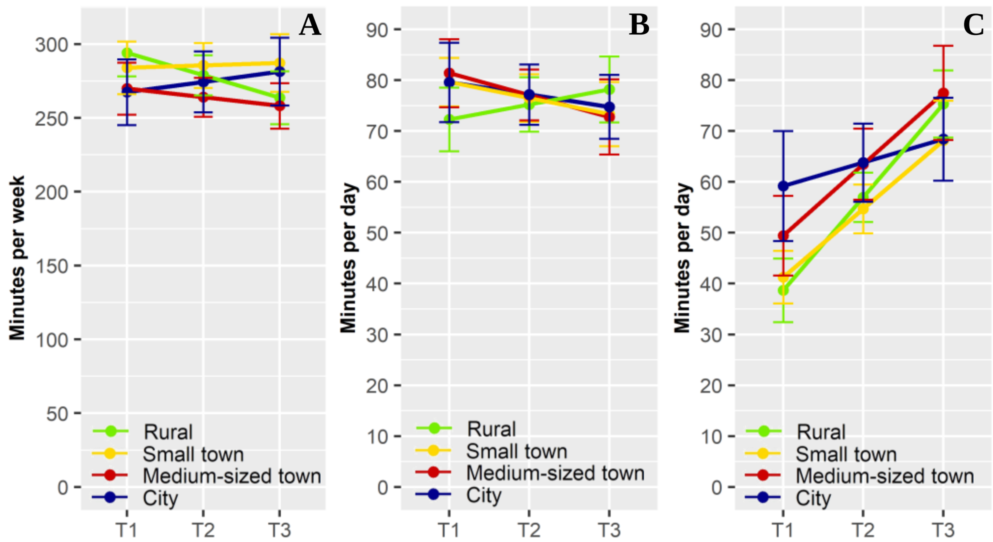
Table 1. Weighted sociodemographic and individual characteristic estimates for each timepoint.

	T1 (2003-2006)	**T2 (2009-2012)**	**T3 (2014-2017)**
Age (SD) in years	11.33 (0.08)	11.24 (0.09)	11.21 (0.10)
Gender (%)			
Female	48.70 (0.93)	48.69 (1.11)	48.43 (1.10)
Male	51.30 (0.93)	51.31 (1.11)	51.57 (1.10)
Body-mass-index			
Underweight	8.60 (0.57)	8.02 (0.75)	8.14 (0.84)
Normal	72.30 (0.95)	70.82 (1.43)	73.35 (1.38)
Overweight	14.15 (0.74)	16.08 (1.04)	12.95 (1.09)
Obese	4.95 (0.49)	5.07 (0.79)	5.56 (0.82)
Socio-economic status (%)			
Low	19.65 (1.13)	18.05 (1.36)	19.31 (1.48)
Middle	60.14 (1.25)	62.75 (1.49)	62.29 (1.52)
High	20.22 (1.03)	19.20 (1.29)	18.41 (1.25)
Level of urbanicity (%)			
Rural	18.82 (3.24)	19.49 (3.36)	16.69 (3.03)
Small town	27.95 (3.82)	27.84 (3.66)	28.58 (3.86)
Medium-sized town	29.01 (3.78)	28.99 (3.46)	30.39 (4.12)
City	24.23 (3.59)	23.78 (3.46)	24.34 (3.79)

Physical activity trends

Physical activity trends are reported in *Table 2*, an overview across all domains can be found in *Figure 1*. Note that hereafter we use the term trend to refer to the linear trend between two timepoints. In rural areas, total physical activity decreased on average by 15.23 minutes per week (95%-CI [-25.34; -5.12], d = 0.09) between two time points, a trend which was not observed for the other areas (see *Figure 1*). Trends were different between areas (Wald-χ^2 = 10.96, df = 3, p = 0.012), with the rural trend being different from the trends in small towns (z = -2.15, p = 0.031) and cities (z = -3.20, p = 0.001). Decreases in leisure-time physical activity between two timepoints were observed across all areas, ranging from 8.52 minutes (95%-CI [-13.46; -3.58], d = 0.09) in small towns to 20.50 minutes (95%-CI [-25.22; -15.78], d = 0.23) in rural areas. Trends were different across urbanicity levels (Wald-χ^2 = 12.44, df = 3, p = 0.006), with the rural trend being different from the trends in small towns (z = -3.38, p = 0.001) and cities (z = -2.15, p = 0.031) (see also line plots in *Appendix A S3*). For outdoor play, decreases in rural areas, medium-sized towns, and cities were observed, ranging from 0.34 days (95%-CI [-0.52; -0.16], d = 0.13) to 0.54 days (95%-CI [-0.70; -0.38], d = 0.21). The trends differed between the four urbanicity levels (Wald-χ^2 = 10.46, df = 3, p = 0.015), with rural areas being different from small towns (z = -3.33, p = 0.001). Physical activity in sports clubs increased on average 13.63 minutes between two time points (95%-CI [6.95; 20.31], d = 0.12) in cities. Trends were different between the four urbanicity levels (Wald-χ^2 = 9.55, df = 3, p = 0.023), indicating that small towns (z = 2.23, p = 0.026) and medium-sized towns (z = 2.97, p = 0.003) differed from cities. As the test for non-linearity was significant for rural areas and cities, we also estimated the change between the single time points. The results are displayed in *Appendix A S4*. Regarding physical education, in all areas except for cities, increases ranging from 2.37 minutes (95%-CI [0.17; 4.57], d = 0.07) in rural areas to 3.06 minutes per week (95%-CI [1.39; 4.73], d = 0.09) in medium-sized towns were observed. For extracurricular physical activity, positive trends were observed in all areas, ranging from 2.56 minutes (95%-CI [1.17; 3.95], d = 0.12) in rural areas to 3.60 minutes in cities (95%-CI [1.74; 5.46], d = 0.17]). The trends were similar across all urbanicity areas (Wald-χ^2 = 1.34, df = 3, p = 0.720).Consistent *age x time interactions* were observed for outdoor play across all areas, showing that only older children and adolescents (10- and 14-year-olds) decreased outdoor play, while slight increases were observed for younger children (4- and 6-year-olds; see *Appendix A S5* for trend estimates and *Appendix A S6* for line plots).

Figure 1. Trends in total physical activity and screen time behaviors.



Note: Box A: Total PA; box B: TV watching; box C: Computer and gaming time; T1: 2003-2006, T2: 2009-2012, T3: 2014 – 2017. Error bars indicate 95% confidence intervals.

Table 2. Linear trend between two timepoints for physical activity and screen time domains.

	Rural				*Small town*				*Medium-sized towns*				*City*			
	B	SE	95%-CI	*d*	B	SE	95%-CI	*d*	B	SE	95%-CI	*d*	B	SE	95%-CI	*d*
Total physical activity (minutes/week)																
Intercept	294.16	8.15	278.19; 310.13		283.98	9.06	266.22; 301.74		269.90	8.96	252.34; 287.46		267.45	11.37	245.16; 289.74	
Linear trend	**-15.23**††	5.16	-25.34; -5.12	0.09	1.63†	5.54	-9.23; 12.49	0.01	-5.83	5.06	-15.75; 4.09	0.03	7.02†	4.69	-2.17; 16.21	0.04
Leisure physical activity (minutes/week)																
Intercept	77.37	4.90	67.77; 86.97		63.74	3.72	56.45; 71.03		58.91	4.55	49.99; 67.83		71.20	9.21	53.15; 89.25	
Linear trend	**-20.50**††	2.41	-25.22; -15.78	0.23	**-8.52**†	2.52	-13.46; -3.58	0.09	**-14.19**	2.41	-18.91; -9.47	0.16	**-10.31**†	4.07	-18.29; -2.33	0.11
Outdoor play (days/week)																
Intercept	5.35	0.14	5.08; 5.62		4.88	0.13	4.63; 5.13		4.65	0.14	4.38; 4.92		4.57	0.17	4.24; 4.90	
Linear trend	**-0.54**††	0.08	-0.70; -0.38	0.21	-0.14†	0.09	-0.32; 0.04	0.05	**-0.37**	0.08	-0.53; -0.21	0.14	**-0.34**	0.09	-0.52; -0.16	0.13
Sports club physical activity (minutes/weeks)[a]																
Intercept	100.32	5.24	90.05; 110.59		118.58	6.12	106.58; 130.58		113.07	6.26	100.80; 125.34		90.96	7.69	75.89; 106.03	
Linear trend	4.95	3.31	-1.54; 11.44	0.04	2.54†	3.63	-4.57; 9.65	0.02	0.09†	3.07	-5.93; 6.11	0.00	**13.63**††	3.41	6.95; 20.31	0.12
Physical education (minutes/week)																
Intercept	85.18	2.68	79.93; 90.43		83.21	2.41	78.49; 87.93		82.11	2.10	77.99; 86.23		81.01	2.22	76.66; 85.36	
Linear trend	**2.37**	1.12	0.17; 4.57	0.07	**2.57**	0.82	0.96; 4.18	0.08	**3.06**	0.85	1.39; 4.73	0.09	2.36	1.32	-0.23; 4.95	0.07
Extracurricular sports activities (minutes/week)																
Intercept	9.64	1.28	7.13; 12.15		7.19	0.88	5.47; 8.91		6.96	0.98	5.04; 8.88		10.35	1.38	7.65; 13.05	
Linear trend	**2.56**	0.71	1.17; 3.95	0.12	**3.17**	0.67	1.86; 4.48	0.15	**3.38**	0.63	2.15; 4.61	0.16	**3.60**	0.95	1.74; 5.46	0.17
TV watching (minutes/day)[b]																
Intercept	72.27	3.19	66.02; 78.52		79.64	2.44	74.86; 84.42		81.39	3.42	74.69; 88.09		79.59	3.98	71.79; 87.39	
Linear trend	2.97††	1.78	-0.52; 6.46	0.05	**-3.14**†	1.58	-6.24; -0.04	0.05	-4.30†	2.53	-9.26; 0.66	0.07	-2.45†	1.98	-6.33; 1.43	0.04
Computer and gaming time (minutes/day)[c]																
Intercept	38.66	3.15	32.49; 44.83		41.27	2.64	36.10; 46.44		49.44	4.01	41.58; 57.30		59.19	5.51	48.39; 69.99	
Linear trend	**18.33**††	2.12	14.17; 22.49	0.23	**13.44**†	2.36	8.81; 18.07	0.17	**14.04**†	2.57	9.00; 19.08	0.18	4.61†	2.89	-1.05; 10.27	0.06

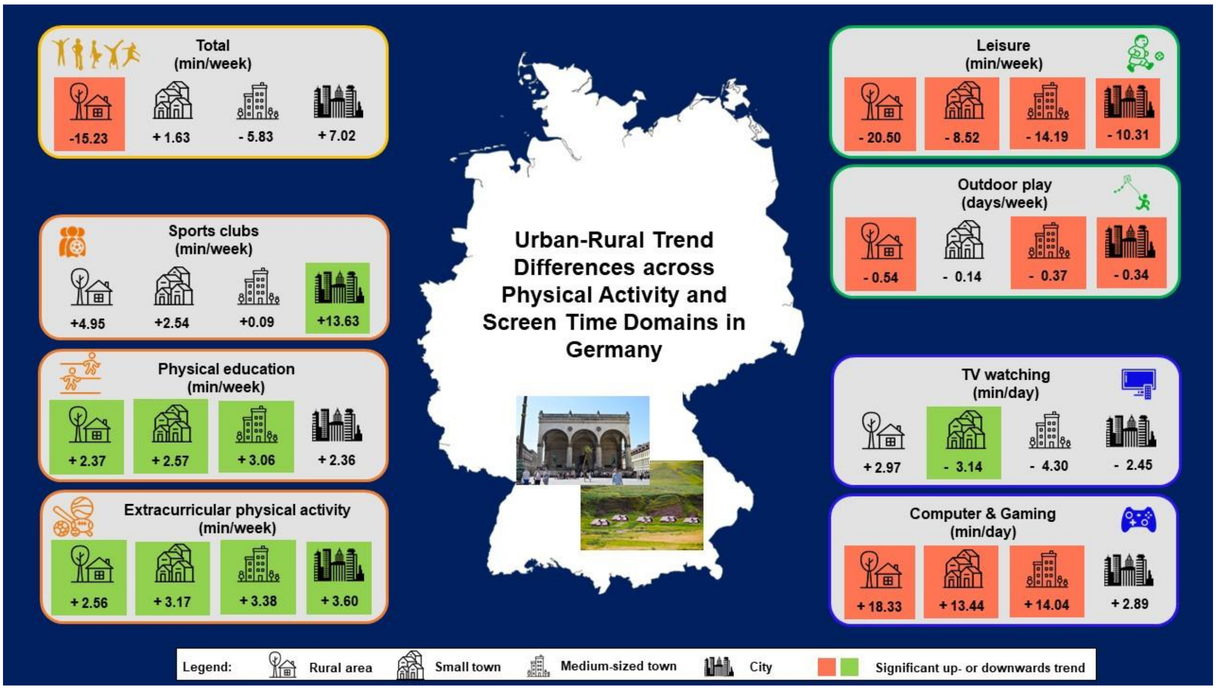
Note: Intercept: centered on T1. Linear trend (B) = mean change between two consecutive timepoints. Standardized mean difference estimate d was calculated by dividing the linear trend by the standard deviation pooled across time and groups. SE = standard error. The intercepts represent engagement in the respective behavior for a typical study participant (middle socio-economic status, healthy weight, age = 11.27 years, gender = 1.49). [a] For rural areas and cities, the trends between T1-T2 and T2-T3 were different at $p < 0.05$. [b] For rural areas, small towns, and medium-sized towns, the trends between T1-T2 and T2-T3 were different at $p < 0.05$. For medium-sized towns, the trend between T1-T2 and T2-T3 was different at $p < 0.05$. Bold values indicate that the confidence interval does not include zero. †† indicates that the trend was different compared to areas with †; trend differences were assessed using the Wald-χ^2-Test

Screen time trends

Trends for screen-based sedentary behavior are reported in *Table 2*. As analyses indicated nonlinear trends for screen-time behaviors, we further estimated the change between the single time points, with results being displayed in *S5*. For TV watching, trends differed between the four urbanicity levels (Wald-χ^2 = 8.38, df = 3, p = 0.039). The positive, although not significant trend in rural areas differed from small towns (z = 2.45, p = 0.014), medium-sized towns (z = 2.35, p = 0.019), and cities (z = 2.02, p = 0.043), where TV watching remained unchanged except for small towns (B = -3.14, 95%-CI [-6.24; -0.04], d = 0.05). For computer and gaming time, positive trends were observed from T1 to T3 in all areas except for cities, ranging from a plus of 13.44 minutes per week in small towns (95%-CI [8.81; 18.07], d = 0.17) to 18.33 minutes (95%-CI [14.17; 22.49], d = 0.23) in rural areas. The trend in rural areas was different from the other areas (Wald-χ^2 = 13.61, df = 3, p = 0.004), showing a stronger increase in rural areas compared to small towns (z = 2.38, p = 0.017), medium-sized towns (z = 2.37, p = 0.018), and cities (z = 3.67, p < 0.001).

For computer and gaming time, interactions showed that only older children (10- and 14-year-olds) increased computer and gaming time, while no changes were observed for younger children (4- and 6-year-olds). Also, interactions showed stronger increases in computer and gaming time in females across all areas, indicating that males and females getting closer in their computer and gaming time over the years. Detailed information regarding the interactions is displayed in *Appendix A S5* and *S6*.

Figure 2. Trends in total physical activity and screen time behaviors across domains.



Numbers highlighted in red indicate significant detrimental developments, numbers highlighted in green indicate significant beneficial developments, numbers not highlighted were not statistically significant. Please see also Table 2 for detailed statistics.

Discussion

With rapidly occurring changes in urban and rural areas, it is crucial to investigate potential disparities across different urbanicity levels in children's and adolescents' health behaviors. The data of this unique epidemiological trend study allowed us to investigate trends in physical activity and screen time in rural and urban areas in children and adolescents aged between four and 17 years. Findings indicate detrimental developments being stronger in rural areas compared to cities. For small towns and medium-sized towns, no clear pattern emerged.

Rural areas were the only areas showing a decline in total physical activity. Additionally, the strongest decreases in leisure-time physical activity and outdoor play were observed in rural areas. These findings are similar to findings of a longitudinal study reporting that children in rural areas showed the strongest decline in moderate-to-vigorous physical activity (Corder et al., 2015). Interestingly, similar trends were also observed in the European adult population, with adults in rural areas showing the strongest decrease in physical activity (Moreno-Llamas et al., 2021). In our study, these trends may be partially explained by demographic developments in rural areas: As more people in working age emigrate from rural areas while elderly people move to and live in rural areas, overall resulting in a population decline in those areas (Federal Ministry of Food and Agriculture, 2020; Brown & Schafft, 2019; Plane & Jurjevich, 2009), this may result in less physical activity opportunities and facilities for children and adolescents, such as attractive playgrounds or various sports clubs. Although decreases in leisure-time physical activity were also observed in cities, which might be due to a general shift to institutionalized physical activity in Germany (Schmidt et al., 2020), in rural areas these effects may be exacerbated through barriers, such as lack of physical activity opportunities, physical distance to physical activity opportunities, and social isolation (Edwards et al., 2014; Taylor et al., 2018). Another explanation could be that, in line with the displacement hypothesis (Mutz et al., 1993), other behaviors, for example engaging in more computer and gaming time, displaced leisure-time physical activity. This displacement may occur at a higher rate in rural areas due to a lack of other appealing leisure-time opportunities. These considerations also align with the results from the interaction for outdoor play, which showed that in rural areas, outdoor play decreased for 10- and 14-year-old children, while in cities, the decrease only appeared for 14-year-old children while 10-year-olds remained stable and four- and six-year-olds caught up with children from rural areas and small towns. This may be due to attractive outdoor play opportunities in larger cities, for example playgrounds or skate parks in the neighborhood, which may not be present in rural areas (Button et al., 2020).

Regarding sports club physical activity, cities showed an upwards trend over the last decade, which was not observed in other areas. A reason for this may be that cities can offer a variety of physical activity programs, while the other areas may be missing resources, specifically human capital, that provide and maintain physical activity programs and initiatives (Edwards et al., 2014). This may result in a limited number of physical activity programs that do not appeal to every child or adolescent. While the upwards trend of sports club physical activity was limited to cities, physical activity in schools, including physical education and extracurricular activities, increased across urban and rural areas. This is probably due children and adolescents of both rural and urban areas coming together in schools and potential environmental physical activity barriers in rural areas, such as a lack of recreational facilities or distance to facilities (Taylor et al., 2018), being less relevant in the school setting. This highlights the potential leadership role of schools in physical activity promotion (Heath et al., 2012; Hills et al., 2015; Pate et al., 2006).

For screen time behavior, our results showed an upwards trend in rural areas, but a downwards trend in all other areas (none-significant except for small towns). For computer and gaming time, increases were observed across all areas except for cities, with the strongest increase in rural areas. Interaction results showed that girls started off lower with computer and gaming time than boys, but showed a stronger increase over the 15 years, hence now spending a similar time on computers and gaming as boys. Also, the increases in computer and gaming time were primarily visible for older children and adolescents (10-year-olds and 14-year-olds). The sharp increase in computer and gaming time, especially for females, while TV watching time remained constant or decreased slightly, is in line with results from other countries (Bucksch et al., 2016). The trends in computer and gaming time may be partially driven by the rapid development in the technology sector, allowing to implement appealing technologies in digital games and competing online against other players (Ampatzoglou & Stamelos, 2010; Rosell Llorens, 2017).

The stronger increase in screen time in rural areas compared to the other areas may be explained by the fact that adolescents in urban areas have more alternative leisure-time opportunities than adolescents in rural areas, thus attenuating the increase. Also, access to digital infrastructure may create a newness effect (Dinnin, 2009) for youth in rural areas as immediate access to the latest digital infrastructure is focused on urban areas (Salemink et al., 2017), which may translate to more screen time in rural areas when they have the opportunity to engage in new technology.

Comparing physical activity and screen time levels at baseline and T3 in rural to the other areas (see *supplement 2b*), our results indicate that sports club and leisure time physical activity as well as computer and gaming time harmonized across the 15 years, while for outdoor play, rural areas are still the area with the second highest levels.

However, considering the trends across rural and urban areas, the absolute differences may be subject to change. Although the effect sizes of the trends are small to medium across the 15 years, it should be considered that if those trends continue like the last years, the effect size will become larger. For example, currently, the effect size for the trend estimate of total physical activity in rural areas is only small across the last decade (d = 0.18) – however, if the trend continues like this, in about 30 years, the negative trend will be at a strong effect size when starting the trend in 2003. In contrast, for cities, based on our models, a positive trend would be expected.

Limitations and future directions

Our study has several limitations which should be considered in the interpretation of the findings. First, physical activity and screen time were self-reported, which is prone to bias. Second, the physical activity domains include all physical activity intensities (light, moderate, vigorous), thus, this examination does not allow conclusions about changes in moderate-to-vigorous physical activity (WHO, 2020). However, the World Health Organization has recently emphasized the importance of all movement behaviors for health, including light physical activity as replacement for sedentary behavior (Ding et al., 2020; WHO, 2020). Our physical activity questionnaire focused on exercise domains for physical activity, active transport such as cycling to school were considered later in the study and thus are not available for all timepoints. However, other research has shown that there exist also differences in this domain between urban and rural children: In New Zealand, adolescents from large urban areas accumulated eight to ten minutes of moderate-to-vigorous physical activity due to school-related commuting each day, while adolescents from rural areas only accumulated five to eight minutes per day (White et al., 2021). In a study in Canadian adolescents, 58% and 56% of moderate-to-vigorous physical activity were accumulated via commuting in urban boys and girls, respectively, whereas rural boys achieved only 24% and rural girls only 17% of their moderate-to-vigorous physical activity through commuting (Rainham et al., 2012). A study in Finland found that independent mobility, including commuting to places such as school, decreased in children and adolescents, with stronger declines in rural areas and small towns compared to inner cities (Kyttä et al., 2015). Finally, urban and rural areas were merely measured by population size with other factors, such as population density, not being considered.

These limitations notwithstanding, overall, our findings indicate that children in rural areas show detrimental physical activity and screen time developments. Our study adds to previous findings of other studies about urban-rural trends in youths' health behaviors and health, such as the faster development of obesity rates in rural areas (Song et al., 2015). Future studies about urban-rural health disparities in children and adolescents should include active living domains, such as commuting to school or walking to the bus, in their assessment of physical activity and use a more comprehensive measure of the residential environment that allows to identify specific factors that relate to those different trends (Dahly & Adair, 2007).

Conclusion

Our study showed a decreasing trend of children's and adolescent's total physical activity in rural, but not urban areas. In addition, the strongest decreases in leisure-time physical activity and outdoor play occurred in rural areas. At the same time, the increasing trend in computer and gaming time was strongest in rural areas. While physical activity promotion across all areas is useful considering low physical activity rates (Guthold et al., 2020), interventions should be specifically target and tailored to children and adolescents in rural areas to counter inequalities regarding a urban-rural physical activity gap. For example, public health funding for local physical activity initiatives in rural areas and environmental interventions to create appealing physical activity opportunities in the neighborhood may be one option to encounter the detrimental development in leisure physical activity and outdoor play. As our findings indicate that physical activity trends across urbanicity levels were not different for the school setting, school-based physical activity programs may be a valuable and inclusive opportunity to promote physical activity of all children and adolescents, including those from rural areas.

Author contributions

CaN: Conceptualization, Methodology, Visualization, Writing – Original Draft; **CW:** Formal analysis, Writing – Review & Editing; **JS**: Methodology, Supervision, Writing – Review & Editing; **MR**: Supervision, Writing – Review & Editing; **DO**: Project administration, Investigation, Data curation, Software, Writing – Review & Editing; **AnW**: Conceptualization, Methodology, Funding acquisition, Writing – Review & Editing; **AlW**: Conceptualization, Methodology, Funding acquisition, Writing – Review & Editing; **ClN**: Conceptualization, Supervision, Writing – Review & Editing

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CHAPTER 3

Urban-rural physical activity differences of children and adolescents in Germany assessed with accelerometers

Slightly modified version of the 2nd article which is currently submitted:

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Introduction

Both nature and nurture shape human health. Global urbanization in the 21st is the most large-scale reorganization of environments humanity has faced in the last centuries, with two-thirds of the global population expected to live in cities by 2050 (UN, 2018). However, the issue of how urban living impacts physical activity in children and adolescents remains under-investigated. This is especially relevant when considering that 81% of children and adolescents are engaging in less than 60 minutes of moderate-to-vigorous physical activity (MVPA) per day, thus failing to achieve health-enhancing physical activity levels as recommended by the World Health Organization (WHO, 2020). As physical activity is positively related to behavioral, mental, and physical health (Biddle et al., 2019; Chaput et al., 2020), while insufficient physical activity is constituting an enormous economic burden with an estimate of INT$48 billion annual health care costs (WHO, 2022), understanding and promoting determinants of physical activity remains a major societal challenge.

To tackle the problem of physical activity, the World Health Organization considers creating active environments as one of four key strategies in its global action plan on physical activity (WHO, 2018). This assumption is supported by ecological models of health behavior, which emphasize the impact of environmental features on physical activity; for example, public sports facilities, traffic safety, and stimulating natural environments may foster engagement in physical activity (Sallis & Owen, 2015). While previous studies investigated associations between city living's environmental characteristics and physical activity in adults (Cerin et al., 2022; Sallis et al., 2020), studies in children and adolescents are sparse. Looking at empirical evidence in children and adolescents, previous studies found park and playground equipment, mixed land use, short distances to facilities, better walkability, and infrastructure for walking and cycling to be associated with youth's physical activity (Nordbø et al., 2020; Smith et al., 2017), features that are commonly more prevalent in urban areas (Sallis, Bull, Burdett, et al., 2016). At the same time, Germany's rural areas are experiencing demographic changes with an aging population and people with higher education moving to urban areas, which is associated with changes in the rural infrastructure, such as fewer schools, education opportunities, public transport options, and shopping and leisure facilities (Federal Ministry of Food and Agriculture, 2020), which may have deteriorated physical activity opportunities for children and adolescents.

Summarizing the evidence on the issue of how urbanization relates to MVPA in youth, to date a highly heterogenous picture arises: in McCormack and Meendering's (2016) systematic review, five studies did not find differences between urban and rural adolescents for moderate-to-vigorous physical activity, nine studies reported higher moderate-to-vigorous physical activity in rural youth, and one study in urban youth. In 2014, McCrorie et al. found adolescents living in more densely populated areas were slightly more likely to be physically active, but in 2020, they could not find significant differences in MVPA (McCrorie et al., 2020). Fan and Cao (2017) reported boys in urban areas were 14% more likely to meet the physical activity WHO physical activity guidelines than their rural peers, a finding that was not true for girls.

However, existing studies are limited in various domains such as the use of (a) self-report instead of reliable device-based measures (b) small non-representative samples, including (c) restricted age ranges in youth, and, (d) inconsistent and rough definitions of urban and rural areas. Therefore, in this study, we tackle the issue of how urban and rural living relates to MVPA in children and adolescents in a large representative sample of German children and adolescents aged six to 17 years, a population especially vulnerable if insufficiently active, using reliable device-based measures and two different systems to assess urbanicity, including Germany's system for political community sizes (discovery study) and the European-wide degree of urbanization (DEGURBA) (GIS) (replication study). Following ecological models (e.g., Sallis and Owen (2015)), we hypothesized an increased volume of MVPA in children living in more urban areas and an increased likelihood of meeting the WHO (2020) physical activity guidelines.

Method

Procedures

Data was obtained from the Motorik-Modul (MoMo) Study (Woll et al., 2021), an in-depth study within the German Health Interview and Examination Survey for Children and Adolescents (KIGGS) conducted by the Robert Koch Institute (Hölling et al., 2012; Kurth et al., 2008). Baseline data (T1) was collected between 2003 and 2006 (Woll et al., 2011), with the first follow-up between 2009 and 2012 (T2), the second follow-up between 2015 and 2017 (T3), and the third follow-up between 2018 and 2022 (T4; Woll et al., 2021). In addition to the participants examined longitudinally, a representative of children and adolescents between four and 17 years was recruited based on census tract data on age, gender, migration, and social status at each follow-up. For this study, we only used data obtained in the second follow-up (T3, named "discovery study" in the following) and the third follow-up (T4 prior to the Covid-19 pandemic, named "replication study" in the following) as accelerometer-data was only collected in those study waves. The study was conducted according to the Declaration of Helsinki. Ethics approval was obtained by the Karlsruhe Institute of Technology and the Federal Office for the Protection of Data. For measurement purposes, participants were invited to examination rooms within proximity to their homes, where they filled out a questionnaire and received the accelerometer. Participants and their parents were informed in detail about the study and data management and provided written informed consent. For participants under the age of 18 years, the presence of a legal guardian was mandatory.

Participants

Study participants were selected based on a multi-stage sampling approach with two evaluation levels (Kamtsiuris et al., 2007). First, a systematic sample of 167 primary sampling units was selected from an inventory of German communities stratified according to the classification system that measures the level of urbanization and geographic distribution. Second, based on the official registers of local residents, an age-stratified sample of randomly selected children and adolescents was drawn. To be eligible for the discovery study, participants had to be part of the second follow-up study of MoMo

(2015-2017; T3), participate in the accelerometry-measurement, and be younger than 18 years. To be eligible for the replication study, participants had to be part of the third follow-up of MoMo (T4; 2018-2022 prior to the pandemic), participate in the accelerometry-measurement, and be younger than 18 years. Due to the Covid-19 pandemic, data could not be collected at all 167 sampling points but had to be interrupted after 128 sampling points were completed. All data used in this study (2018-2020) had been collected prior to the first Covid-19 related lockdown in Germany in March 2020 (Nigg et al., 2021; Schmidt et al., 2020).

Measures

Socio-demographic and health variables. For each participant, gender, age, socio-economic status, and weight status were assessed. The socio-economic status includes information about the parents' education, monthly household income, and job qualification and level. This information is used to create a score between three and 21, with higher values representing a higher socio-economic status (Lampert et al., 2014). Height and weight were measured by trained research staff and the weight status of participants was determined based on the cut-off points of the International Obesity Task Force [IOTF] (Cole et al., 2000; Cole et al., 2007).

Physical activity. A detailed description of the use of accelerometers in the MoMo study is available elsewhere (Burchartz, Manz, et al., 2020). Participants were asked to wear an accelerometer (ActiGraph GT3x+ or ActiGraph wGT3X-BT) for eight consecutive days, with the first day not being considered. The devices were handed out to participants by qualified research assistants with important aspects being summarized on a leaflet to take home. Participants were instructed to place the accelerometer laterally on the right hip, which was supervised by a research assistant. Data was sampled using a frequency of 30 Hz. The software ActiLife (version 6.13.3) was used to convert the downloaded data into 1-second-epochs. Data were further processed into 15-second-epochs using the software "MATLAB". Non-wear time was defined as 90 minutes without consecutive zero/non-zero counts based on the Choi algorithm (Choi et al., 2011). Two-minute intervals of non-zero counts with the up- / downstream 30-minute consecutive zero count windows were allowed to detect artificial movements (Choi et al., 2011). To be considered a valid dataset, participants had to wear the device for more than eight hours on at least four weekdays and one weekend day. Two cut-off point systems were applied that are commonly used for the specific age groups of six to ten-year-olds (Evenson et al., 2008) and for eleven to 17-year-olds (Romanzini et al., 2014) to determine physical activity intensity.

Urbanicity. In the discovery study, the participant's address data was not available for data protection issues. Hence, we assessed the level of urbanicity based on the German national categorization system for political community sizes, a categorization system that is used to investigate influences on mobility (Research Information System on Mobility and Traffic, 2020). While there is no consensus on political community sizes, the following categorization has been commonly applied in federal reports and statistics (Wittwer, 2008): 1) city (≥ 100,000 citizens); 2) medium-sized town (20,000 – 99,999); 3) small town (5,000 – 19,999), and 4) rural (< 5,000 citizens). We decided to use this system to allow for policy-relevant conclusions of our study and comparability with previous studies (Nigg et al., 2022).

In the replication study, we obtained data on the degree of urbanization (DEGURBA) from the German Federal Statistics Office's community information system. The DEGURBA classification is a European-wide classification system that uses a combination of geographical contiguity and minimum population density threshold applied to 1 km^2 population grid cells to determine the urbanization degree for local administrative units – usually communes. Based on these grid cells, three urbanicity levels are determined: 1) Cities, representing densely populated areas, with at least 50% of the population living in urban clusters; 2) Towns and suburbs, representing intermediate densely populated areas, with at least 50% of the population living in urban cluster and less than 50% living in urban centers, and 3) Rural areas, with at least 50% of the population living in rural grid cells (EU et al., 2021; eurostat). Using ArcGIS Pro (version 2.8.0), we calculated the closest (sub-)community to the participant's home address and matched the urbanicity degree of the corresponding community with the participant (Nigg et al., 2021).

Statistical analysis

All analysis was conducted using R Studio (version 4.2.2) (R Core Team, 2013). To investigate the relationship between urbanicity and MVPA, we used multiple linear regression models. We entered urbanicity degree as predictor of interest for MVPA, with rural areas being the reference category. To assess the relationship between urbanicity and the WHO guidelines, we used logistic regression models. First, we plotted the relationship between the variables included in the model and our outcome. As the plotting revealed a non-linear association between age and MVPA, we formed three age groups based on the data plotting and theoretical assumptions: 6-10 years, which is the typical age during which children attend primary school; 11-13 years as the early adolescent years, and 14-17 years as the adolescent years. Model assumptions were visually inspected using the package "performance" for both linear and logistic regression (Lüdecke et al., 2021). If assumptions seemed to be violated, we used the package "robustbase" to obtain robust regression estimates (Maechler et al., 2022). The results were compared to the non-robust regression estimates. We report the results of the non-robust model if the results remained substantially unchanged with the robust method. Based on previous findings, we included age group (reference category: six to ten-year-olds), gender (reference category: boys), socioeconomic status, and weight status (reference category: normal weight) as covariates in the model (Fernández-Alvira et al., 2013; Sallis, Bull, Guthold, et al., 2016; Schmidt et al., 2020; Sterdt et al., 2014). As associations between environmental features and physical activity may vary based on age and gender (Kowaleski-Jones et al., 2016), we calculated interactions between the urbanicity degree and gender and age in the linear regression models and stratified the analysis by gender and age group in the logistic regression model. To generate result tables, we used the package "sjPlot" (Lüdecke, 2021).

To examine the influence of missing data on our results, we imputed missing data in a sensitivity analysis including all participants in both the discovery and replication study who had agreed to wear an accelerometer. For each participant who did not fulfill the wear-time conditions to be considered as a valid accelerometer dataset, we set accelerometer wear-time and MVPA as missing data. For imputation, we used the Multivariate Imputation via Chained Equations (MICE) package (Van Buuren & Groothuis-Oudshoorn, 2011), which can handle data missing at random or missing completely at random (Rubin, 1976). For each variable containing missing values, an imputation model was specified and the algorithm iteratively imputed the missing values with multiple possible values to account for the uncertainty of the missing value imputation and increase the plausibility for missing at random (Zhang, 2016). We generated 20 datasets with 20 iterations, using predictive mean matching (pmm) for continuous variables and polytomous regression (polyreg) imputation for categorical variables. The imputation model included all covariates (agegroup, gender, socio-economic status, weight status, and accelerometer wear-time) as well as the outcome (MVPA). Fulfillment of WHO guidelines was calculated from the imputed MVPA results. All analyses were repeated with the 20 data sets imputated and pooled results were compared to the results of the complete-case analysis.

Results

Descriptives

In the discovery study, a total of $N = 2{,}190$ had complete information regarding the variables that were included in our models, while in the replication study, a total of $N = 923$ had complete data, with the information presented in *Table 1*. For details regarding socio-demographic information stratified by urban-rural status, see *Appendix B Table A.1 and Table A.2*.

Table 1. Sample information.

	Discovery study (N = 2,190)	Replication study (N = 923)
Urbanicity discovery study		
Rural	449 (20.5%)	
Small town	822 (37.5%)	
Medium-sized town	587 (26.8%)	
City	332 (15.2%)	
Urbanicity replication study		
Rural areas (thinly populated areas)		324 (35.1%)
Towns and suburbs (intermediate density areas)		391 (42.4%)
Cities (densely populated areas)		208 (22.5%)
Gender		
Boys	1031 (47.1%)	461 (49.9%)
Girls	1159 (52.9%)	462 (50.1%)
Age group		
6-10 years	584 (26.7%)	392 (42.5%)
11-13 years	818 (37.4%)	313 (33.9%)
14-17 years	788 (36.0%)	218 (23.6%)
Age in years Mean (SD)	12.40 (3.30)	11.20 (3.34)
Socio-economic status score Mean (SD)	14.1 (3.81)	15.5 (3.28)
Weight status		
Underweight	203 (9.3%)	86 (9.3%)
Normal weight	1617 (73.8%)	706 (76.5%)
Overweight	288 (13.2%)	111 (12.0%)
Obese	82 (3.7%)	20 (2.2%)
MVPA Mean minutes/day (SD)	51.6 (23.7)	55.2 (24.0)
WHO guidelines		
Not fulfilled	1502 (68.6%)	596 (64.6%)
Fulfilled	688 (31.4%)	327 (35.4%)

Association between urbanicity and average MVPA per day

Table 2 presents the results of the multiple linear regression model of the discovery study (Adjusted R^2 = 0.31, $F(11, 2178) = 90.94$, $p < .001$) and the replication study (Adjusted R^2 = 0.31, $F(10, 912) = 41.53$, $p < .001$). In the discovery study, children in cities engaged on average in 7.12 minutes more MVPA per day than children from rural areas ($\beta = 0.30$, $p < .001$). There was also a tendency that children in small towns ($\beta = 0.09$, $p = .075$) and medium-sized towns ($\beta = 0.10$, $p = .068$) engaged in more MVPA per day compared to children and adolescents from rural areas. These findings were confirmed in the replication study, with children and adolescents living in cities engaging on average in 5.73 minutes more MVPA per day than children from rural areas ($\beta = 0.24$, $p = .002$). In both the discovery and the replication study, we investigated interactions with age and gender, however, none of them turned out to be significant (results not shown).

Table 2. Multiple linear regression results with moderate-to-vigorous physical activity (MVPA) as outcome.

	Discovery Study (*N* = 2,190)					**Replication Study (*N* = 923)**				
	B	*SE*	*95%CI*	*β*	*p*	*B*	*SE*	*95%CI*	*β*	*p*
(Intercept)	74.84	1.29	72.30;77.38	0.98	**<.001**	72.53	1.56	69.46;75.59	0.72	**<.001**
Urbanicity discovery study (ref. rural)										
Small town	2.07	1.16	-0.21;4.35	0.09	.075					
Medium-sized town	2.28	1.25	-0.17;4.73	0.10	.068					
Cities	7.12	1.46	4.26;9.97	0.30	**<.001**					
Urbanicity replication study (ref. rural areas)										
Towns						2.42	1.53	-0.58;5.43	0.10	.114
City						5.73	1.81	2.18;9.27	0.24	**.002**
Age group (ref. 6-10 years)										
11-13 years	-21.50	1.09	-23.64;-19.35	-0.91	**<.001**	-19.73	1.56	-22.79;-16.68	-0.82	**<.001**
14-17 years	-30.34	1.16	-32.61;-28.08	-1.28	**<.001**	-26.59	1.77	-30.07;-23.11	-1.11	**<.001**
Gender (ref. boys)	-11.43	0.85	-13.09;-9.77	-0.48	**<.001**	-10.32	1.33	-12.93;-7.72	-0.43	**<.001**
Socio-economic status	0.16	0.12	-0.06;0.39	0.03	.162	-0.07	0.21	-0.47;0.34	-0.01	.752
BMI (ref. normal)										
Underweight	-0.18	1.47	-3.06;2.71	-0.01	.905	-2.58	2.29	-7.08;1.93	-0.11	.262
Overweight	-3.65	1.27	-6.14;-1.16	-0.15	**.004**	-8.68	2.07	-12.74;-4.62	-0.36	**<.001**
Obese	-5.95	2.25	-10.35;-1.54	-0.25	**.008**	-11.40	4.57	-20.36;-2.44	-0.47	**.013**
Accelerometer wear-time	0.04	0.01	0.03;0.06	0.15	**<.001**	0.02	0.01	0.01;0.03	0.08	**.005**

Association between urbanicity and compliance with the WHO (2020) physical activity guidelines

Table 3 presents the results of the logistic regression model for the discovery study (Nagelkerke's R^2 = 0.28) and the replication study (Nagelkerke's R^2 = 0.33). In the discovery study, children and adolescents living in a medium-sized town (*OR* = 1.43, *p* = .024) or in a city (*OR* = 2.04, *p* < .001) were more likely to meet the physical activity guidelines compared to children and adolescents living in rural areas. The stratified analysis revealed similar results for boys and girls, however, when stratified by age group, differences occurred: Adolescents between 14 and 17 years living in a medium-sized town (*OR* = 2.10, *p* = .033) or city (*OR* = 3.81, *p* < .001) were more likely to meet the physical activity guidelines than their rural counterparts. For six to ten-year-old children, the association was in a similar direction, but non-significant (medium-sized town: *OR* = 1.67 *p* = 0.054); city: *OR* = 1.82, *p* = .065). For 11-13-year-old adolescents, no evidence for urban-rural differences was observed. The detailed results can be found in the *Appendix B*, *Table A.3 and A.4.*

Table 3. Logistic regression results regarding compliance with the WHO (2020) physical activity guidelines.

	Discovery study (*N* = 2190)			**Replication study (*N* = 923)**		
Predictors	*Odds Ratio*	*95%CI*	*p*	*Odds Ratio*	*95%CI*	*p*
(Intercept)	2.51	1.85;3.41	**<.001**	2.10	1.45;3.03	**<.001**
Urbanicity discovery study (ref. rural)						
Small town	1.18	0.88;1.58	.275			
Medium sized town	1.43	1.05;1.95	**.024**			
City	2.04	1.44;2.90	**<.001**			
Urbanicity replication study (ref. rural areas)						
Towns and suburbs				1.41	0.96;2.08	.079
Cities				1.87	1.20;2.91	**.006**
Gender (ref. boys)						
Girls	0.35	0.28;0.43	**<.001**	0.39	0.28;0.54	**<.001**
Socio-economic status	1.01	0.98;1.04	.580	1.01	0.96;1.06	.666
BMI (ref. normal)						
Underweight	1.28	0.91;1.80	.157	0.84	0.49;1.45	.534
Overweight	0.63	0.45;0.86	**.005**	0.29	0.15;0.55	**<.001**
Obese	0.52	0.28;0.92	**.029**	0.08	0.01;0.68	**.021**
Age group (ref. 6-10 years)						
11-13 years	0.18	0.14;0.23	**<.001**	0.17	0.12;0.25	**<.001**
14-17 years	0.08	0.06;0.11	**<.001**	0.07	0.04;0.13	**<.001**
Accelerometer wear-time	1.003	1.001;1.004	**<.001**	1.002	1.001;1.004	**.011**

In the replication study, children and adolescents living in cities were more likely to meet the physical activity guidelines (*OR* = 1.20, *p* = .006). A similar, but non-significant direction was also observed for children and adolescents in towns and suburbs (*OR* = 1.41; *p* = .079). When stratified by gender, the results revealed that only girls in cities were more likely to meet the physical activity guidelines (*OR* = 2.09, *p* = .023), while for boys, a similar, but non-significant association was observed (*OR* = 1.72; *p* = .069). When stratified by age group, the results revealed that city living was only associated with an increased likelihood of meeting the guidelines in six-to-ten-year-old children (*OR* = 2.03, *p* = .020), but not in adolescents aged 11-13 (*p* = 0.165) or 14-17 years (*p* = .122). The detailed results are displayed in the *Appendix B*, *Table A.5 and A.6*.

Sensitivity analysis

Including all participants who agreed to wear an accelerometer in the analysis resulted in *N* = 2,734 participants in the discovery study (*n* = 465 participants without valid accelerometer data; *n* = 88 with missing information on sociodemographic characteristics or weight status) and *N* = 1,192 participants in the replication study (*n* = 245 participants without valid accelerometer data; *n* = 28 with missing information on sociodemographic characteristics or weight status). Correlation analysis revealed that in both studies, missigness of valid accelerometer data was positively related to the age group. The result patterns remained similar when missing data were imputed (see *Appendix B Tables A.7* and *A.8*).

Discussion

In two large samples of children and adolescents across Germany applying device-based assessment of physical activity with two different assessments of urbanicity, both our discovery and replication study showed that compared to rural areas, children and adolescents in cities spent more time in MVPA, independent of gender and age. Children and adolescents from urban areas were more likely to meet the WHO (2020) physical activity guidelines, with gender and age differences being observed. This provides high-quality evidence on the association of urbanicity and physical activity, therewith contributing to a research discussion of utmost importance. The greatest difference was observed between children living in cities versus those residing in rural areas. These findings extend previous results from a study that investigated urban-rural physical activity trends in Germany’s children and adolescents based on self-report, showing that rural areas have been experiencing a physical activity decline over the last 15 years (Nigg et al., 2022).

Our finding of heightened MVPA in urban youth may be explained by more MVPA-opportunities in urban compared to rural areas. From an ecological perspective, our finding that urban youth engage in more MVPA may trace back to the fact that there are more opportunities for MVPA in urban areas compared to rural areas. For example, in one study, children in rural areas were four times more likely to report they couldn't exercise because parks and playgrounds were too far from their homes or because sidewalks and bike lanes were missing, compared to children from suburban large towns (Taylor et al., 2018).

However, during times of crisis, such as the Covid-19 pandemic, rural living seems conducive for physical activity: In a study conducted during the first Covid-19 lockdown in Germany, children and adolescents in less densely populated areas increased their self-reported daily life physical activity by about 45 minutes per day, while children and adolescents in highly densely populated areas increased their daily life physical activity by only ten minutes per day (Nigg et al., 2021). This may be explained by the fact that during the lockdown, the physical activity opportunities obtained through urban living were restricted (e.g., public play and sports ground closures) whilst rural areas may have offered more open space for playing outside with a safe distance to other people (Nigg et al., 2021).

Existing pre-Covid studies on urban-rural differences in physical activity differed in numerous aspects from the here presented investigation. In particular, the age-ranges of children and adolescents investigated were highly different (e.g., Machado-Rodrigues et al., 2014; McCrorie et al., 2020; Moore et al., 2014), the measurement of urbanicity and rurality were diverse, ranging from urban influence codes to population density measures (McCormack & Meendering, 2016), the measurement of physical activity from self-reports to device-based assessment, and the conduct ranged across the last two decades, a time of rapid urbanization processes and land use changes (e.g, McCrorie et al., 2020; Salvati et al., 2018; Springer et al., 2006; Stathakis et al., 2015).

Nonetheless, our finding in a large sample of children and adolescents across the age range from six to 17 years using device-based assessment of physical activity and GIS system-based assessment of urbanicity is in line with results from studies applying self-reported (Liu et al., 2008) and accelerometer-measured physical activity assessment (Moore et al., 2013). In contrast, one study with accelerometer-measurement reported no differences in MVPA between urban and rural youth (McCrorie et al., 2020), and Machado-Rodrigues et al. (2014), as well as Moore et al. (2014) found less MVPA in urban girls compared to their rural counterparts, respectively.

Regarding the results of meeting the physical activity guidelines, the main results differ from studies conducted in Canada (Manyanga et al., 2022) and China (Zhu et al., 2019), where no differences between urban and rural youth were observed. However, the study in Canada was conducted with adolescents between twelve and 17 years (Manyanga et al., 2022), an age range for which we also did mostly not find support for differences in the likelihood of meeting the guidelines between urban and rural areas when stratifying the analysis by age group. A potential reason for this could be that physical activity opportunities in urban areas are no longer attractive to adolescents as other aspects, such as being active on social media, are becoming increasingly important (mpfs, 2021). Hence, physical activity levels of urban and rural adolescents may converge, leading to overall low physical activity levels in Germany's adolescents (Burchartz et al., 2021).

In addition, results of the replication study revealed that urbanicity degree was only associated with an enhanced likelihood of meeting the guidelines in girls, but not in boys. While these gender disparities are not well understood, in our study, this may indicate that especially girls in Germany, who have on average lower physical activity levels than boys (Woll et al., 2021), benefit from urban living regarding physical activity.

For future research, there are promising paths to gain more specific insights to inform policy, health guidelines, and interventions on how to further improve MVPA in children and adolescents living in cities and especially youth living in rural environments. First, information about the physical activity type, e.g., whether children and adolescents achieved the MVPA-levels by running to the school bus (active transport) versus by playing soccer with friends (sports and exercises) (Burchartz, Anedda, et al., 2020) would help to assess the impact on physical activity to target interventions. Therefore, future studies can combine accelerometry with real-time assessment of the physical activity types, e.g., via electronic diaries prompting participants directly after their physical activity engagement therewith combining device-based intensity measurement with an ecologically valid assessment of physical activity types. Second, to design environments that promote physical activity in children and adolescents, it is important to understand how the features of the urban environment relate to their physical activity. To allow conclusions about relevant characteristics of physical activity, combining global positioning systems (GPS), global information systems (GIS), and accelerometry is a promising approach (Jankowska et al., 2015; Reichert et al., 2019; Reichert et al., 2020).

Some aspects of our work require further refinement in future research. First, our cross-sectional design does not allow any causal conclusions. Therefore, to enable insights above the sole association of urbanicity and physical activity, e.g., into the directionality of effects and potential third (moderation) variables, future studies can make use of longitudinal designs and experimental approaches (see e.g., Craig et al. (2012). Second, in our discovery study, we parametrized urbanicity by reported population sizes and based on the political categorization of urbanicity. While this method can be questioned regarding its limited sensitivity, in our replication study, we applied a parameterization using the European-wide DEGURBA degree, which replicated the results of the discovery study.

Conclusion

We here provide novel and robust evidence that youth city dwellers in Germany engage in more MVPA than their rural counterparts. While global physical inactivity makes physical activity promotion necessary across all geographical areas (Guthold et al., 2020), our findings suggest that rural communities should be explicitly targeted to prevent adverse health events and address urban-rural inequalities. For example, since in the school setting, similar urban-rural physical activity developments have been observed across the last 15 years (Nigg et al., 2022), this context poses a promising starting point to reach children and adolescents across geographical areas.

Given the outstanding value of physical activity engagement for human's physical and mental health (Biddle et al., 2019; Chaput et al., 2020), our finding of significantly heightened MVPA levels in Germany's youth city dwellers comes with positive implications for ongoing urbanization yet raises critical future research questions to inform policy and city planning: While heightened MVPA in city dwellers can benefit youth health in times of urbanization, studies researching which specific features of the urban environment foster which kind of human physical activity are critical for targeted interventions aiming to sustainably increase physical activity.

Here, rapid digitization offers highly promising tools such as unobtrusive geolocation sensing via smartphone apps and advanced geoinformatics methods such as lidar data to extract environmental features. Combinations with further advanced ambulatory research tools (e.g., electronic diaries on smartphones, smartphone sensing) can open avenues to more comprehensive insights into health behaviors and specific health indicators of youth's everyday life in both the rural and urban context.

Author contributions

MR: Conceptualization, Methodology, Writing – Original Draft; **CaN**: Conceptualization, Methodology, Visualization, Formal analysis, Writing – Original Draft; **AB:** Project administration, Investigation, Data curation, Software, Writing – Review & Editing; **DJ**: Writing – Review & Editing; **ML**: Writing – Review & Editing; **JW**: Formal analysis, Writing – Review & Editing; **JKR**: Writing – Review & Editing; **BHM**: Writing – Review & Editing; **UEP**: Supervision, Writing – Review & Editing; **ClN**: Conceptualization, Writing – Review & Editing; **JS**: Supervision, Writing – Review & Editing; **AW**: Conceptualization, Funding acquisition, Writing – Review & Editing;

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CHAPTER 4

Going green: The impact of the geospatial and conceptual configuration of the natural environment in child and adolescent health research studies

Slightly modified version of the 3rd published article:

Nigg, C., Burchartz, A., Niessner, C., Woll, A., & Schipperijn, J. (2022). The Geospatial and Conceptual Configuration of the Natural Environment Impacts the Association with Health Outcomes and Behavior in Children and Adolescents. *International Journal of Health Geographics, 21*, 9. https://doi.org/10.1186/s12942-022-00309-0

Introduction

Childhood and adolescence are sensitive developmental periods, which makes it important to identify determinants that prevent mental illness (Patel et al., 2018) and foster physical activity and physical health (Guthold et al., 2020), in this way promoting that children and adolescents flourish and become healthy adults. In the light of rapidly changing environments due to urbanization and climate change, the environment, especially green space, have been increasingly recognized as an important factor and determinant of health and health behavior (WHO, 1986), specifically for physical activity (Devarajan et al., 2019; Remme et al., 2021), physical health (Nieuwenhuijsen, 2018), and mental health (Bratman et al., 2019). Theoretically, green space in the form of parks and trails, constitutes attractive opportunities to engage in physical activity, such as active play or bicycling (Sallis & Owen, 2015). Multiple conceptual models exist that connect exposure to green space and mental health, including mechanisms via ecosystem services (e.g., reduced air pollution and heat), psychological benefits (e.g., reduced stress and affective restoration), and health behaviors (e.g., social interactions and physical activity) (Hartig et al., 2014; Markevych et al., 2017; Zhang et al., 2021) as well as physical health, e.g. via pathways of reduced air pollution, noise, and temperature (Nieuwenhuijsen, 2018).

However, while findings regarding green space and physical health in children and adolescents are limited to date (Dadvand & Nieuwenhuijsen, 2019), findings regarding associations between green space, mental health, and physical activity in children and adolescents are highly heterogenous: A recent systematic review found inconsistent associations between green space (distance to, count/proportion, or type of green space) and different physical activity domains and well-being (Nordbø et al., 2020). These heterogenous findings may be explained by prevailing methodological issues.

Methodologically, there has been no consensus on how to assess the built environment via geographic information systems (GIS) in health research. For example, a comprehensive review of GIS derived built environment measures in physical activity research showed large variability and a lack of definition of built environment variables (Brownson et al., 2009), hindering comparisons across studies. Also, when looking specifically at studies investigating GIS-derived green space in relation to physical activity and mental health in children and adolescents, assessment methods were highly heterogeneous regarding buffer sizes, ranging from 50m to 8050m, buffer type, including network distance to green space as well as circular buffers for the proportion of green space within a certain area, and green space type (Nordbø et al., 2018).

Additionally, in the geographical literature, the problem of the relationship between a spatial variable and the outcome of interest being dependent on the spatial unit has been recognized as modifiable areal unit problem (MAUP) (Jelinski & Wu, 1996; Openshaw, 1984). The MAUP consists of both the scale problem, referring to different and arbitrary sizes of spatial aggregation (e.g., aggregating green space data within a 500m vs. a 1000m buffer), and the zone problem, referring to the configuration of the spatial zone (e.g., application of administrative boundaries vs. individual-level buffers) (Jelinski & Wu, 1996). The MAUP has also been observed when examining geographical contexts in health research: In a study with adults, the relationship between built environment variables (e.g., mixed land use, pedestrian infrastructure) and active transport varied by buffer size and type, with this variation being inconsistent across the built environment variables, thus making it challenging to select an ideal geographical scale that fits all (Clark & Scott, 2014). Similar results were obtained when examining associations between different accelerometer measures of adult's physical activity and selected built environment measures (Mavoa et al., 2019), children's active school travel behavior (Mitra & Buliung, 2012), and when investigating green space in relation to outdoor physical activity (Klompmaker et al., 2018). Considering mental health, the relationship between neighborhood socio-economic deprivation and the purchase of psychiatric medication was dependent on the geographical assessment of the neighborhood via micro-area, parishes, or postal codes (Jakobsen, 2021). Regarding physical health, parameters of walkability showed heterogenous relationships with obesity depending on the geographical scale being used, and the best model fit was achieved when different geographical scales for each parameter were included (Yamada et al., 2012).

However, although some studies investigated how the choice of the geographical scale influences the association with a specific health parameter or health behavior, there is a lack of studies that i) investigated different operationalizations of green space and used various buffer sizes and buffer types in children and adolescents ii) explored variations across different health domains, and iii), took sociodemographic characteristics of the sample for those variations into account. Hence, this study aims to investigate

1) How the relationship between green space and physical activity, mental health problems, and physical health varies by nature operationalization, buffer type, and buffer size
2) How this variation occurs across age, gender, and socio-economic status.

Methods

Data was obtained from the Motorik-Modul Study (MoMo). The MoMo study applies a cohort-sequence design to investigate physical fitness, physical activity, and health indicators in children and adolescents between four and 17 years in Germany (Woll et al., 2021). For this study, we only used cross-sectional data from the latest Wave 3.1 (2018-2020) as this was the only study wave for which address data of the participants could be obtained.

Participants and procedures

The participants for the MoMo study Wave 3 (2018-2022) were selected based on a nationwide multi-stage sampling approach with two evaluation levels to maximize representativeness (Kamtsiuris et al., 2007): First, a systematic sample of 167 primary sampling units was selected from an inventory of German communities stratified according to the classification system that measures the level of urbanization and geographic distribution (Kurth et al., 2008). The probability of any community being picked was proportional to the number of citizens younger than 18 years in that community. Second, based on the official registers of local residents, an age-stratified sample of randomly selected children and adolescents was drawn.

Due to the Covid-19 pandemic, data could not be collected at all 167 sampling points but had to be interrupted after 128 sampling points were completed. All data used in this study (Wave 3.1; 2018-2020) had been collected prior to the first Covid-19 related lockdown in March 2020. Participants were invited to examination rooms within proximity to their homes for measurement purposes. Study participation was voluntary, and participants' guardians provided written consent. For children under the age of eleven years, parents were asked to fill in the questionnaire together with the child. The study was conducted in accordance with the Declaration of Helsinki. Ethics approval was obtained by the ethics committee of the Karlsruhe Institute of Technology. The Federal Commissioner for Data Protection and Freedom of Information was informed about the study and approved it.

Measures

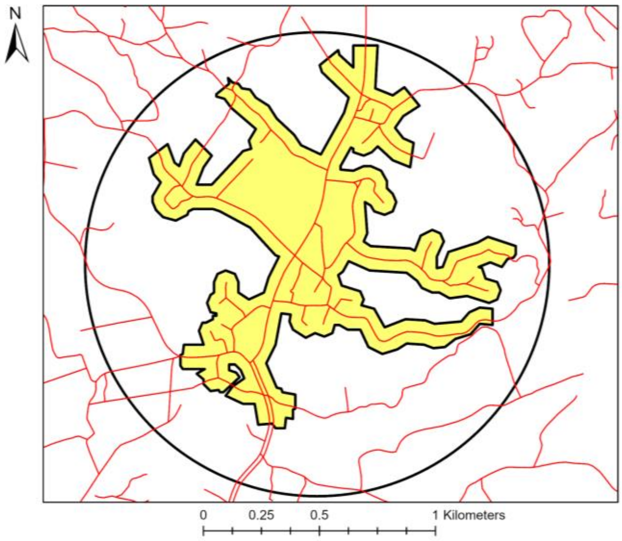
Sociodemographic characteristics and body-mass-index (BMI). Participants reported age, gender, and socio-economic status. The socio-economic status is a multidimensional score based on information of both parents regarding occupational status, education, and net income, which is computed based on the procedures of Lampert and colleagues (Lampert et al., 2014). Based on the score quintiles, a three-level variable was created (socio-economic status low: first quintile; medium: second to fourth quintile; high: fifth quintile). Height and weight were assessed by trained staff and BMI categories were established based on the cut-off points of the International Obesity Task Force (Cole et al., 2000; Cole et al., 2007).

Nature types and buffer development. First, all address data of MoMo Wave 3 were geocoded using the address batch of the Federal Agency for Cartography and Geodesy (BKG, n.a.). Second, the digital land cover dataset DE-LBM2018 in vector format was obtained from the Federal Agency for Cartography and Geodesy, containing information about land cover and land use. Land cover information is based on multitemporal image data (mainly RapidEye: 5m ground resolution, 5 channels). Land use information was obtained from the ATKIS Basis-DLM about settlements, traffic, vegetation, and water bodies with a minimum mapping area of one hectare. Both land use and land cover data were transformed to comply with the European CORINE Land Cover classification (CLC) by the Federal Agency (BKG, 2020b). Based on this data, we developed three different indices: 1) nature index, which contains both green space and blue space, 2) green space index, which includes only vegetated areas and excludes water bodies and non-vegetated areas; and 3) accessible green space, which excluded agricultural areas. The appropriate CLC-classification for each index was selected and transformed into a raster dataset, using the cell assignment type maximum combined area and a cell size of 10mx10m.

We decided for the definition of these three indices based on conceptual considerations. One index should represent the natural environment as a whole, thus including all outdoor areas that allow individuals to be exposed to any elements of nature (Calogiuri & Chroni, 2014), hence including both green space areas (e.g., urban green space, agricultural areas, forests) as well as semi-natural (e.g., beaches, rocks) and blue space (e.g., wetlands and water bodies) in the geospatial configuration. Although health research on blue space is still in its infancy, previous study results indicate that green space and blue space may have different relationships with health outcomes (De Vries et al., 2016; Nieuwenhuijsen et al., 2018; Nutsford et al., 2016; Völker & Kistemann, 2015), thus, one nature index was concentrated on green space as this is a frequently used indicator in health research (Browning & Lee, 2017; Davis et al., 2021). The third nature indicator, accessible green space, was created with a special focus on the usability of green space, as this may be especially relevant for physical activity and muscular fitness. Hence, agricultural areas were excluded as they are often not accessible (Matthews et al., 2000).

All nature indices calculations were conducted with ArcGIS Pro (version 2.6.3). Next, circular buffers with Euclidean distances from 100m, 250m, 500m, and 1000m were created around each participant's home address. To compute street-network buffers, we obtained additional geographical data from the Federal Agency for Cartography and Geodesy (Basis-DLM) that contains topographical objects with an accuracy of -/+ 3m for streets and paths (BKG, 2020a). For our purposes, we created a dataset that excluded motor highways and federal streets as they are only accessible with a motorized vehicle and thus could not be used in a physical activity context. Next, we computed street-network buffers using the Service Area Solver within the Network Analyst extension of ArcGIS Pro for the distances 1000m, 3000m, and 5000m. The "high precision" polygon generation option was applied with a trim distance of 50m and allowing overlap. Both the circular and street-network buffers were intersected with each of the land cover included in each index to obtain the percentage of natural land cover within the specified buffer distance (see *Figure 1*).

Figure 1. Example of a circular buffer and street-network buffer with a buffer distance of 1000m, respectively.



The area within the black circle shows the area that is considered for the natural environment if a 1000m circular buffer distance is used, the yellow-colored area shows which area is considered for the natural environment if a 1000m street-network buffer is used. The red lines represent streets and paths.
Geobasisdaten: © GeoBasis-DE / BKG (2020)
User conditions: https://sg.geodatenzentrum.de/web_public/nutzungsbedingungen.pdf

Moderate-to-vigorous physical activity. We decided for moderate-to-vigorous physical activity (MVPA) as a crucial health behavior during childhood and adolescence due to its numerous health benefits (Biddle et al., 2019; Chaput et al., 2020) and as the built environment has been shown to relate to children's and adolescents' physical activity (Nordbø et al., 2020). Details about accelerometry use in the MoMo study are elsewhere available (Burchartz et al., 2020). Briefly, participants between six and 17 years were asked to wear an ActiGraph GT3x+ or ActiGraph wGT3X-BT accelerometer for seven consecutive days. As not all participants agreed to wear an accelerometer, those associations could only be explored in a sub-sample. Participants were instructed to place the accelerometer on the right hip and to wear it during waking hours. Data was sampled with a frequency of 30 Hz. Downloaded data was converted into one-second-epochs and re-integrated into 15-second-epochs. Non-wear times were detected based on the Choi-algorithm (Choi et al., 2011). To be considered a valid accelerometer dataset, participants had to wear the device for more than eight hours on at least four weekdays and one weekend day. To determine MVPA, two cut-off point systems were applied that are commonly used for the specific age groups, i. e., Evenson cut-offs for six-to-ten year-olds (Evenson et al., 2008) and Romanzini cut-offs for eleven-to-17 year-olds (Romanzini et al., 2014).

Muscular fitness. We used the single item standing long jump to assess muscular fitness as this has been suggested to be a good general index of muscular fitness in youth (Castro-Piñero et al., 2010) and this has been frequently applied in this age group (Eberhardt et al., 2020). Participants were standing behind a starting line with their feet together. They were asked to push forward vigorously, jump as far as possible, and land with both feet. The distance was measured from the starting line to the back of the heel closest to the starting line. Each participant jumped twice, with the maximum score (centimeters) being retained (Worth et al., 2015).

Mental health problems. Mental health problems were assessed using the German version of the Strength and Difficulties Questionnaire (SDQ; Klasen et al., 2003), which is an established assessment tool for mental health problems in children and adolescents (Tsang et al., 2012). The SDQ consists of five subscales: emotional symptoms, conduct problems, hyperactivity/inattention, peer relationship problems, and prosocial behavior. All subscales consist of five items with response options ranging from 0 (“Does not apply”) to 2 (“Does apply”). For this study, we only worked with the overall SDQ scale, consisting of all scales but the prosocial behavior scale. A sum-score was created, with higher scores indicating greater mental health problems. SDQ total difficulty scores were constantly related to an increased odds of clinical mental disorders in a population sample of children and adolescents (Goodman & Goodman, 2009) and are sensitive to identify individuals with clinically significant mental disorders (Goodman et al., 2000). Validity and reliability have been reported (Essau et al., 2012; Klasen et al., 2003).

Statistical analysis

All statistical analyses were conducted in R (version 4.1.2) (R Core Team, 2013). To explore the association between the different indices, buffer types, and buffer sizes, we used multiple linear regression. First, we examined the distribution of the outcome variables. Visual examination confirmed no substantial distribution from normality. Second, for each nature index type as well as buffer size and type, we ran one multiple linear regression model for each outcome (MVPA, standing long jump distance, and SDQ score), respectively. Our main interest was the association between nature buffer type and size and the outcome. Based on previous findings, we considered gender, socio-economic status, age, and BMI as covariates in each model (Fernández-Alvira et al., 2013; Sallis et al., 2016; Schmidt et al., 2020; Sterdt et al., 2014) (see also *Appendix C A1*). Third, as previous research has shown inequalities in the use of and access to natural environments (Schipperijn et al., 2010; Wüstemann et al., 2017) as well as in the association between built environment variables and health outcomes (Astell-Burt et al., 2014; Sillman et al., 2022), we calculated interactions between the natural environment predictors and socio-demographic indicators (age, gender, and socio-economic status). In addition, for the outcome MVPA, we distinguished between weekdays (Monday-Friday) and weekend days (Saturday-Sunday) as physical activity patterns may differ due to structural changes (Burchartz et al., 2022). For all models, we investigated model parameters and potential model assumption violations using the package “see” (version 0.7.0) (Lüdecke, 2022).

Results

Descriptive results

Overall, 2,843 children and adolescents between four and 17 years participated in the MoMo study Wave 3.1 between 2018 and 2020, which was the sample that was considered to analyze associations between natural environments and standing long jump distance as well as natural environments and mental health problems. Participants were on average 10.46 (SD = 3.49) years old, 48.3% were female, 15.1% were categorized as overweight or obese, and 19.5% were categorized as youth with low socio-economic status. We included only those participants in the analysis that had complete data on all variables including co-variates, resulting in N = 2,493 for standing long jump distance and N = 2,341 for mental health problems. For the accelerometer sub-sample, 949 children and adolescents between six and 17 years provided valid accelerometer data. Participants were on average 11.22 (SD = 3.34) years old, 49.8% were female, 14.5% were categorized as overweight or obese, and 17.8% as participants with low socio-economic status. We included only those participants in the analysis that had complete data on all variables including co-variates, resulting in N = 923. A detailed overview of socio-demographic information, weight status, and study variable descriptive results can be found in the supplementary material for each of the specific samples that were included in the final analysis (*Appendix C Table A1*).

Natural environment and moderate-to-vigorous physical activity (MVPA)

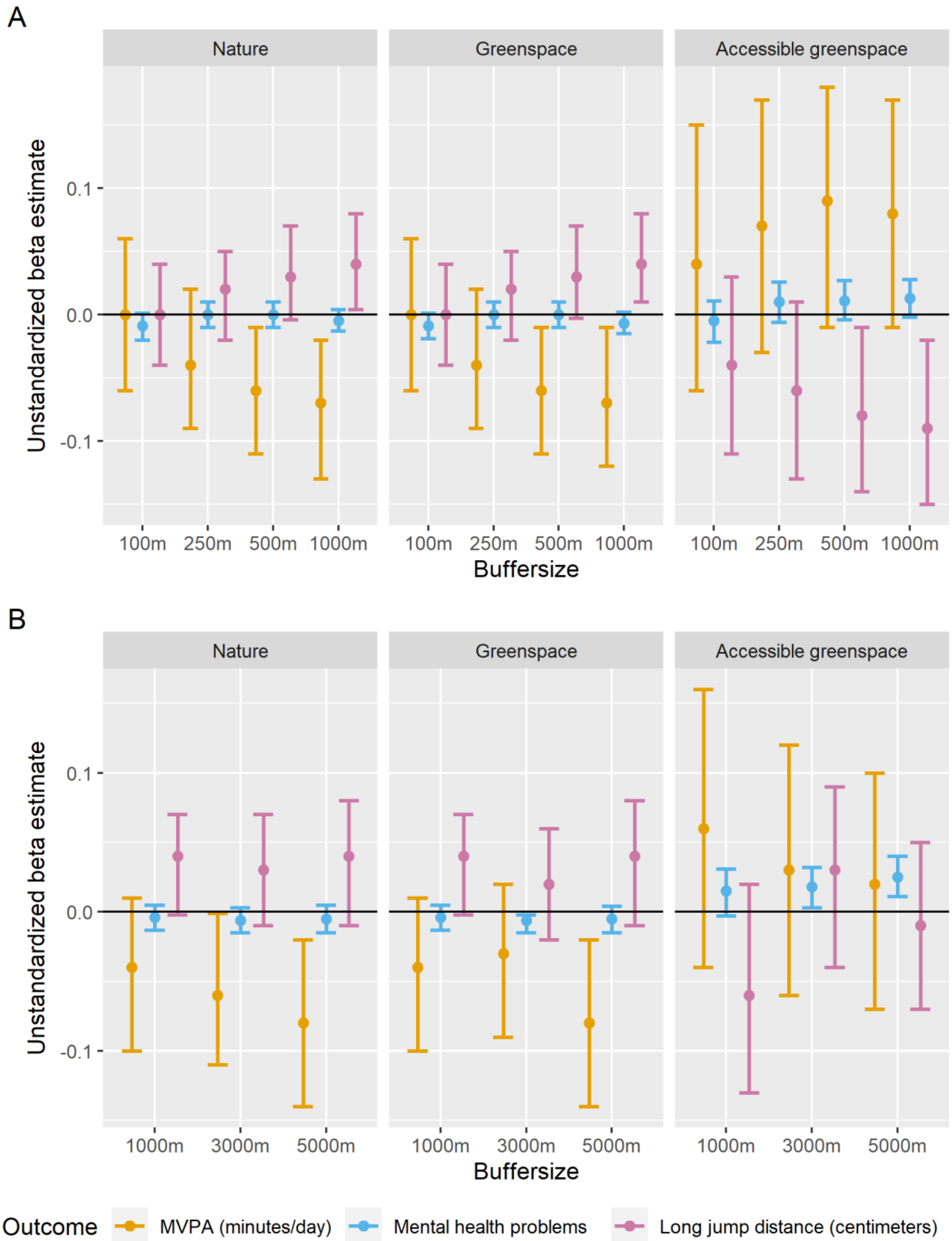
As our main interest was to explore associations between different nature indices, buffer types, and buffer sizes and the respective health outcomes or behavior, we only report the unstandardized regression coefficient for the fully adjusted models. More detailed information can be obtained in *Appendix C* (see *Tables A3-A6*).

Multiple regression analysis revealed a heterogenous picture regarding the association between the natural environment and physical activity. More specifically, the nature and green space indices were negatively associated with MVPA for the 500m and 1000m circular buffer as well as for the 3000m and 5000m street-network buffer, indicating that more natural environment relates to less MVPA. However, none of the accessible green space buffer types or distances were associated with MVPA (see *Figure 2*).

Next, we calculated interactions to explore potential variations based on individuals' characteristics. The results showed that the relationship varied by socio-economic status: Compared to youth with medium socio-economic status, nature within circular buffer distances from 100m to 250m was consistently related to lower MVPA in youth with higher socio-economic status across the three nature definitions. This was not observed for youth with low socio-economic status. However, the 3000m and 5000m accessible green space street-network buffer distances were negatively related to youth's MVPA with lower socio-economic status compared to youth with medium socio-economic status. This was not observed for youth with high socio-economic status (see *Appendix C Figure A1*).

When distinguishing between weekday and weekend MVPA, negative associations were observed between nature circular (250m-1000m) and street-network buffers (1000m-5000m), green space circular (500m-1000m) as well as green space street-network buffers (1000m-5000m) and weekday MVPA, but not with weekend MVPA. None of the accessible green space buffer types and sizes was related to MVPA neither on weekdays nor on the weekend (see also *Appendix C Figure A2*).

Figure 2. Variations of unstandardized beta regression coefficients of each nature index, buffer type, and buffer size across health outcomes.



Panel A: Unstandardized beta estimates for circular buffers. Panel B: Unstandardized beta estimates for street-network buffers. Sample size: N = 923 for MVPA; N = 2,493 for standing long jump distance; N = 2,341 for mental health problems. Error bars represent 95% confidence intervals. All models were adjusted for age, gender, BMI, and socio-economic status. Please see Additional File Table A6 for estimates of the co-variates.

Natural environment and muscular fitness

Distinct relationships also occurred for standing long jump: While both the nature and green space 1000m circular buffer were related to greater standing long jump distance, accessible green space (500m and 1000m circular buffer) was related to shorter jump distance (see *Figure 2*). However, for accessible green space (250-1000m circular buffer; 1000m street-network buffer), interaction analysis revealed that age moderated the association, indicating that the negative relationship between accessible green space and standing long jump distance only occurred for adolescents, but not for children (see *Appendix C Figure A3*).

Natural environment and mental health problems

Accessible green space street-network buffers (3000-5000m) were positively related to the SDQ score, indicating greater mental health problems with more green space (see *Figure 2*). Interaction analysis revealed distinct associations depending on participants' characteristics (see *Appendix C Figures A4 and A5)*. For socio-economic status, the results showed that both nature and green space circular (500m) and street-network-buffers (1000m) were related to less mental health problems for children and adolescents with low socio-economic status. For children and adolescents with high socio-economic status, less mental health problems were consistently observed across the nature and green space street-network buffers (1000m-5000m). However, the accessible greenspace street-network buffer (3000m) was associated with greater mental health problems in children and adolescents with low socio-economic status. Regarding age, interaction results revealed that all accessible greenspace circular and street-network buffers (except for the 100m circular buffer) were associated with greater mental health problems in adolescents, but not in children.

Discussion

The goal of this study was to explore variations in the relationship between natural environments and different health outcomes in children and adolescents. Our study showed heterogenous results depending on buffer size and buffer type and expands previous research by demonstrating that this variation also depends on the nature definition, the health outcome under investigation, and the sample's characteristics.

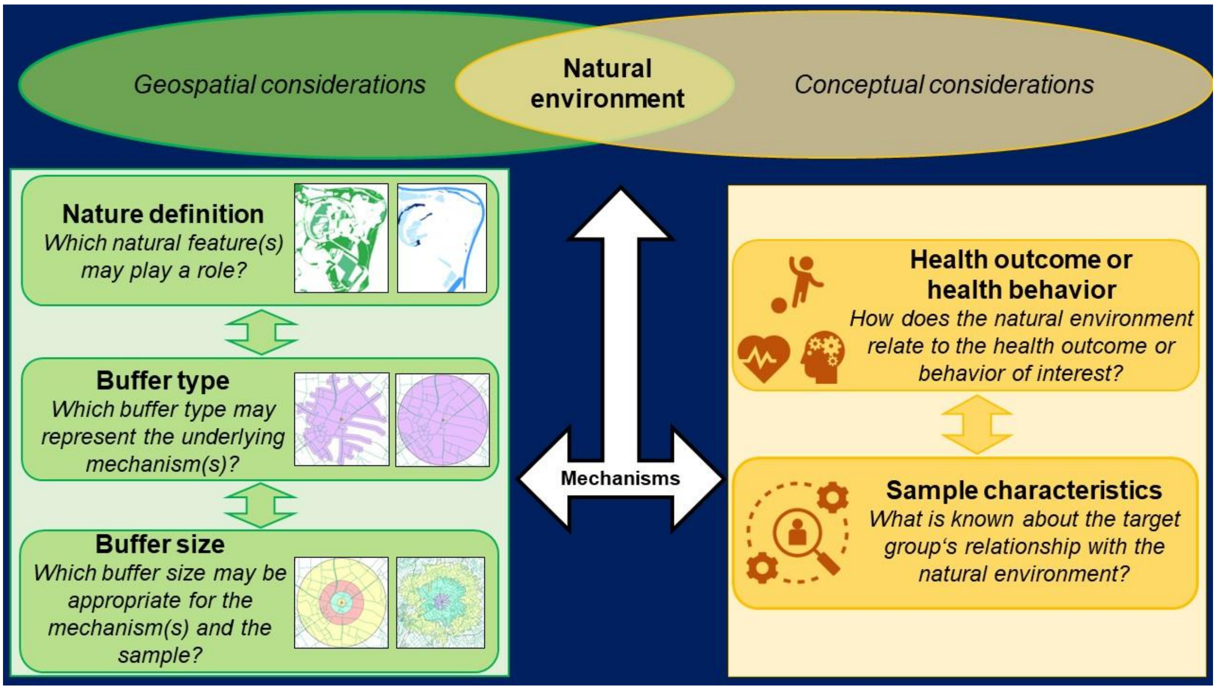
More specifically, our results showed that some buffer sizes of the natural environment and green space were statistically significant negatively related to physical activity behavior. However, when only accessible green space (excluding agricultural areas) was considered, no relationship emerged. Further, the relationships only emerged for natural environments and green space with weekday physical activity, while there was no association with weekend day physical activity observed. Also, the result differed by socio-economic status. While we do not have a clear explanation for these results, a potential reason may be that more exposure to natural environments reflects less access to other environmental features that are related to children's and adolescent's physical activity, such as short distances to leisure and sports facilities, mixed land use, or infrastructure for walking and cycling (Nordbø et al., 2020; Smith et al., 2017; Sterdt et al., 2014). Additionally, during childhood and adolescents, other aspects, such as peer- and parental social support (Sterdt et al., 2014), may be more important for physical activity engagement than residential green space. These heterogenous results for physical activity based on green space definition and buffer sizes are in line with a previous study in adults that investigated green space type (NDVI vs. land-use data) and various circular buffer sizes (ranging from 100m-3000m) in relation to outdoor physical activity (Klompmaker et al., 2018). Similar to the variations observed in this study, Klompmaker et al. (2018) found that compared to people in the lowest quintile of greenspace exposure, people in higher quintiles (representing people with more green space exposure) had a lower likelihood of being at least 150 minutes per week active outdoors for the 100m buffer and 500m-3000m buffers, but not for the 300m buffer.

For long jump distance, statistically significant positive associations emerged for nature and green space (1000m circular buffer), whereas a statistically significant negative relationship occurred for the same buffer size and type when looking at accessible green space. We were unable to find previous studies that investigated green space types and buffers in relation to muscular fitness, however, a systematic review investigating variations of buffer size in relation to physical health outcomes (e.g., obesity, cardiovascular disease) in children and adults also found that the observed relationship was dependent on the buffer size, with the likelihood of greenness being associated with physical health being the highest for buffers between 500m-999m when using home addresses as buffer centers (Browning & Lee, 2017). The authors argued that this indicates that individuals with high green density in the broader neighborhood have better physical health than individuals with high green density in their immediate surroundings but low green density in the broader neighborhood (Browning & Lee, 2017).

For mental health problems, two accessible green space street-network buffers were statistically significant related to greater mental health problems, whereas there were no statistically significant relationships with any of the other buffers when looking at the complete sample, which is in line with previous inconsistent results summarized in a systematic review due to a high variability in the metrics used to quantify natural environments (Davis et al., 2021).

These heterogenous results demonstrate that it is vital to consider the nature definition as well as buffer size and buffer type carefully when configuring the natural environment for one's study. In the following, we outline some guiding questions as a framework that may be used when deciding on how to choose the appropriate nature variable in one's study. We argue that it is necessary to integrate both geospatial and conceptual considerations when configuring the natural environment for one's study. A conceptual framework that may be used to guide one's decisions on the configuration is presented in *Figure 3* and discussed in the following.

Figure 3. Conceptual framework integrating geospatial and conceptual considerations for developing and choosing a nature assessment method in health research studies.



Nature definition

In our study, we assessed nature in three different ways: a) nature, including both green and blue space, hence representing any land-use area that could be counted as a natural environment; ii) green space, which excluded water-based areas, and iii) accessible green space, excluding agricultural areas as they are often not accessible to the public. Overall, associations varied across nature definitions and health outcomes or health behavior.

Hence, we argue that it is important to consider which geospatial definition of nature aligns best with the conceptual assumptions and potential mechanisms linking nature and the health outcome under investigation. GIS provide multiple options to operationalize natural environments. For example, for green space, common methods include remote sensing from satellite images to detect the density of green vegetation, resulting in the normalized difference vegetation index (NDVI) (NASA, 2000), or using national land use databases (James et al., 2015). However, green space operationalized as NDVI or land use may represent different underlying mechanisms: If one assumes that the mechanism underlying the green space – health relationship is related to vegetation density, NDVI could be the most appropriate measure. In contrast, if one assumes that the mechanism underlying the green space – health relationship is driven by the use of green space for activity or recreation, operationalizing green space via land-use data is probably more appropriate. It has been previously demonstrated that using the NDVI index or land cover and land use data yields heterogenous results regarding the relationship with overweight/obesity and physical activity (Klompmaker et al., 2018).

Beyond the geographical definition of the natural environment, specific mechanisms that may link nature and the health outcome under investigation should be considered when deciding which types and features of the natural environment should be included. For example, decreased air pollution has been suggested as one important mechanism that mediates the relationship between nature exposure and mental well-being (Zhang et al., 2021). When air pollution is expected to be a central mechanism, it may be appropriate to exclude water-based areas as their mitigating effect on air pollution is considered much weaker compared to green space (White et al., 2020). However, when considering social cohesion and interactions as a potential mechanism, the inclusion of both green space and blue space may be appropriate (Hartig et al., 2014; White et al., 2020). If the quality of the natural environment is assumed to play a role, aspects like biodiversity or amenities may be appropriate to consider (Wood et al., 2018). This can be expanded to considering the mechanisms in the context of the sample's characteristics: For example, a recent review outlined potential mechanisms of green space interventions for mental health considering contextual conditions and people's characteristics, concluding that mechanisms such as escaping from everyday life and being alone in natural environments may be specifically relevant for psychologically vulnerable people, while mental health benefits from natural environments for women may be mitigated due to a higher aversion to the outdoors (Masterton et al., 2020).

Thus, we argue that it is vital to conceptualize the underlying mechanism between the natural environment and the health outcome while considering the unique characteristics of the sample that may impact those mechanisms prior to the analysis.

Buffer type

In our study, we used two different individualized buffer types, including circular buffers and street-network buffers, which showed distinct and partially inverse relationships with the health outcome under investigation. Other typical buffer types include administrative boundaries (e.g., census tracts) or grid cells (Clark & Scott, 2014; Mavoa et al., 2019). As outlined in the introduction, the choice of buffer type and buffer size determines the spatial configuration, which often has a large influence on the relationship under investigation, known as the MAUP (Jelinski & Wu, 1996). To minimize this problem, several approaches exist, e.g., the use of disaggregated data (Clark & Scott, 2014). Similar to the nature definition, considering the outcome under investigation and the potential underlying mechanism may be useful when deciding on the buffer type. For example, when examining the natural environment in relation to physical activity, one may assume that accessibility to the natural environment, such as a walking path along a river, is vital. This can be captured when using a network buffer, but less so when using circular buffers (Frank et al., 2017). In contrast, when investigating mental health outcomes, visual exposure may be more important than accessibility. Hence, a circular buffer may be appropriate (Tost et al., 2019). Furthermore, the buffer type may also depend on the study's objective. For example, if the goal is to inform policymakers about green space interventions within communities, administrative community boundaries may be appropriate in combination with statistical methods that account for the clustering of the data within the communities, such as multilevel modeling (Clark & Scott, 2014). To create individual-level buffers, another, more advanced approach is to assess one's actual activity space using ambulatory assessment methods, such as logging devices that record one's whereabouts using global positioning systems, thereby allowing to match environmental characteristics and time with high spatial and temporal resolution (James et al., 2016). This approach can be extended to other sensors, such as accelerometers (Klinker et al., 2015) and e-diaries (Reichert et al., 2021) to assess behavior and psychological constructs in the context of natural environments. The value of such approaches becomes clear when considering the uncertain geographic context problem, referring to how much the spatial area used for a study deviates from the true causal geographically relevant context (Kwan, 2012). For example, a study with US adolescents showed that half of the participants spent 92% of their outdoor time outside their census tract area of residence (Basta et al., 2010). In this case, assessing the neighborhood via the census tract would not represent a relevant geographical context. Another study showed that the closest urban green space was not the one that was used most, with the use being dependent on the features and facilities of the particular green space (Schipperijn et al., 2010). Ambulatory assessment methods that capture one's actual activity space, such as combining accelerometry use with geolocation tracking, can overcome such problems as they provide utilization information, such as time spent in green space and physical activity levels whilst being exposed to green space (Jankowska et al., 2015; Marquet et al., 2022). However, caution about causal inferences is also necessary with ambulatory assessment approaches as new challenges, such as the selective mobility bias, with individuals actively seeking places for specific purposes, such as a park for physical activity or specific restaurants based on their food preferences, may arise (Chaix et al., 2013; Plue et al., 2020).

Buffer size

In our study, we used buffer sizes from 100m to 1000m for circular buffers and 1000m to 5000m for the street-network buffers based on previous health research studies with children and adolescents (Nordbø et al., 2018). For the overall sample, the 500m to 5000m buffer distances were the ones that mainly played a role, with distinct relationships depending on buffer type, nature definition, and health outcome, which is an inherent problem addressed in the MAUP (Clark & Scott, 2014; Jelinski & Wu, 1996). When looking at the results of the interaction analysis by gender, age, and socio-economic status, we observed that different buffer sizes were relevant for different subgroups and that those relationships were again distinct. For example, for children and adolescents with high socio-economic status, circular buffer sizes ranging from 100m to 500m were consistently related to less MVPA compared to youth with medium socio-economic status. For mental health problems, street-network buffers of 1000m to 5000m for nature and green space were related to greater mental health problems in children and adolescents with high socio-economic status compared to children and adolescents with medium socio-economic status. However, in children and adolescents with low socio-economic status, less mental health problems were observed for the 1000m circular and 3000m street-network accessible green space buffers, but greater mental health problems for the 500m circular and 1000m street-network accessible green space buffers compared to youth with medium socio-economic status.

This makes the scale choice of the buffer size as an integral part of the spatial configuration as the nature definition and buffer type. To address this issue, it has been suggested, amongst others, to conduct a sensitivity analysis using different buffer sizes to explore the magnitude of the MAUP in one's data (Jelinski & Wu, 1996). While a sensitivity analysis allows investigation of the scope of the MAUP, we argue that the primary buffer size should be determined a-priori based on both geospatial and conceptual considerations that link the natural environment to the health outcome under investigation. For example, a previous study investigating momentary associations between urban green space and mood used 100m circular buffers around participants' geolocations for assessing momentary green space based on the assumption that mood benefits would be the result of visual green space exposure and considering that surrounding buildings in the city allow only a limited view (Tost et al., 2019). In addition, this study supported their buffer size choice with a quantitative analysis that estimated the visual range in the city (Tost et al., 2019). On a more general level, conceptually, smaller buffer sizes seem to provide better assessments than larger buffer sizes when using ambulatory assessment approaches for geolocation data in health research (Houston, 2014).

Furthermore, our analysis revealed that the choice of scale should not only be considered in the context of the nature definition, buffer type, and health outcome, but also the context of the sample. Especially in large datasets with heterogenous participants, this may require specifying buffer sizes for sub-groups. Here again, conceptual and geospatial considerations should be integrated. For example, it was shown that socio-economically disadvantaged groups experience less green space access and quality (Chen et al., 2020; Hoffimann et al., 2017), which also mirrors in differential use of green space for physical activity purposes of people with different income levels (Spencer et al., 2020). In contrast, for mental health, another study showed that green space had a stronger relation to a reduced likelihood of depressive symptoms in pregnant women with lower education (McEachan et al., 2016). Gender- and age-based differences occurred in children and adolescents, with a longer distance to parks being related to less physical activity of six-to-eleven year-old boys and girls, but only to less physical activity of male adolescents (twelve to 17 years), whereas there emerged no relationship for female adolescents (Kowaleski-Jones et al., 2016). These empirical findings should be conceptually considered when deciding on the buffer size for one's study and how this may impact the underlying mechanisms linking the natural environment to health outcomes and behavior.

Strengths and limitations

Our study has several limitations. First, the cross-sectional character of our dataset does not allow causal inferences. Second, we used federal land cover and land use data that does not consider private natural environments, such as gardens. Third, while we do have GIS-based information regarding residential natural environments, we do not have information regarding the utilization of the natural environment through children and their parents. Finally, for physical activity, we only had a sub-sample of participants who agreed to wear an accelerometer for one week, potentially inducing selection bias. Comparing accelerometer participants (= sub-sample) with the sample that did not agree to wear an accelerometer or had invalid accelerometer data, we observed statistically significant differences regarding socio-economic status (participants with low socio-economic status being less likely to be part of the accelerometer sub-sample), BMI (participants with overweight/obesity being less likely to be part of the sub-sample), and exposure to the natural environment, with participants of the sub-sample having statistically significant more nature exposure for the majority of the nature and buffer types and buffer sizes. However, when looking at effect sizes, these effects were small. No statistically significant differences were observed regarding age and gender.

Nonetheless, we would like to highlight that this is one of the first studies that investigated variations in the association between natural environments and health in a broad sample of children and adolescents, considering various geospatial configurations, health outcomes and behavior, and sample characteristics.

Conclusion

The goal of this study was to demonstrate varying relationships between natural environments and selected examples of health outcomes and behavior based on nature definition, buffer type, and buffer size while accounting for specific sample characteristics. As there is no consensus on the geospatial configuration of the natural environment in health research, our second aim was to provide a framework and guiding questions that may facilitate the spatial configuration of the natural environment in future studies. We argue that future studies should integrate geospatial considerations (nature definition, buffer type, and buffer size) with conceptual considerations (health outcome and behavior, sample characteristics), taking into account potential mechanisms, to provide better reasoning and understanding of the relationship between natural environments and health (behavior).

Authors' contributions

CN1 conceptualized and designed the current article’s research questions, performed the geospatial and statistical analysis, interpreted the data, and drafted the manuscript. CN2 organized data acquisition and revised the manuscript critically for important intellectual content. AB organized data acquisition, analyzed accelerometer data, and revised the manuscript critically for important intellectual content. AW conceptualized, designed, and obtained funding for the cohort study, provided substantial input in the framing of the research questions, and critically revised the manuscript for important intellectual content. JS conceptualized and designed the current article’s research questions, supervised the geospatial and statistical analysis, data interpretation, and manuscript drafting, and provided substantial intellectual content. All authors read and approved the final manuscript.

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CHAPTER 5

Going green: Associations between green space and children's and adolescent's physical activity across urban and rural areas

Slightly modified version of the 4th article which is currently submitted:

Nigg, C., Fiedler, J., Burchartz, A., Niessner, C., Woll, A., & Schipperijn, J. (submitted). Distinct Associations between Green Space and Youth's Physical Activity in Urban and Rural Areas - Results of the MoMo Study. *Landscape & Urban Planning*.

Introduction

Physical inactivity is a major societal challenge, predicted to lead to 500 million new cases of non-communicable diseases (e.g., hypertension) and mental disorders (e.g., depression) between 2020 and 2030, and incurring health care costs of US$ 27 billion annually (WHO, 2022). Since engaging in physical activity is positively associated with mental, physical, and behavioral health (Chaput et al., 2020), the World Health Organization (WHO) recommends children and adolescents to engage in an average of 60 minutes of moderate to vigorous physical activity (MVPA) daily (WHO, 2020). However, only about 20% of children and adolescents meet these physical activity recommendations globally and in Germany (Aubert et al., 2022).

To tackle physical inactivity, the Global Action Plan on Physical Inactivity by the WHO (2018), building on socio-ecological models (Sallis & Owen, 2015), emphasizes the importance of creating active environments that facilitate engagement in physical activity for people of all ages. Specifically, the WHO calls for action to strengthen access to green space for physical activity promotion (WHO, 2018). From a conceptual point of view, green space is expected to enhance human health via three pathways, including mitigation through harm reduction (e.g., heat reduction), mental restoration through restoring capacities (e.g., via stress recovery), and in this context most importantly, prevention through building capacities, such as engagement in physical activity (Markevych et al., 2017). Hence, conceptually, it is expected that green space facilitates physical activity of children and adolescents.

However, empirically, several systematic reviews present mixed results regarding the relationship between distance to, proportion, or type of green space, and physical activity in children and adolescents (McGrath et al., 2015; Nordbø et al., 2020). While methodological heterogeneity regarding green space definition as well as buffer types and sizes may be one reason for this (Nigg, Niessner, et al., 2022), another reason may also be that the green space context has been neglected. More specifically, the association between green space and physical activity may vary across urban and rural areas due to their different characteristics. For example, compared to metropolitan areas, rural areas have less developed public open green space, referring to areas that primarily consist of vegetation but also have some construction compared to undeveloped green space (King & Clarke, 2015). Hence, green space in rural areas may be two-sided coin, with some green space being perceived as unsafe due to drug and gang activities, while other green space locations, such as state parks, being perceived as a facilitator of children's recreational exercise and physical activity (Findholt et al., 2011; Hennessy et al., 2010). However, to date, studies investigating the built environment in relation to physical activity across the urban-rural continuum in children and adolescents are rare (Hansen et al., 2015). This seems to be even more important since in Germany, children and adolescents from rural areas show decreasing trends in recreational and exercise activity (Nigg, Weber, et al., 2022). Drawing upon the few studies that investigated associations between green space and physical activity along the urban-rural continuum, a study with US adolescents between 12 and 17 years showed that park accessibility was associated with regular physical activity for urban, but not rural adolescents (Babey et al., 2008). Similar results were found in another study with 10-year-old children in England, where perceived park availability predicted physical activity in urban, but not semi-urban and rural children (Craggs et al., 2011). In a study with older adolescents in Germany, vegetation cover (assessed via the normalized differentiated vegetation index – NDVI) was associated with more total MVPA for adolescents in urban, but not rural areas in the Wesel region, while in the Munich area, green space was unrelated to MVPA in both urban and rural regions (Markevych et al., 2016).

In summary, research investigating associations between green space and physical activity along the urban-rural gradient is scarce. Existing research focused on park access and park availability in adolescents while there is a lack of studies investigating associations between land-cover based green space and physical activity across a broad age range of children and adolescents (McGrath et al., 2015). In addition, research was mainly conducted in North America (Nordbø et al., 2020). Hence, the purpose of this study was to explore the associations between green space and physical activity across urban and rural areas in Germany in children and adolescents. We expected that associations between green space and physical activity would differ across urban and rural areas.

Methods

The Motorik-Modul Study (MoMo) is a study in Germany that investigates physical activity, physical fitness, and health indicators in children and adolescents aged four to 17 years using a cohort-sequence design (Woll et al., 2021). We utilized cross-sectional data from survey period "Wave 3 (2018-2020)" of the study, as this was the only wave for which we could obtain the address data of the participants.

Participants and procedures

To select participants for MoMo survey period "Wave 3 (2018-2022)", a nationwide multi-stage sampling approach was used with two evaluation levels to ensure representativeness (Kamtsiuris et al., 2007). First, a systematic sample of 167 primary sampling units was chosen from an inventory of German communities stratified by urbanization and geographic distribution (Kurth et al., 2008), with the probability of selection proportional to the number of citizens younger than 18 years in each community. Second, an age-stratified sample of randomly selected children and adolescents was drawn from the official registers of residents.

Due to the Covid-19 pandemic, data collection had to be interrupted after 128 of 167 sampling points were completed. All data used in this study were collected before the first Covid-19 lockdown in March 2020. Participants were invited to nearby examination rooms for measurement purposes. Study participation was voluntary with written consent obtained from participants' parents or guardians. Parents or guardians of children under the age of eleven years were asked to fill in the questionnaire together with their children. The study was conducted in accordance with the Declaration of Helsinki and ethics approval was obtained from the ethics committee of the Karlsruhe Institute of Technology, with approval from the Federal Commissioner for Data Protection and Freedom of Information.

Measures

Socio-demographic characteristics and body-mass-index (BMI). Regarding participants' characteristics, the study collected information on age, gender, and socio-economic status. The latter was determined by a multidimensional score computed based on both parents' occupation, education, and net income data (Lampert et al., 2014). Trained staff assessed participants' height and weight to establish BMI categories using the International Obesity Task Force's cut-off points (Cole et al., 2000; Cole et al., 2007).

Urbanicity. From the German Federal Statistics Office community information system, we obtained data on the degree of urbanization (DEGURBA). The DEGURBA classification system is used across Europe to determine the level of urbanization in local administrative units, typically municipalities. It combines geographical contiguity and a minimum population density threshold applied to 1 km^2 population grid cells to assess the degree of urbanization. Based on this assessment, the system assigns three urbanicity levels: 1) Rural areas, with over 50% of the population living in rural grid cells, 2) Towns and suburbs, representing intermediate densely populated areas with over 50% of the population living in urban clusters and less than 50% living in urban centers, and 3) Cities, representing densely populated areas with over 50% of the population living in urban clusters; (EU et al., 2021). Using ArcGIS Pro (version 2.8.0), we identified the closest (sub)-community to each participant's home address and matched the corresponding community's urbanicity degree with the participant (Nigg, Oriwol, et al., 2021).

Green space assessment. The development and processing of geospatial data to operationalize the natural environment in the MoMo study have been described previously (Nigg, Niessner, et al., 2022). Briefly, we obtained digital land cover and land use data (DE-LBM2018) from the Federal Agency for Cartography and Geodesy which was transformed by the Federal Agency to comply with the European CORINE Land Cover classification (CLC). We decided to use land cover and land use data instead of vegetation-based green measures (e.g., NDVI), since we assumed from a conceptual perspective that green space facilitates physical activity via green space use, with the overall vegetation cover playing a minor role and as non-usable green space is also included in vegetation-based measures. In addition, we obtained street network data from the dataset Basis-DLM that contains topographical objects with an accuracy of -/+ 3m. For our purposes, we excluded highways and federal streets as they are only accessible with a motorized vehicle and are thus irrelevant in a physical activity context. Next, we operationalized green space as vegetated and semi-natural areas, such as forests, green urban areas, or pastures, but excluded agricultural areas since they are often not accessible (Matthews et al., 2000). In addition, blue space, such as wetlands and water bodies were excluded since previous study results indicate that blue and green space have distinct relationships with health (Nutsford et al., 2016). Next, based on the street data, we computed 1000m-street network buffers around the participant’s residential address using the service area solver within the Network Analyst extension of ArcGIS Pro (version 2.6.3). We intersected the 1000m-street network buffers with the green space layer to calculate the percentage of green space within each network buffer (range: 0-1). Based upon conceptual and geospatial considerations (Nigg, Niessner, et al., 2022), we decided to use the 1000m-street-network buffer distance since this is considered as a walkable neighborhood distance (Millward et al., 2013), thus being practically relevant to emerging climate-friendly and active living design concepts, such as the 15-minute-city (Allam et al., 2022). Additionally, established studies investigating associations between the built environment and physical activity, such as the International Physical Activity and Environment Network (IPEN) Adolescent Study (Cain et al., 2021), used this buffer type and size, facilitating comparability (Nordbø et al., 2020).

Moderate-to-vigorous physical activity. A detailed explanation regarding accelerometer use in the MoMo study can be found elsewhere (Burchartz, Manz, et al., 2020). Participants in the study were instructed to wear an accelerometer (ActiGraph GT3x+ or ActiGraph wGT3X-BT) for eight consecutive days, with the first day not being included in the analysis. The devices were provided to participants by qualified research assistants together with a leaflet summarizing important aspects of device placement and handling. Supervised by a research assistant, participants were instructed to place the accelerometer on the right hip and to wear it during waking hours. The data was sampled using a frequency of 30 Hz and downloaded data was processed into 1-second epochs. Participants were required to wear the device for more than eight hours on at least four weekdays and one weekend day for their data to be considered valid. Two cut-off point systems were used to determine physical activity intensity for specific age groups: six to ten-year-olds (Evenson et al., 2008) and eleven to 17-year-olds (Romanzini et al., 2014).

Statistical analysis

All analyses were conducted using R Studio (version 4.2.2). To investigate the relationship between green space and MVPA, we used multiple linear regression models based upon green space quartiles (bottom [1st] quartile; middle [2nd] quartile; upper [3rd] quartile; top [4th] quartile) and stratified by urbanicity degree. Since the distribution of residential green space differed across urban and rural areas, we first created separate datasets for each urbanicity category. For the analysis, green space was grouped into quartiles for each urbanicity category (see *Appendix D Table S1* for threshold and mean values for each quartile) and the bottom quartile was set as the reference category. Since previous studies showed physical differences based on the socio-demographic characteristics of age, gender, socioeconomic status, and weight status, we included these variables as co-variates in each model (Sterdt et al., 2014). For weight status, we collapsed the categories “overweight” and “obese” into one category due to too low case numbers in the latter one. Since data plotting revealed a non-linear association between age and MVPA, we formed two age groups based on the data plotting and theoretical assumptions, with one category including six to ten-year-olds and the other category including eleven to 17-year-olds. In addition, we included accelerometer wear time as covariate as well as the season during which accelerometer data were collected since MVPA may depend on seasonal characteristics, such as temperatures (Turrisi et al., 2021). Based upon the German meteorological weather service, we assigned each month to a season: spring (March-May), summer (June-August), autumn (September-November), and winter (December-February). Furthermore, results of previous studies indicate that associations between green space and physical activity may vary between populations group, such as youth’s age, gender, and socio-economic status (Rigolon et al., 2021; Sanders et al., 2015; Young et al., 2014). Hence, within each urbanicity level, we calculated interactions between the green quartiles and age group, gender, and socio-economic status. Model assumptions were visually inspected and confirmed using the package “performance” (Lüdecke et al., 2021).

To examine the influence of missing data on our results, we imputed missing data in a sensitivity analysis including all participants who had agreed to wear an accelerometer. For participants not fulfilling the accelerometer wear time conditions, wear time and MVPA were set as missing data. Using the Multivariate Imputation via Chained Equations (MICE) package (Van Buuren & Groothuis-Oudshoorn, 2011), for each variable containing missing values, an imputation model was specified, with the algorithm iteratively imputing multiple possible values for the missing values, accounting for the uncertainty of the missing value imputation and increasing the plausibility for missing at random. Data were imputed for each urbanicity level separately. For each urbanicity level, we used polytomous regression (polyreg) imputation for categorical variables and predictive mean matching (pmm) for continuous variables to generate 20 datasets with 10 iterations. We included all predictors and co-variates as well as the outcome (MVPA) in the imputation model.

Results

Descriptive statistics

Of 1,211 children and adolescents participating in the MoMo Study between 2018 and 2020, 949 children and adolescents between six and 17 years provided valid accelerometer data. We included only those participants in the analysis that had complete data on all variables including co-variates, resulting in *N* = 923. Participants with complete data were on average 11.22 (*SD* = 3.34) years old, 50.05% were girls, and 14.19% were categorized as overweight or obese. Of all participants, 35% lived in rural areas, 43% in towns and suburbs, and 23% in cities. A detailed overview of socio-demographic information, weight status, and study variable descriptive results for participants with complete data can be found in *Table 1* and for all participants (*N* = 1,211) in the *Appendix D (Table S6)*.

Table 1. Descriptive information about the study sample

	Rural areas (*N* = 324)	**Town/suburb** (*N* = 391)	**Cities** (*N* = 208)	**Overall** (*N* = 923)
Gender				
Boys	164 (50.62%)	195 (49.87%)	102 (49.04%)	461 (49.95%)
Girls	160 (49.38%)	196 (50.13%)	106 (50.96%)	462 (50.05%)
Age in years (*Mean, SD*)	11.55 (3.38)	10.99 (3.40)	11.00 (3.14)	11.19 (3.34)
Age groups				
6-10 years	155 (47.84%)	212 (54.22%)	113 (54.33%)	480 (52.00%)
11-17 years	169 (52.16%)	179 (45.78%)	95 (45.67%)	443 (48.00%)
BMI				
Underweight	34 (10.49%)	31 (7.928%)	21 (10.10%)	86 (9.317%)
Normal weight	236 (72.84%)	306 (78.26%)	164 (78.85%)	706 (76.49%)
Overweight/obese	54 (16.67%)	54 (13.81%)	23 (11.06%)	131 (14.19%)
Socio-economic status (*Mean, SD*)	14.73 (3.06)	15.97 (3.33)	15.99 (3.31)	15.54 (3.28)
Season				
Summer	63 (19.44%)	36 (9.207%)	31 (14.90%)	130 (14.08%)
Autumn	117 (36.11%)	104 (26.60%)	62 (29.81%)	283 (30.66%)
Winter	81 (25.00%)	167 (42.71%)	57 (27.40%)	305 (33.04%)
Spring	63 (19.44%)	84 (21.48%)	58 (27.88%)	205 (22.21%)
Greenspace (%)				
Mean (SD)	0.14 (0.15)	0.13 (0.11)	0.14 (0.10)	0.14 (0.13)
Min, Max	0.00, 0.94	0.00, 0.59	0.00, 0.45	0.00, 0.94
Accelerometer wear time in min/day (*Mean, SD*)	823.38 (111.97)	811.58 (102.97)	827.11 (124.75)	819.22 (111.43)
MVPA in min/day (*Mean, SD*)	51.88 (23.79)	55.61 (24.18)	59.43 (23.57)	55.16 (24.05)

Associations between green space and physical activity (MVPA min/day)

Regression results of the main effects are displayed in *Table 2*. Results showed that green space was negatively related to physical activity in rural areas, but not in small towns/suburbs, or cities. More specifically, in rural areas, compared to children and adolescents in the bottom quartile, children and adolescents in the middle quartile spent 6.74 (95%CI [13.02;-0.46]) and in the upper quartile 6.77 (95%CI [-12.25;0.22]) minutes less in MVPA per day, while there was no statistically significant difference for the top quartile.

Table 2. Multiple linear regression analysis with green space stratified by urbanicity level predicting MVPA (minutes/day)

	Rural areas					Small towns and suburbs					Cities				
	B	*SE*	*β*	*95%CI*	*p*	*B*	*SE*	*β*	*95%CI*	*p*	*B*	*SE*	*β*	*95%CI*	*p*
(Intercept)	70.73	3.64	0.79	63.56;77.90	**<0.001**	74.41	4.42	0.78	65.71;83.11	**<0.001**	68.06	4.36	0.37	59.45;76.67	**<0.001**
Green space (reference: Bottom [1st] quartile)															
Middle [2nd] quartile	-6.74	3.19	-0.28	-13.02;-0.46	**0.035**	-0.27	2.94	-0.01	-6.05;5.51	0.927	3.29	3.87	0.14	-4.34;10.92	0.396
Upper [3rd] quartile	-6.77	3.19	-0.28	-13.05;-0.50	**0.035**	-0.35	3.02	-0.01	-6.28;5.59	0.909	0.20	3.86	0.01	-7.41;7.81	0.958
Top [4th] quartile	-6.01	3.17	-0.25	-12.25;0.22	0.059	1.22	3.04	0.05	-4.76;7.20	0.689	-0.05	3.87	-0.00	-7.69;7.59	0.990
Gender (ref. boys)	-0.52	0.37	-0.07	-1.26;0.21	0.164	0.42	0.32	0.06	-0.21;1.05	0.189	-0.49	0.41	-0.07	-1.30;0.33	0.238
Age group (ref. 6-10 years)	-8.81	2.29	-0.37	-13.32;-4.30	**<0.001**	-11.48	2.09	-0.48	-15.60;-7.37	**<0.001**	-12.38	2.78	-0.53	-17.87;-6.90	**<0.001**
Socio-economic status	-23.49	2.35	-0.99	-28.11;-18.87	**<0.001**	-21.67	2.17	-0.90	-25.93;-17.41	**<0.001**	-23.41	2.85	-0.99	-29.04;-17.78	**<0.001**
BMI (ref. normal weight)															
Underweight	0.97	3.73	0.04	-6.37;8.30	0.795	-4.44	3.91	-0.18	-12.13;3.25	0.257	-3.14	4.63	-0.13	-12.28;5.99	0.498
Overweight/obese	-8.96	3.10	-0.38	-15.05;-2.86	**0.004**	-11.47	3.07	-0.47	-17.51;-5.43	**<0.001**	-7.97	4.41	-0.34	-16.66;0.72	0.072
Season (ref. summer)															
Autumn	6.41	3.19	0.27	0.14;12.68	**0.045**	-4.04	4.11	-0.17	-12.13;4.04	0.326	14.48	4.39	0.61	5.82;23.13	**0.001**
Winter	0.78	3.38	0.03	-5.87;7.44	0.817	-2.87	3.79	-0.12	-10.32;4.58	0.449	8.30	4.41	0.35	-0.39;16.99	0.061
Spring	7.76	3.66	0.33	0.56;14.97	**0.035**	4.49	4.13	0.19	-3.62;12.61	0.277	7.60	4.36	0.32	-0.99;16.19	0.082
Wear time	0.02	0.01	0.08	-0.00;0.04	0.086	0.02	0.01	0.09	-0.00;0.04	0.051	0.00	0.01	0.02	-0.02;0.03	0.783
N	324					391					208				
R^2 / R^2 adjusted	0.323 / 0.297					0.309 / 0.287					0.381 / 0.342				

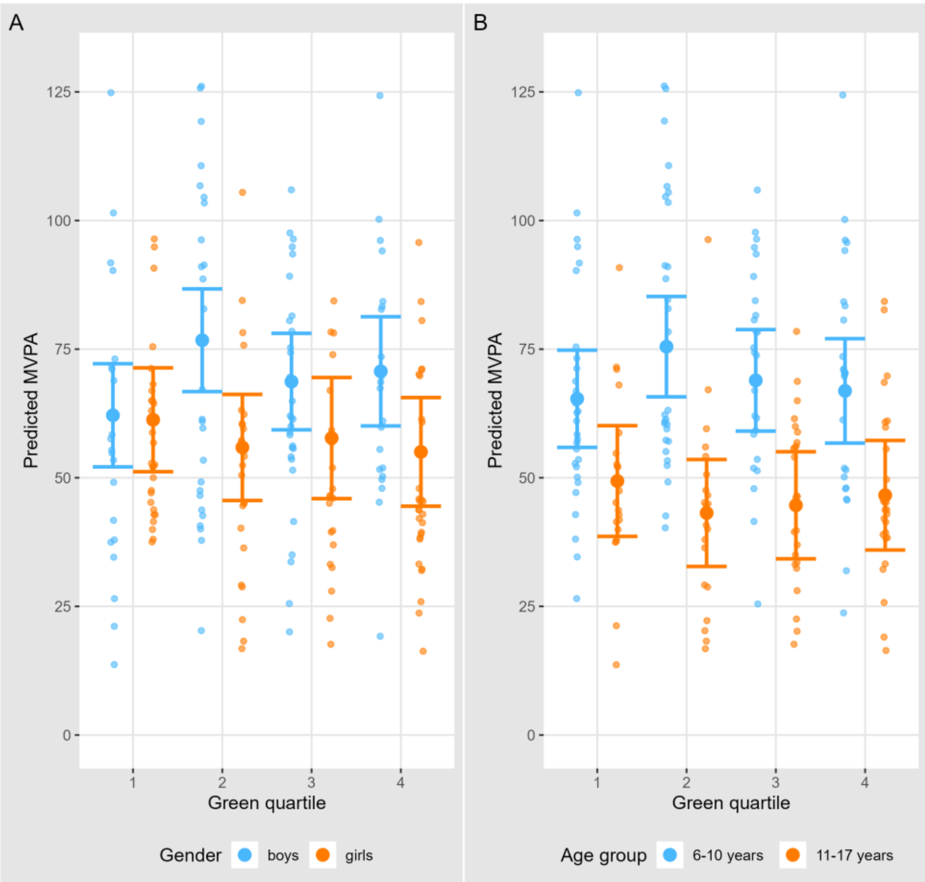
Note: For better interpretability of the intercept, socio-economic status and accelerometer wear time were grand-mean centered. BMI = body-mass-index; ref. = reference

Interaction effects between green space and socio-demographic characteristics regarding MVPA (min/day)

Several interactions based on socio-demographic characteristics emerged. In cities, compared to boys in the bottom green quartile, boys in the middle quartile engaged in 14.58 (95%CI [3.27;25.90]) more MVPA minutes, while girls were similar across green quartiles. No gender differences were observed within the bottom green quartile, but for the middle green quartile (B = 7.60, 95%CI [3.27;25.90]): Boys spent 76.73 (95%CI [66.81, 86.65]) and girls only 55.89 (95%CI [45.65, 66.14]) minutes in MVPA in the middle green quartile (see also *Figure 1A*). For rural areas, a contrasting association was observed: Boys in the upper green quartile spent 11.19 (95%CI [-19.69;-2.69]) and in the top quartile 10.55 (95%CI [-19.40;-1.70]) minutes less in MVPA compared to the bottom green quartile, while girls showed similar MVPA engagement across green quartiles. Gender differences were similar across green quartiles (see also *Appendix D Table S2*).

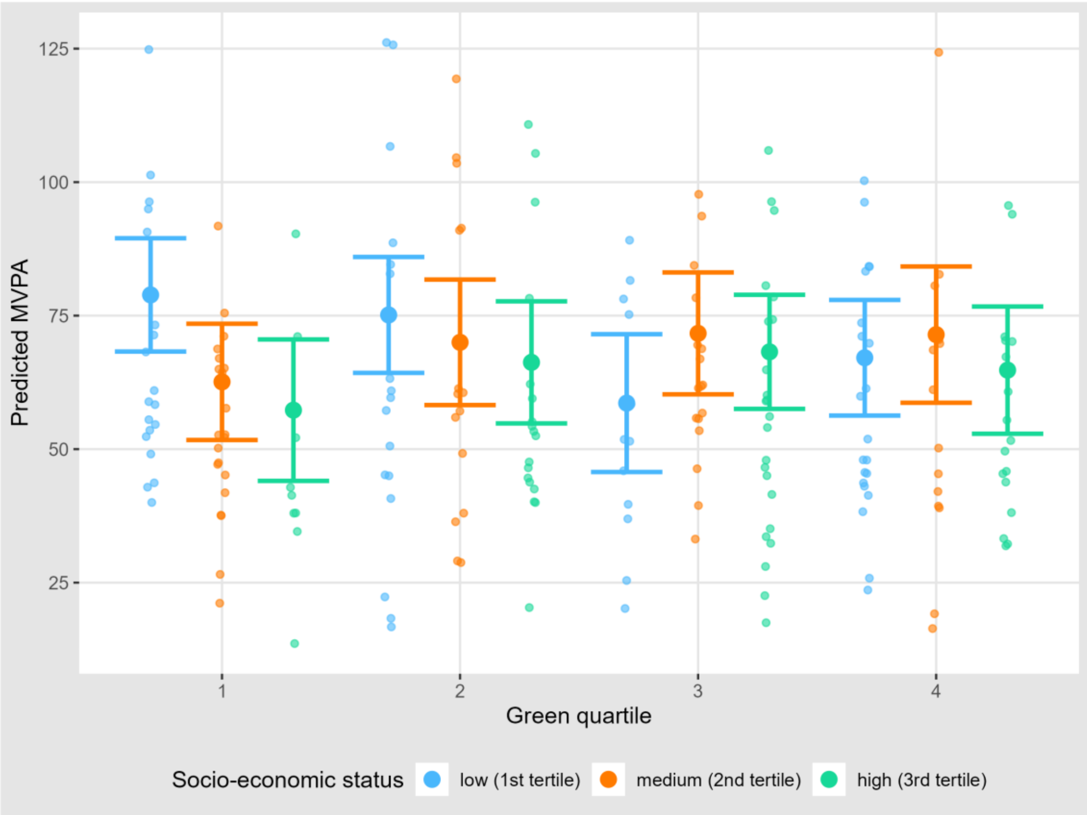
Regarding age differences, in cities, compared to children (six to ten years) in the bottom green quartile, children in the middle green quartile engaged in 10.13 (95%CI [0.26;20.00]) more minutes in MVPA, while adolescents (eleven to 17 years) showed similar MVPA engagement across green quartiles. In the bottom green quartile, adolescents engaged in 15.99 (95%CI [-26.99;-4.99]) minutes less MVPA than children. Interaction analysis revealed that gender differences were even more pronounced in the middle green quartile (B = 7.71, 95%CI [-31.55;-1.12]), with children engaging in 75.48 (95%CI [65.79, 85.17]) and adolescents engaging in 43.15 (95%CI [32.83, 53.48]) minutes of MVPA. In rural areas, children in the middle green quartile engaged in 11.74 (95%CI [-21.24;-2.24]) and in the upper quartile in 11.17 (95%CI [-20.26;-2.08]) minutes less MVPA compared to children in the bottom green quartile. For adolescents, MVPA engagement was similar across green quartiles. Age group differences were similar across quartiles (see also *Figure 1B* and *Appendix D Table S3*).

Figure 1. Gender (A) and age group (B) moderating the association between green space and MVPA in cities.



Regarding the socio-economic status (see also *Appendix D Table S4*), in rural areas, youth with an average socio-economic status in the middle and third green quartile engaged in less MVPA compared to youth with an average socio-economic status in the bottom quartile. In cities, a higher socioeconomic status was related to less MVPA in the bottom green quartile. MVPA was similar across green quartiles for youth with an average socio-economic status. However, green space and socio-economic status interacted for youth in the upper (B = 3.40, 95%CI [1.18;5.62]) and top (B = 2.57, 95%CI [0.30;4.84]) green quartile. To allow for more robust conclusions in cities, we split city youth into socio-economic status tertiles (1st tertile: low, 2nd tertile: medium, 3rd tertile: high) and calculated an additional model (see also *Appendix D Table S5*). Results revealed that youth with a low socio-economic in the middle green quartile status spent 20.26 (95%CI [-34.05;-6.48]) minutes less in MVPA compared to low socio-economic status youth in the bottom green quartile. In the bottom green quartile, compared to youth with low socio-economic status, youth with a medium and high socio-economic status spent less time in MVPA. However, results from the interaction analysis showed that for the upper and top green quartile, the differences between the socio-economic status groups vanished (see *Figure 2*). Result patterns were similar when missing data was imputed and included in the analysis (see *Appendix D Table S7-S10).*

Figure 2. Socio-economic status moderating the association between green space and MVPA for city youth.



Discussion

Using device-based physical activity and objective green space assessment, we found that associations between green space and health-enhancing physical activity (MVPA) differed across urban and rural areas in a large sample of children and adolescents across Germany. Furthermore, relationships were moderated differently by socio-demographic characteristics in urban and rural areas.

More specifically, for the whole sample, we found that in rural areas, green space was associated with less physical activity for children and adolescents in the middle and upper green quartiles. For towns and cities, no such relationships emerged. The negative association for rural compared to town and urban areas may be the result of the green space context and quality being different in rural compared to more urban areas. For example, two qualitative studies with rural parents, adolescents, and children in North America investigated physical activity opportunities and barriers, showing that parks were predominantly mentioned as a place that was unsafe for physical activity due to train tracks close by as well as drug and gang activities (Findholt et al., 2011; Hennessy et al., 2010). Beyond safety aspects, other characteristics seem to play a role to use green space for physical activity, which includes physical characteristics, such as green space infrastructure (e.g., parking lots, bike racks; Schipperijn et al. (2013)) but also social aspects such as a community feeling and the presence of other people as a protective network (Noël et al., 2021). Since those features may not be prevalent in rural green space, this may explain our results to some extent. For towns and suburbs, green space was consistently unrelated to physical activity, with the reasons for this remaining to be further investigated.

Furthermore, our results indicate that the association between green space and physical activity varied based on socio-demographic characteristics. Children between six and ten years in cities in the middle green quartile showed enhanced MVPA engagement, reinforcing age group differences. In contrast, rural children between six and ten years displayed lower physical activity levels in the middle and upper green quartiles. For adolescents in both rural areas and cities, MVPA engagement was similar across green quartiles. This supports previous results regarding distinct green space-physical activity associations across urban and rural areas in children (Craggs et al., 2011) and adolescents (Babey et al., 2008). A reason for this may be that compared to adolescents, children collect more MVPA through outdoor play (Nigg, Niessner, et al., 2021) and thus, for them, green space may be more important. The converse associations between green space and MVPA in rural areas and cities may be again explained by the type of green space exposure. For example, a study with parents of children between six and twelve years focusing on play environments showed that undeveloped natural spaces, e.g., forests, are less used by children than developed outdoor green spaces, such as playgrounds (Gundersen et al., 2016). Since developed green space is more likely in cities than in rural areas (King & Clarke, 2015), this may explain the distinct associations between green space and physical activity in cities and rural areas. Practically speaking, this means that the availability of abundant undeveloped or agricultural green space in rural areas does not compensate for the lower availability of developed green spaces in relation to children's physical activity. For that reason, it is important to also provide high quality developed green spaces in rural areas.

The same pattern as for age group was observed for gender: While city boys in the middle quartile show increased physical activity engagement, rural boys showed decreased MVPA in the upper and top green quartiles compared to the lowest green quartile. In both cities and rural areas, girls displayed similar MVPA engagement across green quartiles. While these effects may be partially confounded by the fact that younger children were also more likely to be boys in our sample, another reason may also be that boys spend in general more time outdoors than girls (Klinker et al., 2014), and engage in more independent mobility than girls, especially in urban areas (Stone et al., 2014). Thus, they may have more opportunities to use green space for physical activity. The negative associations between green space and physical activity may be also reinforced by decreasing levels of independent mobility in rural areas (Kyttä et al., 2015). Interestingly, the benefits of green space for MVPA in cities were only observed for the middle green quartile. This may indicate again that for green space to be beneficial for MVPA, it must be combined with other physical and social environment characteristics (Findholt et al., 2011; Hennessy et al., 2010; Noël et al., 2021; Schipperijn et al., 2013).

Finally, we found that associations between physical activity and green space were moderated by socio-economic status for city youth: City youth with a low socio-economic engaged in most MVPA in the bottom green quartile, which was not the case for youth with medium and high socio-economic status. However, with low socio-economic status youth tending to engage in less physical activity with more green space, physical activity levels assimilated across socio-economic status groups. Although a recent systematic review found that most studies exhibited stronger health benefits of green space for people with low socio-economic status, the same review also showed that associations between green space and health benefits varied across socio-economic status groups (Rigolon et al., 2021). In our study, this finding may be the result of gentrification, referring to the process in which neighborhoods of lower socio-economic status receive an increased influx and investment of residents with higher socio-economic status (Hwang & Lin, 2016). This problem has also been encountered in the urban greening context (Sax et al., 2022), showing that equal provision of neighborhood green space does not guarantee the same health benefits for all neighborhood residents (Lennon et al., 2019). More specifically, urban green space is often designed for the needs of higher-income residents (Anguelovski et al., 2019). This may reflect also in our results, with green space not fulfilling the needs of low socio-economic status youth, leading to displacement (Sax et al., 2022) and thus to less green space use and physical activity. Hence, for green space to benefit everybody, it is necessary to design green space in a way that also considers the needs and everyday lives of vulnerable and marginalized groups (Anguelovski et al., 2020). Another explanation for those results could be the deprivation amplification hypothesis, stating that poorer populations live in contextually disadvantaged areas (Nogueira, 2010). This hypothesis was for example confirmed in one playground study, showing that poorer children also had lower quality playgrounds (Buck et al., 2019). Transferred to our study, this may indicate that poorer children are exposed to more low-quality green space compared to youth with medium or high socio-economic status, which may lead to less green space use.

Strengths, limitations, and future research directions

A great strength of our study is that we investigated associations between objectively assessed green space via individual-level street-network buffers and device-based assessed physical activity across urban and rural areas in a broad age range of children and adolescents with varying socio-demographic characteristics, while previous studies focused predominantly on children or adolescents in urban areas within a limited age range or within a specific sub-population (e.g., Babey et al., 2008; Craggs et al., 2011; Markevych et al., 2016; Oreskovic et al., 2014; Young et al., 2014).

However, our study does not come without limitations. First, the cross-sectional character of our study limits any causal conclusions. Second, we calculated green space based on the land cover and land use data, which merely considers the quantitative amount of green space, while qualitative characteristics of green space were neglected. Evaluating specific green space characteristics, including green space type (Hunter et al., 2019) as well as green space infrastructure and design that may serve as facilitators of green space use in youth, such as playground or sports fields, walking paths, barbeques, and public access toilets (Edwards et al., 2015) may provide valuable information to explain distinct associations between green space and physical activity for urban and rural areas well as for different subpopulations. This would also provide valuable information to guide green space planning for active living in both urban and rural areas. Furthermore, we focused on general health-enhancing physical activity, operationalized as MVPA, but did not assess specific activity domains. For example, a previous study with rural children showed that parks were negatively related to active commuting, but unrelated to total daily MVPA (Oreskovic et al., 2014), whereas other studies emphasize natural environments as being facilitators for active recreational and exercise activities (Findholt et al., 2011; Hennessy et al., 2010). Furthermore, while we selected green space, buffer type, and buffer size based on conceptual and practical considerations as well as previous evidence (Nigg, Niessner, et al., 2022), we cannot be sure that all our metrics were relevant to our study sample, known as the uncertain geographic context problem (Kwan, 2012). Hence, using ambulatory assessment methods in a smaller sample via combining accelerometers for physical activity assessment with geolocation tracking in future studies would allow for capturing individual's activity space as well as green space utilization information (Reichert et al., 2021).

Conclusion

Our study found that green space and physical activity show distinct associations across rural areas and cities, with green space in rural areas being associated with less physical activity. Furthermore, in cities, boys and younger children may benefit from some green space, while the opposite trend was observed for rural areas. Socially disadvantaged children and youth engaged in less physical activity with more green space. Further studies should investigate green space quality characteristics and how they relate to physical activity across urban and rural areas. Our findings are important to support planning policies for creating inclusive active living environments across urban and rural areas.

Author contributions

CaN: Conceptualization, Methodology, Formal analysis, Visualization, Writing – Original Draft; **JF**: Formal analysis, Writing – Review & Editing; **AB**: Project administration, Investigation, Data curation, Software, Writing – Review & Editing; **MR**: Supervision, Writing – Review & Editing; **ClN**: Conceptualization, Methodology, Writing – Review & Editing; **AW**: Conceptualization, Methodology, Funding acquisition, Writing – Review & Editing; **JS**: Methodology, Supervision, Writing – Review & Editing

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CHAPTER 6

Going green and active: Psychosocial and physiological health effects of nature-based physical activity in children and adolescents

Slightly modified version of the 5th published article:

Mnich, C., Weyland, S., Jekauc, D., & Schipperijn, J. (2019). Psychosocial and Physiological Health Outcomes of Green Exercise in Children and Adolescents - A Systematic Review. *International Journal of Environmental Research and Public Health*, *16*, 4266.
https://doi.org/10.3390/ijerph16214266

Introduction

Physical activity (PA) is associated with numerous health benefits in children and adolescents, including improved cardiovascular health, mental health, bone strength, fitness levels, weight, and quality of life (Janssen & Leblanc, 2010; Wu et al., 2017). PA also impacts children's cognitions, resulting in improved achievements at school (Fedewa & Ahn, 2011) and improved cognitive functions (Alvarez-Bueno et al., 2017). In addition, PA during youth is related to long-term benefits in adulthood including a reduced risk of depression, hypertension, and type 2 diabetes (Fernandes & Zanesco, 2010; McKercher et al., 2014), making PA a core aspect of youth's short- and long-term health.

Natural environments are also associated with positive effects for youth. Access to green spaces is associated with improved mental and general well-being and lower stress (McCormick, 2017; Söderström et al., 2013), lower depression rates in children (Maas et al., 2009), milder symptoms of ADHD (Taylor & Kuo, 2011) as well as improved cognitive and emotional outcomes (Dadvand et al., 2015; Sharp et al., 2018; Wu et al., 2014). Green spaces are also related to fewer behavioral problems (Markevych, Tiesler, et al., 2014), hyperactivity, peer and conduct disorder problems (Flouri et al., 2014; Richardson et al., 2017). Looking at physical health outcomes, green spaces are associated with longer sleep (Söderström et al., 2013), lower blood-pressure (Kelz et al., 2015; Markevych, Thiering, et al., 2014) and lower rates of overweight, obesity, and sedentary behavior (Dadvand et al., 2014) in children.

A body of research has already explored the role of the natural environment for children's PA. One study showed that children between 8-14 years who experience more than 20 minutes of daily exposure to green spaces engaged in nearly 5 times more daily MVPA than children without daily exposure to green spaces (Almanza et al., 2012). Four other studies revealed that outdoor time in children aged 3-14 years has positive effects on PA, sedentary behavior, and cardiorespiratory fitness (Gray et al., 2015; Larouche, Garriguet, Gunnell, et al., 2016; Larouche, Garriguet, & Tremblay, 2016; Larouche et al., 2018). However, the causality of the found relations is unclear due to a lack of RCTs.

Having shown the benefits of both natural environments and PA individually, there might be sub-additive, additive or synergistic effects of combining both components (Shanahan et al., 2016). Green exercise (GE) is defined by Pretty and colleagues as "adopting physical activities whilst at the same time being directly exposed to nature" (Pretty et al., 2003, p. 7). Accordingly, GE does not only comprise PA taking place in green environments (e.g. parks and forests), but also in blue spaces (e.g. rivers and lakes) and any other environment containing natural components. Pretty also distinguished between different levels of engagement with nature: viewing nature (e.g. looking at a forest picture), being in the presence of nature incidentally while engaged in other activities (e.g. cycling to school), and involvement and participation in nature (e.g. trail running), with all three levels shown to impact mental health (Pretty, 2004). Regarding activity, GE includes both PA as well as planned and structured exercise in green settings.

The benefits of GE have already been explored in adults. A systematic review by Lahart et al. (2019) compared the effects of indoor and outdoor PA for physical and mental-wellbeing in adults. Results indicated lower perceived exertion scores for GE and a better response for affective valence. Findings about other outcomes were inconsistent. Other studies have shown better restorative effects and affective responses (Calogiuri et al., 2015), improved mental health (Brown et al., 2014), and reduced state anxiety (Mackay & Neill, 2010; Pretty et al., 2007) for GE compared to exercise indoors or in concrete environments. While one could argue that these effects appear after any exercise program, another study found that GE had a greater influence on improved mood and stress scores than exercise alone (Wooller et al., 2018).

As these studies only included adult participants, less is known about how GE impacts children's physiological and psychosocial health outcomes. Various studies have examined the relationship between the natural environment and PA, but only few studies have looked at the benefits beyond increased PA levels. Four systematic reviews were found that investigated benefits of physical activity in natural settings, but they mostly include adults and if they also included children and adolescents, they did not treat them as a separate target group (Coon et al., 2011; Eigenschenk et al., 2019; Lahart et al., 2019; Manferdelli et al., 2019).

The aim of this work is to fill this research gap. Therefore, this systematic review serves three purposes:

1) Provide an overview about the physiological and psychosocial outcomes of PA in natural environments (GE) in children and adolescents
2) Demonstrate the effectiveness of GE in terms of the outcomes assessed
3) Based on the overview of existing evidence, outline future research directions to study GE in children and adolescents

Materials and Methods

The PRISMA Statement has been used for this systematic review (Moher, 2009) and the study protocol has been registered with PROSPERO [CRD42019136385].

Search strategy and eligibility criteria

A systematic literature search was conducted on 11th February 2019, using the databases Web of Science (All Databases), PubMed, APA PsychNET, and ERIC. The primary search was based on title, abstract and keywords, using Boolean logic for the combination of search terms. Additional, possibly relevant studies were identified using the "snowball principle" by screening the references of all included studies (Greenhalgh & Peacock, 2005) and of the four systematic reviews that had already been carried out in this field (Coon et al., 2011; Eigenschenk et al., 2019; Lahart et al., 2019; Manferdelli et al., 2019).

Search terms were based on previous reviews and agreement between the first and third author, resulting in a search strategy with three parts with synonyms for 1) nature, 2) PA and exercise, and 3) children and adolescents. The search has not been restricted to certain outcomes to allow for the inclusion of a comprehensive body of literature. Search strategies for all databases can be found in the study protocol; as an example, the following strategy had been used in the Web of Science database: "Title=(green OR natur* OR outdoor OR outside OR park OR green space*) AND Title=(physical* activ* OR exercis* OR walk* OR cycl* OR hik* OR leisure time OR leisure-time OR recreation*) AND Topic=(child* OR adolescen* OR youth OR young people OR student* OR pupil*)".

The components of the PICOS question, including the components population, intervention, comparison, outcomes, and study design, were answered to define the eligibility criteria and are presented in *Table 1*. Beyond the PICOS question, only single-study articles published in peer-reviewed journals in English language between 2000 and 2019 were considered. This time period was chosen due to the fact the definition of "GE" was published in 2003 (Pretty et al., 2003). Considering the conceptual development and the publication process that it takes until a manuscript is published, such as the publication with the GE definition, three more years before the actual publication were included.

Table 1. Study selection criteria.

PICOS	Eligibility criteria
Population	• Study participants younger than 18 years
Intervention	• Any PA/exercise conducted in nature (independent variable) • Measurement of PA/exercise
Comparison	• No firm comparison group determined
Outcomes	• Any psychosocial or physiological outcome measured and reported • Psychosocial outcomes: individual's social and psychological aspects, including, but not limited to cognitions, emotions, and mental health (de Oliveira et al., 2013; Vizzotto et al., 2013) • Physiological outcomes: bodily changes due to stimuli response (Salomon, 2013)
Study Design	• No limitations regarding the study design

Screening and study selection

Reference results of the database search were exported to the reference program EndNote and duplicates removed. Studies were screened for inclusion criteria based on title in a first step, followed by abstract and full-text screening. The screening process was conducted by the first two authors independently. The two authors discussed their results and full-texts were included in the analysis based on mutual agreement. References of the included studies were scanned for other relevant articles independently, the results discussed, and studies included based on the first two authors' mutual agreement. If there was no consent, a third author was consulted for a final decision. Relevant data about the included articles was extracted by one author, comprising authors and year, study design, country of study and participants, type of GE and procedure, outcomes, outcome measurements, and results including the main quantitative results. The second author then reviewed the data extraction sheets. Included studies were sent to a member of the "Green exercise research group" of the University of Essex (UK) who gave feedback about any other studies familiar to him in this area.

The "Effective Public Health Practice Project" (EPHPP) was used for bias risk assessment of the included studies (Thomas et al., 2004). The tool was applied to the included studies independently by two authors and the final rating determined based on consensus. The EPHPP tool can be used for observational, cross sectional, pre-post, cohort and randomized controlled trial designs (Armijo-Olivo et al., 2012) and has for example been used previously in a systematic review assessing health outcomes of e-bike use (Bourne et al., 2018). The EPHPP tool has six equally weighted categories that are included in an overall-rating to assess the study quality: selection bias, study design, confounders, blinding, data collection methods, and withdrawals and dropouts. The withdrawal and dropout-category was also applied to cross-sectional studies as this contains information about the percentage of participants that completed the study. Data collections methods were considered as reliable and valid if at least 50% of the measurement instruments used in the study were reported as valid and reliable.

Each category received a strong (1), moderate (2), or weak rating (3), which was the basis for the overall rating of the study: strong (no weak ratings), moderate (one weak rating) and weak (two or more weak ratings). Two additional categories, intervention integrity and analyses, are included in the tool, but not in the overall rating (Thomas et al., 2004). Statistical methods were reported as appropriate if sufficient statistical power was reported. The EPHPP tool has shown to be suitable for use in systematic reviews (Deeks et al., 2003) and has fair inter-rater reliability and excellent agreement for the final rating (Armijo-Olivo et al., 2012).

Results

The study selection process is presented in Figure 1. A total of 1,161 articles were identified in the four databases: 773 articles in Web of Science, 110 studies in PubMed, 139 studies in APA PsychNET, and 252 studies in ERIC. Through the snowball principle and contacts with our network, another 14 studies were added to the screening process. After the duplicates had been removed, a total of 955 studies remained for screening. At the end of the process, 14 articles representing 11 studies that met the inclusion criteria could be identified. One cohort study was published in three different articles (Gopinath, Baur, et al., 2011; Gopinath et al., 2012; Gopinath, Hardy, et al., 2011). Two of these articles differed only in the outcome whereas the study population and design were the same, the other article used a different design. Therefore, the two similar articles were treated as one in this review, the third one is listed separately.

Figure 1. Flow diagram of the study selection process.

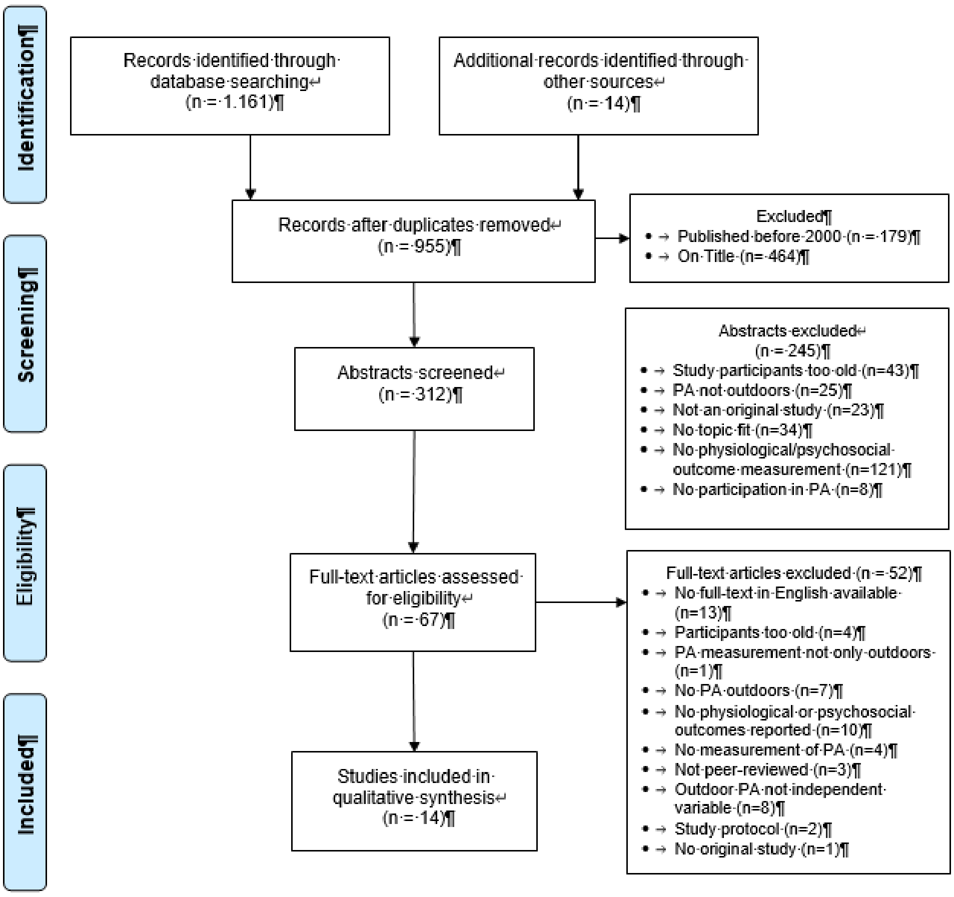

Table 2 presents a summary of the studies included. Appendix E contains detailed quantitative results. No studies published between 2000 and 2008 matched the inclusion criteria. Several study designs were represented: eight intervention studies (five crossover randomized controlled trials (RCTs), two non-randomized controlled trials (CTs), one single group pre-post design), two prospective cohort studies, and three cross-sectional studies. Studies were conducted in the UK (n=5), the US (n=5), Australia (n=2) and Japan (n=1). The number of participants varied widely across studies, with a total of 9,402 youth across studies. While the RCTs included between 14 and 86 study participants, the cohort studies included between 775 and 5,238 participants. All of the studies looked children aged 6-13 years, with two exceptions looking at four-year-olds (Parsons et al., 2018) and 17-year-olds (Gopinath et al., 2012).

PA frequency, intensity, time, and type varied across studies. Looking at outdoor PA time, most of the intervention studies (n=5) were short-term studies with one-time interventions taking 15-20 minutes (Duncan et al., 2014; Faber Taylor & Kuo, 2009; Reed et al., 2013; Wood et al., 2013; Wood et al., 2014). The other intervention studies looked at effects over five days (Barton et al., 2015), four weeks (Flynn et al., 2017), and four months (Raney et al., 2019). In a prospective cohort study, participants were asked to report the amount of outdoor PA during an average week (Gopinath et al., 2012), cross-sectional studies asked for the amount of PA on an average day (Hammond et al., 2011), during an average week (Gopinath, Baur, et al., 2011; Gopinath, Hardy, et al., 2011), and during the last 24 hours (Parsons et al., 2018).

Looking at the frequency of outdoor PA, all short-term studies conducted a one-time intervention (Duncan et al., 2014; Faber Taylor & Kuo, 2009; Reed et al., 2013; Wood et al., 2013; Wood et al., 2014). The longer intervention studies included daily activities during school recess (Barton et al., 2015; Raney et al., 2019), another study reported 274 outdoor PA bouts over four weeks for all participants together (Flynn et al., 2017). In a prospective cohort study and two cross-sectional studies, participants were asked to report their frequency of participation in outdoor PA, ranging from "very often" to "never" (Liu et al., 2015). The other studies reported the total amount of outdoor PA, but not the frequency (Gopinath, Baur, et al., 2011; Gopinath et al., 2012; Gopinath, Hardy, et al., 2011; Hammond et al., 2011). The type of PA varied widely across studies, including orienteering (Barton et al., 2015; Wood et al., 2014), ergometer cycling (Duncan et al., 2014; Wood et al., 2013), walking (Faber Taylor & Kuo, 2009), sports games and aerobic activities (Gopinath, Baur, et al., 2011; Gopinath et al., 2012; Gopinath, Hardy, et al., 2011) and general PA outdoors without type specification (Flynn et al., 2017; Hammond et al., 2011; Liu et al., 2015).

Regarding outdoor PA intensity, two studies reported moderate PA levels (Duncan et al., 2014; Wood et al., 2013), three studies reported moderate to vigorous physical activity (MVPA) (Barton et al., 2015; Raney et al., 2019; Wood et al., 2014), two other studies did not measure intensity, but assumed that the activities that could be chosen in the measurement met the MVPA intensity (Gopinath, Baur, et al., 2011; Gopinath et al., 2012; Gopinath, Hardy, et al., 2011), and one study reported light PA and MVPA (Parsons et al., 2018). All other studies did not report PA intensity levels (Faber Taylor & Kuo, 2009; Flynn et al., 2017; Hammond et al., 2011; Liu et al., 2015; Reed et al., 2013).

Looking at the reported outcomes, more psychosocial outcomes (n = 15) than physiological outcomes (n = 6) were examined. Psychosocially, self-esteem was the most assessed outcome, being measured in four studies (Barton et al., 2015; Flynn et al., 2017; Reed et al., 2013; Wood et al., 2013; Wood et al., 2014). Physiologically, blood pressure was the most assessed outcome, being measured two times (Duncan et al., 2014; Gopinath, Hardy, et al., 2011). All other outcomes were measured at most two times and with different measurement instruments. Therefore, pooling results and conducting a meta-analysis was deemed inappropriate. Regarding gender, one cohort study, investigating the relationship between self-reported health and continuous participation in outdoor PA, reported an increased odds ratio for the overall study population and boys, while the results for girls were not significant (Liu et al., 2015). No other studies reported gender differences related to the outcome.

Table 2. Characteristics of the included studies.

Author/ year	Study design	Participants and country	Type of green exercise and procedures	Outcome Variable(s)	Measurement instrument(s)	Results	Quality assessment
Barton et al. (2015)	Crossover RCT	52 boys and girls Mean age: 9 years UK	Intervention and control condition in both urban and rural school, available during lunch time break (55 min) at both schools Intervention: 5 days of nature-based orienteering (NBO) Control: 5 days provision of playground sports equipment (PSE) on not-green playground during recess	Self-esteem (SE)	Accelerometer Rosenberg SE scale	○= SE	Weak SB: 3, SD: 2, C: 2, B: 3, DCM: 3, WD: 3
Duncan et al. (2014)	Crossover RCT	14 children (50% female) Mean age: 10 years UK	Two 15-minute bouts of cycling at in two lab conditions Intervention: green condition (viewing a film of cycling in a forest) Control condition: viewing a black screen	Blood pressure (BP) Heart rate Mood state response	Automated oscillometric device Heart rate monitor Fatigue, tension and vigor subscales of Brunel Mood State Inventory	↓↓ systolic BP 15 minutes post-exercise ○= systolic BP or diastolic BP immediately post-exercise ↑= HR immediately and 15 min. post-exercise ↑ fatigue score ↓= vigor score ○= tension	Weak SB: 3, SD: 1, C: 1, B: 3, DCM: 1, WD: 1
Faber Taylor & Kuo (2009)	Crossover RCT	17 children with (12% female) attention deficit hyperactivity disorder (ADHD) Mean age: 9 years USA	20-minute guided walk in three different settings Intervention: park (green area) Control 1: residential area Control 2: downtown area	Attention Child's rating of settings	Digit Span Backwards (DSB) 3-point-scale for children to rate walk as fun, relaxing, interesting, scary, boring, weird, and/or uncomfortable	↑↑ Digit Span Backwards score post-intervention ↑↑ fun rating = ratings for relaxing, interesting, scary, boring, weird, and/or uncomfortable	Moderate SB: 3, SD: 1, C: 1, B: 1, DCM: 1, WD: 2
Flynn et al. (2017)	One group	27 children in 16 families (51.9% female)	Four-week outdoor PA family intervention	PA self-efficacy	Weekly PA activity logs (filled in by parents)	○ PA enjoyment and self-efficacy ↑ PA social support	Weak SB: 3, SD: 2, C: 1, B:

	pre-post	Mean age: 11 years USA		PA enjoyment PA social support	Self-administered survey for children on PA enjoyment, SE, and social support		3, DCM: 2, WD: 3
Gopinath et al. (2011)	Cross-sectional	1765 children (48.3% female) (Gopinath, Hardy, et al., 2011), 1492 children (49.3% female) (Gopinath, Baur, et al., 2011) Mean age: 7 years Australia	Comparison of children Exposure: low, middle and high tertile of outdoor PA Control: low, middle and high tertile of indoor PA Linear associations between BP and indoor / outdoor PA	Retinal Arteriolar and venular Diameter Systolic BP Diastolic BP Mean arterial BP	Questionnaire on PA (proxy-report through parents) Retinal photography Automated sphygmomanometer	= retinal arteriolar and venular diameter = systolic and diastolic BP Linear association between indoor PA and ↓ diastolic BP and ↓ mean arterial BP, ○ systolic BP ○ outdoor PA and BP outcome	Weak SB: 2, SD: 3, C: N/A, B: N/A, DCM: 3, WD: 1
Gopinath et al. (2012)	Prospective cohort study	Cross-sectional: 1094 adolescents (56.1 % female) longitudinal: 775 children and adolescents Mean age: 12 years at basline, 17 years at follow-up Australia	5-year cohort study. Comparison of children cross-sectionally (at follow-up) and longitudinally. QoL was only measured at follow-up. Comparison of children Exposure: low, moderate and high tertile of outdoor PA Control: low and moderate-high tertile of indoor PA	Health related quality of life (QoL)	Questionnaire on PA Pediatric Quality of Life Inventory 4.0	↑ QoL in control group in low tertiles ↑↑ QoL comparing high and moderate-high tertiles	Weak SB: 2, SD: 2, C: N/A, B: N/A, DCM: 3, WD: 3
Hammond et al. (2011)	Cross-sectional	140 parents (84% female) of children between 6 and 13 years USA	One-time questionnaire accessed through parents (proxy-reporting) to report about children's health problems and PA in two settings Exposure: PA outdoors Control: PA indoors	Health problems	Health inventory Questions on outdoor and indoor organized activities and sports	○= health problems (body pain/discomfort, trouble sleeping, repeated upset stomach, feeling tired/having low energy)	Weak SB: 3, SD: 3, C: N/A, B: N/A, DCM: 3, WD: 1
Liu et al. (2015)	Prospective cohort study	5238 children (52.2% female) Mean age: 6 years at baseline, 12 years at follow-up	6-year cohort study (baseline at age 6). Questionnaire on frequency of outdoor PA and self-reported health at baseline and follow-up. Exposure: frequent outdoor PA	Self-reported health	Self-report questionnaire about outdoor PA Dartmouth Primary Care Cooperative	↑↑ self-reported health at baseline and follow-up	Weak SB: 2, SD: 2, C: N/A, B: N/A,

		Japan	Control: infrequent outdoor PA		project Charts (Self-report instrument about health)		DCM: 3, WD: 3
Parsons et al. (2018)	Cross-sectional study	447 children (51.5% female) Mean age: 4 years USA	Data collection on sleep and PA indoors and outdoors in child-care centers Exposure: outdoors Control: indoors	Sleep duration	Sleep diary filled in by parents and child care center staff Accelerometer Observation of outdoor and indoor PA through child care center staff	○= sleep duration	Weak SB: 2, SD: 3, C: N/A, B: N/A, DCM: 3, WD: 1
Raney et al. (2019)	Non-randomized controlled trial	437 children (51.1% female) 5th grade students USA	Outdoor PA in school playgrounds during 20 minutes recess Intervention: playground greening at one school Control: no greening	Antisocial interactions	Accelerometers System for Observing Play and Leisure Activity in Youth (SOPLAY) System for Observing Children's Activity and Relationships During Play (SOCARP)	↓↓ of physical and verbal conflicts after 4 months ↓ of minutes spent alone and ↑ increase of minutes spent in small groups in intervention group	Weak SB: 3, SD: 1, C: 3, B: 3, DCM: 1, WD: 3
Reed et al. (2013)	Crossover RCT	86 boys and girls Age: 11-12 years UK	Running over 1.5 miles in two settings; participants engaged in both conditions Intervention: green setting Control: urban non-green setting	SE Exercise enjoyment Perceived exertion	PA questionnaire for adolescents Fitnessgram Pacer Test Rosenberg SE Scale Ratings of Perceived Exertion Scale	↑= SE = ratings of perceived exertion and enjoyment	Weak SB: 3, SD: 3, C: N/A, B: N/A, DCM: 3, WD: 1
Wood et al. (2013)	Crossover RCT	25 children (56% female) Age: 11-12 years UK	Laboratory condition: All participants engaged in two constant load tests on a cycle ergometer (10 minutes) whilst viewing two types of picture series Intervention: natural environment pictures	SE Mood	Rosenberg SE scale Adolescent Profile of Mood States Questionnaire (PMSQ)	↑= SE and fatigue ↓= tension ○= depression, anger, vigor and confusion	Weak SB: 3, SD: 1, C: 1, B: 2, DCM: 3, WD: 1

			Control: built environment pictures				
Wood et al. (2014)	Crossover RCT	60 children (50% female) Mean age: 13 years UK	Participants engaged in two orienteering courses (20 minutes, respectively) Intervention: natural environment Control: built environment	SE	Accelerometer Rosenberg SE scale	↑= SE	Weak SB: 3, SD: 1, C: 1, B: 3, DCM: 2, WD: 3

Table legend: ↑ increase; ↑↑ stronger increase / effect in intervention / exposure group compared to control group; ○ no effect /association; = no differences between intervention/exposure and control group; ↓ decrease; ↓↓ stronger decrease / effect in intervention / exposure group compared to control group; If = is combined with another symbol (e.g. ↑=), this means that both intervention/exposure and control group had the same effect; SE = self-esteem; BP = blood pressure; SB = selection bias, SD = study design, C = Confounders, B = Blinding, DCM = Data collection methods, WD = Withdrawals / Dropouts, N/A = Not applicable.

Quality of the evidence

In *Appendix E*, the results of the quality assessment are presented by study. Except for one moderate rating (Faber Taylor & Kuo, 2009), all studies were rated as low quality. The poorest ratings were obtained in the categories of selection bias (n = 9, category mean rating = 2.86), blinding (n = 6; mean = 2.63), and data collection methods (n = 8; mean = 2.36). Reliability and validity of data collection methods (Barton et al., 2015; Gopinath, Baur, et al., 2011; Gopinath et al., 2012; Gopinath, Hardy, et al., 2011; Parsons et al., 2018; Reed et al., 2013; Wood et al., 2013) and blinding (Barton et al., 2015; Duncan et al., 2014; Flynn et al., 2017; Raney et al., 2019; Reed et al., 2013; Wood et al., 2014) were often not reported. The categories of confounders, blinding, and intervention integrity were not applicable in six studies due to their observational or cross-sectional design (Gopinath, Baur, et al., 2011; Gopinath et al., 2012; Gopinath, Hardy, et al., 2011; Hammond et al., 2011; Liu et al., 2015; Parsons et al., 2018). As most of the RCTs were crossover-trials with participants completing both conditions, no between-group differences could be responsible for the outcomes in both conditions, resulting in a strong rating (mean = 1.25) of the confounder-section. Reporting of withdrawals and dropouts varied across studies (mean = 1.86). None of the studies – except for one crossover RCT with complete data for all participants – considered the “intention to treat” principle in the statistical analysis and only four studies (Faber Taylor & Kuo, 2009; Flynn et al., 2017; Hammond et al., 2011; Reed et al., 2013) reported statistical power.

Effectiveness of GE

First, study outcomes and study characteristics will be summarized in terms of effectiveness.

Physical activity in the green condition was superior to the control condition for six outcomes. Six studies reported a superior effect of GE compared to the control group for five psychosocial outcomes (attention, health-related quality of life, self-reported health, social support, and antisocial interactions) (Faber Taylor & Kuo, 2009; Flynn et al., 2017; Gopinath et al., 2012; Liu et al., 2015; Raney et al., 2019) and one physiological outcome (diastolic blood pressure (BP)) (Duncan et al., 2014). Each effect was only reported once. All studies were longitudinal studies (two crossover RCTs (Duncan et al., 2014; Faber Taylor & Kuo, 2009), one non-randomized CT (Raney et al., 2019), one single-group pre-post study (Flynn et al., 2017), and two cohort-studies (Gopinath et al., 2012; Liu et al., 2015)). In the single-group study (Flynn et al., 2017), there was no control-group, only comparison with baseline data, limiting the ability to draw causal conclusions. The crossover RCTs and single group study had a small number of participants, ranging from 14 to 27 (Duncan et al., 2014; Faber Taylor & Kuo, 2009; Flynn et al., 2017), the non-randomized CT had 437 participants (Raney et al., 2019) and the cohort-studies ranged from 775 to 5,239 participants (Gopinath et al., 2012; Liu et al., 2015). One study allowed only children diagnosed with attention deficit hyperactivity disorder (ADHD) as participants (Faber Taylor & Kuo, 2009). Participants of the intervention studies were all around the same age (9-12 years), while the cohort studies had baseline data of participants aged six and 12 years, respectively, with a follow-up period of five years (Liu et al., 2015) and six years (Gopinath et al., 2012). The crossover RCTs applied short-term interventions of 15-20 minutes (Duncan et al., 2014; Faber Taylor & Kuo, 2009), the other intervention studies were four weeks (Flynn et al., 2017) and four months (Raney et al., 2019). One study was rated as moderate study quality (Faber Taylor & Kuo, 2009), all other ones as low.

Physical activity is effective, but there was no difference between the green and the control condition for five outcomes. Four studies reported an effect of exercise on four psychosocial outcomes (self-esteem, vigor, tension, and fatigue) (Duncan et al., 2014; Reed et al., 2013; Wood et al., 2013; Wood et al., 2014) and one physiological outcome (heart rate, (Duncan et al., 2014)), but no differences between the GE condition and the control group could be observed. All studies were crossover RCTs, with sample size ranging between 14 and 86 children and with an average age of 10-13 years. PA in green and control conditions had a duration between 10 and 20 minutes. All studies were conducted by the same research group and were rated as low quality.

Physical activity does not show an effect in any condition / no differences between exposure and control group for 15 outcomes. Ten studies reported no effect of PA or no difference between exposure and control group in terms of 11 psychosocial outcomes (self-esteem, vigor, tension, anger, depression, confusion, setting rating, PA self-efficacy and enjoyment, self-reported health) (Barton et al., 2015; Duncan et al., 2014; Faber Taylor & Kuo, 2009; Flynn et al., 2017; Hammond et al., 2011; Reed et al., 2013; Wood et al., 2013) and four physiological outcomes (systolic and diastolic BP, retinal diameter, sleep duration) (Duncan et al., 2014; Gopinath, Baur, et al., 2011; Gopinath, Hardy, et al., 2011; Parsons et al., 2018). Six were intervention studies (four RCTs (Duncan et al., 2014; Faber Taylor & Kuo, 2009; Reed et al., 2013; Wood et al., 2013) and one non-randomized CT (Barton et al., 2015), and one single group pre-post design (Flynn et al., 2017)), and three cross-sectional studies (Gopinath, Baur, et al., 2011; Gopinath, Hardy, et al., 2011; Hammond et al., 2011; Parsons et al., 2018). Sample size varied from 17 to 85 participants in the intervention studies and from 140 to 1,765 in the cross-sectional studies. Participants of the intervention studies were between 9-12 years, and four to 13 years in the cross-sectional studies. Intervention duration varied between 15 minutes and five days in the intervention studies. Except for one study (Flynn et al., 2017), all studies were rated as low quality.

Physical activity in the control condition is more effective than in the green condition for three outcomes. Two studies, reporting one psychosocial outcome (health-related life quality (Gopinath et al., 2012)) and two physiological outcomes (diastolic and mean arterial BP, (Gopinath, Baur, et al., 2011)), found a superior effect of indoor PA compared to outdoor PA. One study used a cohort design (Gopinath et al., 2012) and the other one a cross-sectional design (Gopinath, Hardy, et al., 2011). Participants were aged seven years in the cross-sectional and 12 (baseline) and 17 (follow-up) years in the cohort study. Participants in both studies were part of the same study population and the studies were conducted by the same researchers. Study quality was rated low for both studies.

Overview of psychosocial and physiological outcomes

In this section, the evidence is summarized based on psychosocial and physiological outcomes.

Psychosocial outcomes. Fifteen different outcomes were reported in the psychosocial category (see *Table 3*). Except for self-esteem, all study outcomes were only assessed by one or two studies with a large variety of measurement instruments. For attention (RCT) and anti-social interactions (non-randomized CT), PA in the green condition showed stronger positive effects than PA in the control condition. Both studies were of low to moderate quality (Faber Taylor & Kuo, 2009; Raney et al., 2019). There was also a positive effect for PA outdoors and increased social support, but due to a single-group design, no conclusions can be drawn about superior effects compared to other settings (Flynn et al., 2017).

When comparing children in the highest tertile of outdoor PA to the highest tertile of indoor PA, health-related qualify of life was higher for children being active outdoors, whereas comparing children in the lowest tertile of outdoor PA to the lowest tertile of indoor PA, children that were active indoors showed higher scores (Gopinath et al., 2012). One cohort-study and one cross-sectional study looked at self-reported health, with the cohort study finding positive effects for frequent outdoor PA compared to infrequent outdoor PA (Liu et al., 2015), whereas the cross-sectional study found no significant associations (Hammond et al., 2011).

Fatigue was reported as significantly higher post-exercise in two crossover RCTs, with no differences in the green and control conditions (Duncan et al., 2014; Wood et al., 2013). Two studies reported results for vigor and tension. One study reported lower levels for each outcome post-exercise, the other study did not report any effect of exercise with no differences between green and control in both studies (Duncan et al., 2014; Wood et al., 2013).

Self-esteem was assessed in four intervention studies with Rosenberg's Self-Esteem scale (Barton et al., 2015; Reed et al., 2013; Wood et al., 2013; Wood et al., 2014). The three RCTs with one, short single bout of exercise (Reed et al., 2013; Wood et al., 2013; Wood et al., 2014) reported increased self-esteem post-exercise, while the other RCT over five days did not find any effects on self-esteem with no differences between green and control condition in both studies (Barton et al., 2015).

For several outcomes, PA did not have an effect in any condition or was not different between green and control condition. This was true for several mood states (Wood et al., 2013), ratings of the environmental setting (Faber Taylor & Kuo, 2009), PA enjoyment (Flynn et al., 2017; Reed et al., 2013), and self-efficacy (Flynn et al., 2017).Except for PA enjoyment, each outcome was only reported in one study.

Table 3. Effectiveness and psychosocial outcomes of green exercise

Psychosocial outcome	***Stronger / only effect intervention / exposure group***	***Effect both in intervention and control group***	***No effect neither in intervention or control group / No differences between exposure and control group***	***Stronger / only effect in control group***
Self-esteem		↑ Reed et al. (2013); Wood et al. (2013); Wood et al. (2014)	Barton et al. (2015)	
Fatigue		↑ Duncan et al. (2014); Wood et al. (2013)		
Vigor		↓ Duncan et al. (2014)	Wood et al. (2013)	
Tension		↓ Wood et al. (2013)	Duncan et al. (2014)	
Anger			Wood et al. (2013)	
Depression			Wood et al. (2013)	
Confusion			Wood et al. (2013)	
Attention	↑ Faber Taylor and Kuo (2009)			
Setting rating			Faber Taylor and Kuo (2009)	
PA self-efficacy			Flynn et al. (2017)	
PA enjoyment			Flynn et al. (2017); Reed et al. (2013)	
Social support	↑ Flynn et al. (2017)			
Health-related quality of life	↑ Gopinath et al. (2012)			↑ Gopinath et al. (2012)
Self-reported health	↑ Liu et al. (2015)		Hammond et al. (2011)	
Antisocial interactions	↓ Raney et al. (2019)			

Please note: ↑ positive association; ↓ negative association.

Physiological outcomes. Six physiological outcomes were reported (see *Table 4*). For systolic BP, one crossover RCT found a positive effect for GE compared to the control condition, while a cohort study found no difference when comparing youth being active outdoors to the ones being active indoors (Duncan et al., 2014; Gopinath, Hardy, et al., 2011). The same crossover RCT found a significant increase for heart-rate post-exercise, but no differences between the conditions (Duncan et al., 2014).

Looking at retinal diameter (Gopinath, Baur, et al., 2011) and sleep duration (Parsons et al., 2018), no effect was found in any condition. Each of these outcomes was only assessed in one study. Contradictory results were found for diastolic BP. A crossover RCT did not find any effect on diastolic BP in any condition (Duncan et al., 2014), while a cohort study did not find any differences in diastolic BP when comparing PA of children indoors and outdoors (Gopinath, Hardy, et al., 2011). Interestingly, contradictory results were found within the same cohort study. While there was no difference in diastolic BP when comparing active children in- and outdoors in tertiles, the regression analysis only found a significant effect for indoor PA, but not for outdoor PA (Gopinath, Hardy, et al., 2011). The same regression analysis also revealed a significant effect for PA indoors on mean arterial BP, but not for PA outdoors (Gopinath, Hardy, et al., 2011).

Table 4. Effectiveness and physiological outcomes of green exercise

Physiological outcome	***Stronger / only effect intervention / exposure group***	***Effect both in intervention and control group***	***No effect neither in intervention or control group / No differences between exposure and control group***	***Stronger / only effect in control group***
Systolic BP	↓ Duncan et al. (2014)		Gopinath, Hardy, et al. (2011)	
Diastolic BP			Duncan et al. (2014); Gopinath, Hardy, et al. (2011)	↓ Gopinath, Hardy, et al. (2011)
Mean arterial BP				↓ Gopinath, Hardy, et al. (2011)
Heart rate		↑ Duncan et al. (2014)		
Retinal diameter			Gopinath, Baur, et al. (2011)	
Sleep duration			Parsons et al. (2018)	

Please note: ↑ positive association; ↓ negative association.

Discussion

Two purposes of this study were to provide an overview of the psychosocial and physiological outcomes of GE in children and adolescents and assess the effectiveness of GE. A total of 21 different outcomes were reported in the assessed studies. Each outcome was investigated by a maximum of two studies, except for self-esteem (four studies). When two studies assessed the same outcome, results were mostly contradictory, but comparisons were difficult due to study heterogeneity. Looking at the heterogeneity of results, quality of the evidence, and methodological considerations, the findings of this review are very similar to the review of Lahart and colleagues about the effects of GE in adults (Lahart et al., 2019). Recommendations for future research investigating outcomes of GE in children and adolescents will be outlined based on a more detailed discussion of the results.

Theoretical background considerations

Except for one study (Faber Taylor & Kuo, 2009), none of the included studies provided a theoretical background to account for the assumed relationships between GE and outcomes. In other studies, Attention Restoration- (Kaplan, 1995) and Stress Reduction Theory (Ulrich, 1983) have been applied

(Barton & Pretty, 2010; Faber Taylor & Kuo, 2009; Mackay & Neill, 2010; Rogerson & Barton, 2015), however, based on these theories, benefits occur through contact with nature and are not dependent on PA levels. Thus, the underlying mechanisms regarding the interaction between the benefits of PA and nature exposure should be explored (Shanahan et al., 2016). An ecological dynamic approach might be useful, assuming beneficial effects of GE due to nature's action and immersive interaction possibilities, the holistic involvement of mind and body, and challenging situations (Araújo et al., 2019). Considering the lack of GE theories, qualitative research could provide valuable in-depth information to develop concepts, theories and hypotheses which could then be tested with quantitative studies. A rigorous RCT with a two (PA or not) by two (natural environment or not) design and four intervention arms (PA in concrete environment, concrete exposure without PA, PA in natural environment, and nature exposure without PA) would allow more confident conclusions.

Assessed outcomes related to GE

For most outcomes, either no effect was found in GE and control group or effects were found for both groups. One reason for this could be the lack of theoretical background. For some outcomes, the assumption behind why the outcome should be different when exercising in the green compared to the non-green condition was not clear. Another explanation could be that it was often not clear if the measurement instruments are appropriate to measure the outcome of interest as validity and reliability were not reported. Thus, future studies should consider the theoretical background regarding GE and youth's development to determine outcomes of interest and report validity and reliability of the measurement instruments.

At the same time, it is also important to investigate outcomes where exercising indoors might result in more positive effects than exercising outdoors, e.g. for feelings of safety and security. On three outcomes (health-related quality of life, diastolic and mean arterial BP), stronger effects were reported for the comparison group (Gopinath et al., 2012; Gopinath, Hardy, et al., 2011). Looking at health-related quality of life, children in the lowest tertile of indoor PA reported better outcomes than children in the lowest outdoor PA tertile (Gopinath et al., 2012). One reason could be that children who are less active might feel safer and more comfortable in an indoor environment with safety being related to PA (Heitzler et al., 2006). Another explanation could be that children that prefer indoor activities do not like being exposed to weather variations. Regarding the better BP outcomes in the indoor PA group, the study's authors explained the better effect of indoor activity with higher intensities during indoor PA compared to outdoor PA (Gopinath, Hardy, et al., 2011). However, the inconsistent results of this study should be taken into consideration. Being aware of any superior effects of indoor PA and any deleterious effects of GE is especially important to adapt the setting accordingly for PA interventions.

Conceptual considerations – what is "green"?

Pretty and colleagues defined GE as any exercise that is done in direct exposure to nature (Pretty et al., 2003, p. 7), referring to areas that include predominantly natural characteristics (Araújo et al., 2019). It is not clearly operationalized how many natural features of an area or the percentage of green in that area in order to be defined as "green". Thus, "green" settings were inconsistent throughout the studies included, which has also been reported as a problem in GE studies with adults (Lahart et al., 2019).

Natural environments offer various landscapes and features, therefore raising the question if different characteristics lead to different outcomes. Regarding self-esteem and mood in adults, stronger effects were found for waterside places, but no differences were reported between urban green space, countryside, wilderness, and woodlands (Barton & Pretty, 2010). Such questions are still open for children and adolescents and should be investigated as youth and adults differ in their environmental perceptions (Van Dyck et al., 2013).

In two included studies, participants were exercising in a lab condition whilst viewing a natural or the control scenery on a screen (Duncan et al., 2014; Wood et al., 2013). Although this might already have positive health outcomes (Pretty, 2004), the experience of nature is limited in several ways, such as the various action possibilities and immersive experiences (Araújo et al., 2019). Another perspective to look at GE comes from nature-based tourism, emphasizing PA in nature that focuses on enjoying natural attractions, stressing the conscious interaction with nature and not only nature experiences that occur in daily life. This is similar to Pretty's level of involvement and participation in nature (Chang, 2014; Pretty, 2004). For adults, better effects of exercising during nature involvement and participation have been found compared to exercising in a control condition (built or indoor environment) for various outcomes, such as night sleep restoration (Gladwell et al., 2016), self-reported mental health (Brown et al., 2014), and directed attention and social interactions (Rogerson et al., 2016). Moreover, outcomes of exercising during nature exposure in adults were also found for indirect ways of nature exposure. Positive effects of nature visuals and nature sounds included improved cognitive directed attention, mood and stress scores, versus the control conditions (Rogerson & Barton, 2015; Wooller et al., 2018). While there are some positive results for adults, research on the different levels of nature exposure in youth is still limited. Especially when considering the amount of time children and adolescents spend on screen-based activities (Börnhorst et al., 2015; Rey-López et al., 2010), applying a screen-based approach for GE might yield positive effects. Thus, it is not only important to investigate different natural features, but also to explore which effects different levels of exposure have on youth and how they differ from each other, such as watching nature video content during exercising on a treadmill, active transportation in nature, and going for a hike.

Characteristics of PA outdoors

Looking at outdoor PA frequency and time in intervention studies, most studies reported a single bout of PA of up to 20 minutes, which is also commonly done when investigating GE in adults (Lahart et al., 2019). While GE already showed effects in adults after five minutes (Barton & Pretty, 2010), it is unclear if this also applies to youth. Therefore, future studies should investigate GE over a longer time period to explore if GE effects depend on PA frequency and time. For example, one of the prospective cohort studies reported significant differences in health-related quality of life when comparing children in the highest tertile of outdoor PA to the highest tertile of indoor PA, while this was not true when comparing the lowest tertiles (Gopinath et al., 2012).

Although intensity levels have been reported in some studies, sub-group analyses have not been conducted to investigate if intensity levels impact the outcome. In adults, self-esteem showed the greatest improvements for moderate GE intensity, while mood had the best improvements when implementing light and vigorous GE (Barton & Pretty, 2010). These relationships are to be explored in future studies for the young age group.

Various types of activities have been reported in the included studies, with most of them being activities that can be implemented in daily life, such as walking, roller-skating, game activities, and general outdoor PA without type specification (Faber Taylor & Kuo, 2009; Flynn et al., 2017; Gopinath, Baur, et al., 2011; Gopinath et al., 2012; Gopinath, Hardy, et al., 2011; Hammond et al., 2011; Liu et al., 2015). Nature offers various action possibilities with a challenging character, such as rock climbing and mountain-biking, that are also called outdoor adventures (Araújo et al., 2019). Compared to daily PA activities, these activities include additional components like a small group setting, an unfamiliar physical environment, and challenges allowing mastery experiences (Mutz & Müller, 2016). While this is worth investigating, it should be carefully considered if the mechanisms leading to outcomes such as changes in a person's self-concept, skills, and attitudes (Mutz & Müller, 2016) are due to GE, the adventurous character or a mixture of both. For children, outdoor play is also a possible type of GE, however, PA levels vary widely during outdoor play (Truelove et al., 2018) so it cannot be considered automatically as GE without measurement, nor is it clear if all playgrounds could be considered green.

Looking at the measurement of GE, most of the intervention studies included in this review used device-based measurements with accelerometer or heart rate monitoring while the researcher reported the setting the participants were exposed to. Another method is the use of validated observation instruments such as SOPLAY and SOPARC (Raney et al., 2019), requiring the researcher's presence for measurement. To assess PA levels in a spatial context objectively, one way would be combining accelerometer, GPS, and GIS-data (Jankowska et al., 2015; Klinker et al., 2014). Several studies included in this review have also used self-report measures such as questionnaires and diaries. However, none of these studies reported validity and reliability of these instruments to assess outdoor PA in children and adolescents. Therefore, development of a valid and reliable self-report GE instrument would be helpful, e.g. when assessing GE in a large number of children or when resources are limited.

Study population and sample size

Except for two studies looking at pre-school children (Parsons et al., 2018) and older adolescents (Gopinath et al., 2012), all studies focused on children 6-13 years old. Due to youth's development, evidence that is valid for one age group might not be applicable to another. To allow conclusions about outcomes of GE across childhood and adolescence, future studies should include different age groups of youth in their study population. Except for two studies with ADHD-children (Faber Taylor & Kuo, 2009) and samples with some overweight participants (Duncan et al., 2014; Flynn et al., 2017), none of the samples had a clinical background. When ethnicity was reported, most participants were Caucasian (Gopinath, Baur, et al., 2011; Gopinath et al., 2012; Gopinath, Hardy, et al., 2011; Parsons et al., 2018) or Asian (Liu et al., 2015). Thus, future studies should investigate GE in young participants across different ethnicities, cultures, backgrounds, and settings.

To determine the appropriate sample size, one cross-sectional and three intervention studies (Faber Taylor & Kuo, 2009; Hammond et al., 2011; Reed et al., 2013; Wood et al., 2013) provided a power analysis. Especially looking at the small sample sizes in some intervention studies (Duncan et al., 2014; Faber Taylor & Kuo, 2009; Flynn et al., 2017; Wood et al., 2013; Wood et al., 2014), which is also a problem in adults (Lahart et al., 2019), future studies should include larger sample sizes to detect small effects and to avoid type II-errors (Cohen, 2013).

Quality assessment

All but one (Faber Taylor & Kuo, 2009) study received a weak rating based on the EPHPP tool. These results are comparable to the review of Lahart and colleagues, who also rated the GE study quality in adults as weak (Lahart et al., 2019). However, the quality assessment results for this review should be viewed with caution, considering the categories and the focus of the quality assessment tool. The aim of the included studies was to explore the relationship between health and youth's GE, thereby focusing less on representative samples. Thus, selection bias might not be as important as other categories of the EPHPP tool. Blinding should also be considered carefully as it is not possible to blind participants to the environmental condition they are exposed to. One study blinded participants to the research question (Faber Taylor & Kuo, 2009), but this might not be possible in other studies due to ethical considerations. Another option is to assess blinding in the context of the outcome measurement: A meta-epidemiological study revealed that lack of blinding only increases the risk of bias for subjective, but not objective outcome measurements (Wood et al., 2008).

For future systematic reviews in this area, a quality assessment tool with a less clinical focus would be helpful. This tool may include the categories of the EPHPP tool, but different categories should receive a different weight, such as focusing less on selection bias and blinding.

Study limitations

This systematic review does not come without limitations. Regarding the included studies, several weaknesses have already been outlined, comprising limited comparability due to heterogeneity of study results and study designs as well as the low quality of the evidence. Another aspect to consider is that in some studies, outdoor PA instead of GE had been investigated, so that it was not clear how much green features were around the participants during PA.

As is common in systematic reviews, the first screening of studies to be included was based on title alone, so that some studies might have been overlooked. The search was limited to studies published after 2000. Including studies before that year might have helped finding more consistent outcomes, even though GE had not been defined yet. The terms included for the study search were phrased to identify studies of non-clinical populations. To explicitly include GE studies in a therapeutic and medical context, some additional search terms would have to be added.

Conclusion and future directions

GE does not have negative effects for children and adolescents compared to exercising in a built or an indoor-environment. There are some indications that PA in nature-based environments has beneficial effects, however, due to the heterogeneity of study results that limits comparisons for specific outcomes and small sample sizes, it is premature to draw conclusions. Considering these findings in the context of the previous systematic review about GE in adults (Lahart et al., 2019), the following recommendations can be applied to children, adolescents, and adults.

Future research should investigate the underlying effects and mechanisms of GE in order to establish GE theories which can be used to determine possible GE outcomes. Especially when establishing GE theories for children and adolescents, a qualitative approach using for example Grounded Theory (Glaser & Strauss, 1967) could be helpful. Another way would be to review current literature on possible mechanisms of both PA and nature contributing to health and combining them in a theoretical framework. While it is important to have a theory for the GE field that includes both PA and nature, it is also essential to test this theory with quantitative methods so that it can be adapted if necessary and applied to future interventions. Both short- and long-term outcomes of interest should be investigated across different cultures and age groups in childhood and adolescence and specific outcomes explored across frequencies, intensities, time, and type of GE. To investigate short-term effects, an ambulatory assessment approach could be promising that allows capturing data on nature, PA, and outcomes of interest in real-time and natural settings of study participants, thus assessing outcomes of GE in daily life (Fahrenberg et al., 2007; Trull & Ebner-Priemer, 2013). For long-term outcomes, using a cohort-study design where GE is measured from childhood over adolescence to adulthood would be helpful to assess outcomes of long-term participation in GE. To test causalities, RCTs with a longer time period could yield valuable results. In such designs, it would be important to expose participants to nature over several weeks or months on a continuous basis (e.g., twice a week) and a meaningful amount of time (e.g., one hour of GE) to investigate long-term effects.

Author Contributions

Conceptualization, C.M.; methodology, C.M.; formal analysis / reviewers, C.M. and S.W.; writing—original draft preparation, C.M..; writing—review and editing, J.S., S.W., and D.J..; visualization, C.M..; supervision, D.J. and J.S.

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CHAPTER 7

In a crisis: Urban-rural physical activity of children and adolescents during Covid-19

Slightly modified version of the 6th published article:

Nigg, C., Oriwol, D., Wunsch, K., Burchartz, A., Kolb, S., Worth, A., Woll, A., & Niessner C. (2021). Population density predicts youth's physical activity changes during Covid-19 - Results from the MoMo study. *Health and Place, 70,* 102619. https://doi.org/10.1016/j.healthplace.2021.102619

Introduction

During Germany's first Covid-19 lockdown from March to May 2020, important institutions for youth including kindergarten, schools, and leisure facilities such as sports clubs and playgrounds, were closed to reduce the risk of infection. A recent review indicates that these measures decreased physical activity across all age groups (Stockwell et al., 2021), which is problematic due to the multitude of physical activity's physical and mental health benefits (Poitras et al., 2016). However, it is not well understood how youth's Covid-19 related physical activity changes relate to the built environment. In general, environmental characteristics, including infrastructure for walking and cycling, short distances to facilities, better walkability, mixed land use, as well as park and playground equipment relate positively to youth's physical activity (Nordbø et al., 2020; Smith et al., 2017). Several of those features are commonly more prevalent in densely populated areas (e.g., infrastructure for walking and cycling, short distance to facilities), promoting theoretically more physical activity in densely populated areas (Sallis, Bull, Burdett, et al., 2016). Thus, population density has been used as a proxy variable to assess associations between the built environment and physical activity (e.g., Hino & Asami, 2021). Yet, a systematic review including studies before Covid-19 reported inconsistent associations between population density and physical activity in children and adolescents, with most studies reporting no associations (Nordbø et al., 2020). However, the association between population density and physical activity may be different during a pandemic where physical distancing is essential to mitigate the spread of a virus, with densely populated areas having a higher potential for human contact and virus transmission. In addition, amenities in densely populated areas (e.g., short walkable/cyclable distances) that allow engagement in daily life physical activity together with the closure of playgrounds may have reduced the potential for physical activity. During Covid-19, we are only aware of one study that investigated the associations between physical activity assessed via step counts and population density in adults (Hino & Asami, 2021). The study showed that step counts decreased more in neighborhoods with higher population density (Hino & Asami, 2021). In adolescents, one study showed that physical activity decreased stronger in urban compared to rural areas (Zenic et al., 2020), however, the study was not nationally representative, did not include children, and the urban-rural dichotomy was only a rough classification of environmental characteristics. In Germany, Covid-19 related physical activity changes in children and adolescents during the first lockdown in April 2020 have already been investigated in a longitudinal sample, showing that sports-related physical activity decreased, while daily life physical activity and the number of active days increased (Schmidt, Anedda, Burchartz, Eichsteller, et al., 2020), but it is unknown how those changes relate to population density, which we investigated in our study. We hypothesize that participants living in areas with higher population density demonstrate less positive physical activity changes.

Materials and Methods

Participants & procedures

Data was derived from the representative Motorik-Modul Study (MoMo), which applies a cohort-sequence design to assess physical activity, physical fitness, and health parameters in children and adolescents aged 4-17 years. Detailed study information is elsewhere available (Woll et al., 2021). For this study, data from Wave 3 (August 2018 – March 2020) was used, with Wave 3 being incomplete due to the Covid-19 pandemic. Preceding the lockdown, participants were invited to examination rooms within proximity to their homes and answered the MoMo physical activity questionnaire on laptops. Participants that had taken part in the study before Covid-19 were asked to fill in the questionnaire again online at the end of April 2020, which was during Germany's first Covid-19 lockdown. For details see Schmidt, Anedda, Burchartz, Eichsteller, et al. (2020). Study participation was voluntary, and participants' guardians provided written consent. The study was conducted in accordance with the Declaration of Helsinki. Ethics approval was obtained by the Charité Universitätsmedizin Berlin ethics committee, by the University of Konstanz, and by the ethics committee of the Karlsruhe Institute of Technology. The Federal Commissioner for Data Protection and Freedom of Information was informed about the study and approved it.

Measures

Sociodemographic data were only assessed before Covid-19. In addition to age and sex, participants' parents were asked for their highest educational degree and were classified as low, medium, and high education based on the CASMIN-classification (Brauns et al., 2003). Children's height and weight were assessed by trained research staff. The body-mass-index (BMI) was calculated and participants were categorized into underweight, normal weight, overweight, and obese based on the cut-off points of the International Obesity Task Force IOTF (Cole et al., 2000). Population density data from 2018 was retrieved from the German Federal Statistics Office's community information system, comprising population density data and geographical center coordinates of communities that are politically independent as well as their sub-communities (destatis, 2018). Using ArcGIS Pro (version 2.8.0), we calculated the closest (sub-)community to the participant's home address and matched the population density data of the corresponding community with the participant.

Physical activity was assessed via the MoMo physical activity questionnaire, consisting of 28 items and assessing sports-related physical activity (including sports clubs, leisure sports, and school physical activity) and daily life physical activity (including free outdoor play, gardening, household work, walking, and cycling) (Jekauc et al., 2013). Both sports-related and daily life physical activity components were combined into one index, respectively. In addition, children were asked to report how many days they are physically active for at least 60 minutes with moderate to vigorous intensity in a typical week prior and during the lockdown, which was reflecting the physical activity guidelines of the World Health Organization when the study was set up (WHO, 2010). Sufficient reliability and validity of the questionnaire have been reported (Jekauc et al., 2013).

Statistical analysis

Data was analyzed with the software IBM SPSS 27. First, we explored differences between study completers and non-completers using independent sample t-test and chi-square tests. As our data had a two-level structure with participants nested within communities, we used a multilevel random intercept model to account for correlation in our data which may otherwise bias standard error estimates. We calculated change scores for the physical activity variables by subtracting pre-Covid physical activity from during-Covid physical activity variables. We centered population density and age on the sample's mean. Following previous procedures, we divided population density by ten so that a one-unit increase represents ten more people within one square kilometer (Beenackers et al., 2018). Sex, parental education, age, and BMI were considered as demographical and individual covariates based on previous findings (Fernández-Alvira et al., 2013; Sallis, Bull, Guthold, et al., 2016; Schmidt, Anedda, Burchartz, Eichsteller, et al., 2020; Sterdt et al., 2014) as well as the respective baseline level variable of our outcome of interest (centered on the sample's mean). We then set up a multilevel model which only included population density and the physical activity baseline variable as a predictor. In the next step, we set up a model which included the covariates sex, age, BMI, parental education, and the respective physical activity baseline. As previous research has shown that associations between population density and physical activity show distinct associations by gender and age (Kowaleski-Jones et al., 2016), we additionally calculated interactions between population density and sex as well as population density and age. Finally, we re-ran the analyses excluding outliers +/-2 standard deviations around the mean to explore the robustness of our results.

Results

A total of 2,843 youth participated in the pre-Covid-19 study, and 1,711 of those participated in the assessment during the lockdown, forming the longitudinal sample (M_{age}=10.36 [SD=4.04] years, female=49.8%; healthy weight=76.8%). A detailed description of our sample including baseline physical activity levels can be found in *supplement S1*. Sociodemographic differences between study completers and non-completers were observed regarding sex (p=0.049, φ=0.04), BMI (p<0.001, V=0.10), and parental education (p<0.001, V=0.09), but not regarding age (p>0.05). A more detailed description of study completers vs. non-completers is available elsewhere (Wunsch et al., 2021).

The inclusion of the covariates improved the model fit based on Akaike's Information Criterion. We report the results of the multi-level model analysis including covariates in *Table* 1, the model without covariates can be found in s*upplement S2*. A typical child increased the number of active days from pre-Covid to during-Covid by 0.47 days per week, engaged in 68.33 fewer minutes of sports-related physical activity per week, and engaged in 37.74 more minutes of daily life physical activity. Increased population density was associated with less positive changes regarding active days per week and daily life physical activity. Demonstrating this on an example: A typical child living in an area with a population density of 100 citizens/km^2 which, for example, is the population density of the small town Müssen, increased the number of active days per week by 0.58 and daily life physical activity by 44.50 minutes per day. In contrast, a typical child living in a densely populated area with 3000 citizens/km^{2,} which is roughly the population density of Frankfurt, did not increase the number of active days per week, while it only engaged in an additional 9.70 minutes of daily life physical activity per day. No association with sports-related physical activity was observed.

Neither interactions between population density and sex nor population density and age were observed. All results remained stable if outliers (+/- 2 SD around the mean) were excluded.

Table 1: Multilevel model with population density predicting physical activity change.

	Δ Days active (days/week)			**Δ Sports-related physical activity (minutes/week)**			**Δ Daily life physical activity (minutes/day)**		
	B	SE	*p*	B	SE	*p*	B	SE	*p*
Fixed effects									
Intercept	0.47	0.07	<0.001	-68.33	10.32	<0.001	37.74	3.94	<0.001
Population density	-0.002	0.00	<0.001	0.07	0.09	0.444	-0.12	0.03	<0.001
Age	-0.13	0.01	<0.001	3.92	1.70	0.021	-6.95	0.66	<0.001
Gender[a]	0.04	0.09	0.648	3.66	12.69	0.773	1.07	5.07	0.834
Parental education[b]									
Low	-0.23	0.26	0.386	-67.67	38.94	0.082	29.83	15.16	0.049
High	-0.36	0.24	0.136	-76.14	33.61	0.024	-37.06	13.92	0.008
BMI[c]									
Underweight	-0.16	0.15	0.283	-12.27	20.59	0.552	-12.29	8.31	0.140
Overweight	-0.32	0.15	0.031	-27.81	21.25	0.191	-0.24	8.49	0.977
Obese	0.06	0.29	0.849	-42.28	41.53	0.309	4.72	17.21	0.784
Baseline level	-0.63	0.03	<0.001	-0.60	0.04	<0.001	-0.48	0.04	<0.001
Random effects									
Intercept	0.07	0.05	0.124	1627.61	925.24	0.079	18.98	118.93	0.873

Please note: population density, age, and baseline levels were grand-mean centered.
[a] reference category: girls
[b] reference category: parents with medium education
[c] reference category: normal weight

Discussion

Our study showed that children and adolescents residing in densely populated areas showed less favorable physical activity changes than children and adolescents living in sparsely populated areas, which is in line with our hypothesis. Our results are supported by previous findings showing that unfavorable changes in adult's physical activity were stronger in densely populated areas (Hino & Asami, 2021), while adolescent's physical activity decreased stronger in urban than in rural areas (Zenic et al., 2020). However, in contrast to the two previous studies, children and adolescents living in densely populated areas did not decrease their physical activity, but only showed less favorable or no changes. A reason for this difference could be that our study comprised a nationwide sample with large variations in population density, whereas two former studies concentrated on one region or city (Hino & Asami, 2021; Zenic et al., 2020), limiting generalizability.

Regarding our findings in the context of the lockdown in Germany, the German lockdown restrictions allowed leaving the house for physical activity, which may have prevented a physical activity decline in youth living in densely populated areas. Specifically, our analysis revealed that youth living in more densely populated areas showed no or fewer increases in daily life physical activity, while sports-related physical activity was not influenced by population density. In Germany, all organized sports institutions (e.g., sports clubs), which are a major contributor to youth's sports-related physical activity (Schmidt, Anedda, Burchartz, Oriwol, et al., 2020), had to close as part of the lockdown. This probably explains why sports-related physical activity is unrelated to population density as lockdown measures were the same across all areas in Germany.

In contrast, there are several explanations why population density has influenced changes in daily life physical activity. In non-Covid-19 times, densely populated areas benefit from short distances to facilities (e.g., schools, shops) as well as leisure time infrastructure (e.g., playgrounds) in terms of physical activity (Sallis, Bull, Burdett, et al., 2016). As all those facilities were closed during the lockdown, walking or cycling to those facilities was of no use.

Furthermore, our analysis showed that daily life physical activity changes were driven by engagement in outdoor play. In less densely populated areas, children may have had multiple opportunities to engage in outdoor play, such as playing on the street, in a yard, or other open spaces. In more densely populated areas, outdoor play opportunities may have been limited due to the disadvantages of densely populated areas, such as traffic exposure and limited physical activity space (Davison & Lawson, 2006; Taylor et al., 2018). The closure of playgrounds as an important physical activity opportunity (Klinker et al., 2014) may have exacerbated this problem.

Finally, fear of Covid-19 in more densely populated areas may have also contributed to this relationship. In children and adolescents, parental involvement in their children's physical activity, such as co-participation, supervision, and encouragement, has been related to physical activity (Beets et al., 2010; Rhodes et al., 2020), which also applies during Covid-19 (Moore et al., 2020). However, adults in Germany living in metropolitan areas with higher population density showed elevated fear levels of Covid-19 compared to adults living in rural areas (with lower population density), which may be due to the fear of getting into larger crowds and being exposed to the virus (Schweda et al., 2021). Thus, in the context of our study, parents in densely populated areas may have shown less support for their children's physical activity out of fear of Covid-19, which may have contributed to no or little changes in daily life physical activity.

There are some limitations of our study that should be considered. All physical activity data is based on self-report and thus prone to recall bias. Since we do not have a control group, we can only theoretically assume a causal relationship between the lockdown and physical activity changes. As our study was interrupted by Covid-19, representativeness in the pre Covid-19 sample is mitigated. Finally, during the follow-up in April 2020, the weather was untypically warm, which may have influenced the physical activity changes. However, as reported previously, physical activity changes remained stable if only baseline participants from April 2019 were considered (Schmidt, Anedda, Burchartz, Eichsteller, et al., 2020).

These limitations notwithstanding, our study sheds light on the role of population density in Covid-19 related physical activity changes. Policymakers should ensure access to places that provide physical activity opportunities for youth living in densely populated areas in a lockdown situation. For example, one option could be to temporarily close down streets for road traffic, which has been related to increased physical activity and play in youth (Umstattd Meyer et al., 2019) as well as in the general population (Pandit et al., 2020), thus contributing to youth's health, especially during a pandemic.

Author contributions

CaN: Conceptualization, Methodology, Formal analysis, Writing – Original Draft; **DO**: Project administration, Investigation, Data curation, Software, Writing – Review & Editing; **KW**: Writing – Review & Editing; **AB**: Investigation, Data curation, Software, Writing – Review & Editing; **SK**: Writing – Review & Editing; **AnW**: Conceptualization, Methodology, Funding acquisition, Writing – Review & Editing; **AlW**: Conceptualization, Methodology, Funding acquisition, Writing – Review & Editing; **ClN**: Conceptualization, Supervision, Writing – Review & Editing

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CHAPTER 8

In a crisis: Research on and the potential of natural environments for psychosocial health and health behaviors during Covid-19

Slightly modified version of the 7th published article:

Nigg, C., Petersen, E., & MacIntyre, T. (2023). Natural environments, psychosocial health, and health behaviors during a crisis – A scoping review in the COVID-19 context. *Journal of Environmental Psychology, 88,* 102009. https://doi.org/10.1016/j.jenvp.2023.102009

Introduction

The COVID-19 pandemic, declared on 11 March 2020, had a major impact on society globally. As of November 2022, the estimated death toll attributed to the virus is more than 6.5 million people (https://bit.ly/3Ud9KGx; Dong et al., 2020). To mitigate the spread of the virus, many governments introduced containment measures such as physical distancing, suspension of social events, and restricted mobility, which resulted in significant social and economic consequences across different sectors (Nicola et al., 2020). Although almost 13 billion vaccine doses against COVID-19 have been administered as of November 2022 (https://bit.ly/3Ud9KGx; Dong et al., 2020), at the time of writing this, COVID-19 was still affecting daily life routines in some places, such as restricted access for visitors in hospitals (BBC, 2022) and travel restrictions to some countries (U.S. Embassy & Consulates in China, 2022). While some places have lifted all COVID-19 restrictions (e.g., Denmark, Switzerland), the short- and long-term effects of the pandemic are visible in several areas of human society, impacting individual's health, well-being, and health behaviors. For instance, across the world, psychological health and well-being have declined across the pediatric and adult population, while psychiatric symptoms and feelings of loneliness have increased due to physical distancing (Bonati et al., 2022; Lee et al., 2020; Loades et al., 2020; Vindegaard & Benros, 2020; Wunsch et al., 2021; Xiong et al., 2020). It is expected that these mental health consequences are not only immediate, but will have long-lasting effects on individuals (Iqbal et al., 2020). Furthermore, as health care systems directed their resources necessarily towards critical care for COVID-19 patients, preventive and chronic care resources were reduced (Tannous & Vahidy, 2022), leading to collateral damage due to missed diagnoses and delayed treatment of other (chronic) diseases (Malagón et al., 2022; Nadarajah et al., 2022). For children born during the pandemic, first results indicate that the neurodevelopment of these children in the early years may be affected compared to children born prior to the pandemic. This is evidenced by lower scores on tests of language and motor skills (Wenner Moyer, 2022), while the consequences of school closures may lead to lifetime welfare losses of children (Fuchs-Schündeln et al., 2022). Additionally, the shift to remote working came with both opportunities, such as enhanced productivity and flexibility, and less commuting time (Oakman et al., 2020), as well as challenges, such as intensified technical, psychological, and emotional work demands (Chan et al., 2022). It is expected that this shift to remote and hybrid working will continue in the future, challenging health behaviors such as movement and dietary behaviors (Peters et al., 2022), which are typically embedded into structures related to work or school (Brazendale et al., 2017). Unfavorable changes in health behaviors were also reported during

COVID-19, such as a decline in physical activity and an increase in sedentary behavior (Stockwell et al., 2021), adverse changes in eating behavior (Bhutani et al., 2021; Herle et al., 2021; Robinson, Boyland, et al., 2021), as well as a substantial risk of problematic alcohol use and overuse of online gaming (Xu et al., 2021). First studies indicate that even after COVID-19 restrictions were lifted, health behaviors such as physical activity did not return to pre-pandemic levels (Koch et al., 2022; Salway et al., 2022). These developments provide an impetus to identify factors beyond a biomedical model that empower the general and especially vulnerable populations, defined as populations that are susceptible to psychological, physical, or social harm, health problems, or neglect (Phillips, 1992; Rogers, 1997) to maintain and promote their psychosocial health and health behaviors during the COVID-19 pandemic (Holmes et al., 2020; Kola et al., 2021) and beyond.

Prior to the COVID-19 outbreak, numerous studies, including reviews, have demonstrated that exposure and access to nature in its various forms, including (urban) green space, blue space such as rivers, private green space, such as gardens, or visual nature experiences are related to improved mental health and well-being and a reduced risk for psychiatric disorders (Bratman et al., 2019; De Bell et al., 2020; Engemann et al., 2019; Jarvis et al., 2021; Tost et al., 2019; White et al., 2020; WHO, 2016). In addition, several studies support the concept that access and exposure to natural environments has the potential to promote physical activity (Remme et al., 2021), while interacting with nature, e.g. via gardening, can promote beneficial dietary behaviors (Beavers et al., 2020; Davis et al., 2011).

The complex underlying mechanisms linking nature to health, well-being, and health behaviors are not entirely elucidated and require further investigation (Kuo, 2015). Potential mechanisms linking nature to health and well-being include reducing harm (e.g., air pollution), restoring capacities (e.g., stress recovery), and building capacities (e.g., physical activity and social cohesion) (Hartig et al., 2014; Markevych et al., 2017). These mediators have also been confirmed in a recent systematic review (Zhang et al., 2021). As a result, nature exposure, including access to biodiversity and recreational activities in nature, are recommended to strengthen psychological resilience (Aerts et al., 2021). In this sense, natural environments can be part of a salutogenic approach (Antonovsky, 1987) to promote health through supportive environments (WHO, 1986), through being a resource that empowers people to promote and protect their own health.

Beyond the impact of the COVID-19 pandemic on psychosocial health and health behaviors, it also influenced people’s use of green space and natural environments. Depending on the containment measure in place, some people have interacted less with nature and others more (Burnett et al., 2021; Geng et al., 2021; Ugolini et al., 2021). This global public health crisis can be considered a unique natural experiment with COVID-19 restrictions affecting people’s daily lives around the world. We are not aware of any reviews that summarized research on a global scale, providing an overview of the role of natural environments for psychosocial health and health behaviors during a public health crisis such as the COVID-19 pandemic. Thus, this review aimed to identify the available evidence related to the role of natural environments regarding psychosocial health and health behaviors since the outbreak of the COVID-19 pandemic. The main question was: What do we know about the existing scientific literature regarding the relationship between natural environments and psychosocial health as well as health-related behaviors in the COVID-19 context? Specifically, we were investigating: a) Which types of nature were investigated in the context of the COVID-19 pandemic?, and b) Which psychosocial health outcomes and health behaviors in relation to nature were investigated during the COVID-19 pandemic?

Materials and Method

Considering this scoping review the first research synthesis on this topic in the COVID-19 context to our best knowledge, we used a structured scoping review and systematic thematic analysis approach to explore our research question. Scoping reviews aim to map key concepts, evidence types, and research gaps in a research field based on a systematic search and knowledge synthesis (Colquhoun et al., 2014). A key strength that distinguishes a scoping review from a systematic review is that a scoping review question covers a “broader” scope (Munn et al., 2018), allowing researchers to be more inclusive regarding diverse methodological approaches within the academic literature. This was particularly relevant as the goal was to investigate the wide range of academic research regarding nature and health (behavior) in the COVID-19 context across diverse populations, outcomes, and nature types. In contrast, systematic reviews generally require imposing restrictions, such as study design restrictions (e.g., only experimental studies) (Sucharew, 2019). The reporting follows the principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis extension for Scoping Reviews (Prisma-ScR; Tricco et al., 2018).

We specifically followed the established five-step process of Arksey and O'Malley (2005), including I) identification of the research question, II) identification of relevant studies, III) study selection, IV) data charting, and V) result summary and report. First, the research group met several times to discuss the research question (step I), which was guided by the PCC mnemonic (*Population*: Humans, *Concepts*: Natural environment, and psychosocial health or health-related behavior, and *Context*: COVID-19) (Peters et al., 2020). The team also agreed on definitions and the breadth of key terms in our research question (natural environment, psychosocial health, and health-related behaviors). We purposely applied a broad understanding and definition of the concepts to allow a comprehensive search and knowledge map. We defined natural environments as real-life and digital outdoor areas with physical features and processes of non-human origin (Hartig et al., 2014). During the screening process, we identified multiple articles that included activities bound to take place in nature. Thus, we expanded our inclusion of articles that focused on nature-based activities. Following the example of Wolsko et al. (2019), we included nature-dependent activities (e.g. skiing, swimming, kayaking), nature consumption-related activities (e.g. fishing, hunting, gardening), and motorized activities in nature (e.g. quad bikes, motor boats) in our definition. Psychosocial outcomes were defined as any psychological or social aspects that are influenced by the environment and biological aspects and their interrelationship with human behavior (Vizzotto et al., 2013), such as well-being, mood, quality of life, self-esteem, or cognition. Health behavior was defined as any behavior associated with health benefits (e.g., physical activity, eating behavior).

Next, we identified relevant databases, and defined search terms as well as inclusion and exclusion criteria (step II). The latter was executed in an iterative process based on internal discussions and preliminary online searches to refine the research question and review execution. Search terms were defined based on the author’s topic-related knowledge. Additional search terms were identified in the titles, abstracts, and keywords of relevant articles in a preliminary search. Following the preliminary search, a comprehensive online search was conducted in the databases Web of Science, Scopus, PubMed, Embase, CINAHL, and Greenfile on April 14, 2021, and updated on July 14, 2022, to include the latest literature in this scope. The search strategy was based on two strings, combining subject headings (MeSH terms) and keywords related to natural environments (e.g. green space, park, digital nature) and COVID-19 (e.g. Sars-Cov-2, pandemic, lockdown). The exhaustive search strategy for this study is provided in the *Appendix F A1*. Studies were included if they a) were published since 2020, b) included data collected since the outbreak of COVID-19, c) were accepted or published in a peer-reviewed journal, d) presented original empirical data collected on human participants, independent of the underpinning methodological approach (quantitative or qualitative), e) assessed the association between natural environments and psychosocial health or health behavior, and f) were written in English, German, or Scandinavian. A protocol presenting the project's objective and planned procedures was registered via the Open Science Framework platform (OSF) on June 6th, 2021 (available online: https://osf.io/ad2sx/).

For study selection (step III), all retrieved records were imported to and processed in Endnote Desktop reference management software (version X9.3.3). Following the removal of the duplicates, first, both the first and second author (C.N. and E.P.) screened independently from each other. Second, all titles that were deemed appropriate for abstract screening by one of the reviewers were included for abstract screening and again independently screened by both reviewers. Third, all abstracts that were deemed appropriate for full-text screening by one of the two reviewers were included for full-text screening and again independently screened by both reviewers (see *Figure 1*). Disagreements were dissolved by discussion. If no consensus could be reached, the third author (T.M.) was consulted. After piloting the data extraction, we decided to systematically extract the following information from each study (step IV): Authors' names, year of publication, study location (country), sample characteristics (size, age, gender, ethnicity), data collection time frame, study design, methodological approach, data collection methodology, study objective, operationalization and measures of the used concepts nature and health/ health behavior, and the main findings. The first and second authors extracted and inputted data from the final articles collection in a Microsoft Word table.

To prepare the extracted data for the report (step V), we adopted a systematic thematic analysis approach to summarize our findings and identify recurring themes. After we had extracted the data, one researcher (C.N.) imported the table into the program MAXQDA Analytics Pro (version 20.4.1). Following the guidelines proposed by Braun and Clarke (2006), we applied initial coding on each article charted in the table. Codes refer to a short phrase or word that summarizes or assign an attribute to a language-based content (Saldaña, 2016), from which we build the data extraction table. Especially relevant for coding were the columns: nature operationalization, measurement, and main findings. Before conducting the systematic thematic analysis, the first author (C.N.) piloted the coding and categorization process and discussed the applied procedures with the second author (E.P.). Then, the authors decided to follow a sequential deductive–inductive analysis process. First, based on our research question, two main categories were established deductively: 1) Nature type investigated during COVID-19, and 2) Health outcomes and health behaviors investigated during COVID-19. Codes that related to the type of nature investigated (e.g., forests, parks, water-based areas) were assigned to the first main category to answer the first research question regarding which type of nature was investigated during the COVID-19 pandemic. Codes relating to the type of health outcome (e.g., well-being, depression) or health behavior (e.g., physical activity, sleeping) were assigned to the second main category to answer the second research question regarding which health outcomes and health behavior were investigated in relation to nature during COVID-19. Codes that did not fit either of the main categories were revisited to develop a more representative code system, resulting in a third main category that was inductively developed during the coding process: 3) Heterogeneity in the nature–health association. This third main category contains codes relating to distinct associations in the nature–health relationship (e.g., varying relationships between nature and health for women and men), thus capturing characteristics which may play a key role in moderating the nature–health relationship. Within all three main categories, sub-categories were developed using a data-driven inductive approach. The initial coding for this procedure was conducted based on the column nature operationalization, measurement, and main findings. If required for context understanding, additional information was obtained from the article. For each article, the first author (C.N.) organized the initial codes first into the three main and then inductively into sub-categories in a systematic, repetitive procedure. As more articles were coded, they were mapped into previously identified sub-categories, and new or second-level sub-categories were established. To illustrate this on an example: First, any mental health and physical activity outcome that were associated with nature were put into the main category "Health outcomes and health behaviors during COVID-19". With more and more codes emerging that related to mental health and physical activity, two first-level sub-categories “mental health” and “health behaviors” were established, with any mental health outcome (e.g., “less stress”, “less anxiety”, “better well-being”) being mapped into the “mental health” sub-category and any physical activity outcome (e.g., “walking”, “exercising”) being mapped into the sub-category “health behaviors”. With ongoing coding, it became clear that there were also distinct themes within the mental health sub-category, leading to second-level mental health sub-categories being established to obtain a more fine-grained picture, such as “Well-being”, “Stress”, “Coping” or “Depression and anxiety”.

Main- and sub-categories were not mutually exclusive, and codes could be mapped into multiple main- and sub-categories. The coding and categorization process was discussed with all authors, and codes and categories were re-arranged and adapted until all authors agreed. As we applied the coding process to synthesize the evidence, we report the number of codes obtained the categories in the result section. A coding protocol that accompanied the coding process as well as the MAXQDA-file containing the full data extraction table with all final codes and the categorization can be found in the data repository: https://osf.io/ad2sx/.

Results

Descriptive study characteristics

After removing duplicates, a total of 9,126 search results were screened based on their titles, resulting in 188 articles representing 187 studies being included in our review. All studies were in English language. Most studies were excluded due to unclear assessment of the physical environment, which in most cases meant that there was only an assessment of whether people were outdoors or indoors, with this type of assessment possibly including any outdoor environment and not only natural environments. A flow diagram of the screening process is presented in *Figure 1*. Most studies used quantitative (*n* = 132) methods, while 30 studies applied qualitative methods and 25 studies mixed methods. Regarding the study design, most studies were of cross-sectional nature (*n* = 150), and 32 studies applied a longitudinal design. Most studies were observational (*n* = 171), while 16 studies used experimental methods. Online surveys were the most common form for data collection (*n* = 132), followed by qualitative interviews (*n* = 24), other survey formats (*n* = 22), such as paper-pencil, and geospatial methods (*n* = 20). Data collection during COVID-19 took most frequently place during the months April (*n* = 60), May (*n* = 54), and June (*n* = 47) in the year 2020. Nature was most frequently assessed via self-report, such as by collecting the self-reported frequency of nature visits (*n* = 150), while 30 studies applied objective methods (*n* = 30), and the rest of the studies relating to nature visitation or exposure (*n* = 15) or exposure to digital nature (*n* = 8). Regarding the population studies, most studies targeted the general population (*n* = 84), followed by studies investigating specifically people living in urban areas (*n* = 42) and university students (*n* = 15). Vulnerable populations were less often included, and consisted of health care workers (*n* = 5), people with physical health problems (*n* = 6; e.g., people with tinnitus or cancer), people with mental health problems (*n* = 4), and people in nursing homes (*n* = 2). Most studies included the adult population (both adults [n = 158] and older adults [n = 128]), whereas children (*n* = 20) and adolescents (*n* = 24) were less studied. Most studies did not have information regarding ethnicity of the study population (*n* = 149), whereas 34 studies had information (*n* = 3 not applicable). Most studies were conducted in the USA (*n* = 36), UK (*n* = 18), China and Spain (*n* = 16, respectively), Italy (*n* = 15), Canada (*n* = 13), Germany (*n* = 11), and Australia (*n* = 10). The methodological characteristics of the articles included are summarized in *Table 1*, a map displaying all countries that studies were conducted in is displayed in *Figure 2*, and the specific number of studies for each country can be found in the *Appendix F Table A1*. An overview regarding the year and months during which data of the included studies was collected can be found in the *Appendix F Figure A1*.

Figure 1. Flow diagram of the screening process

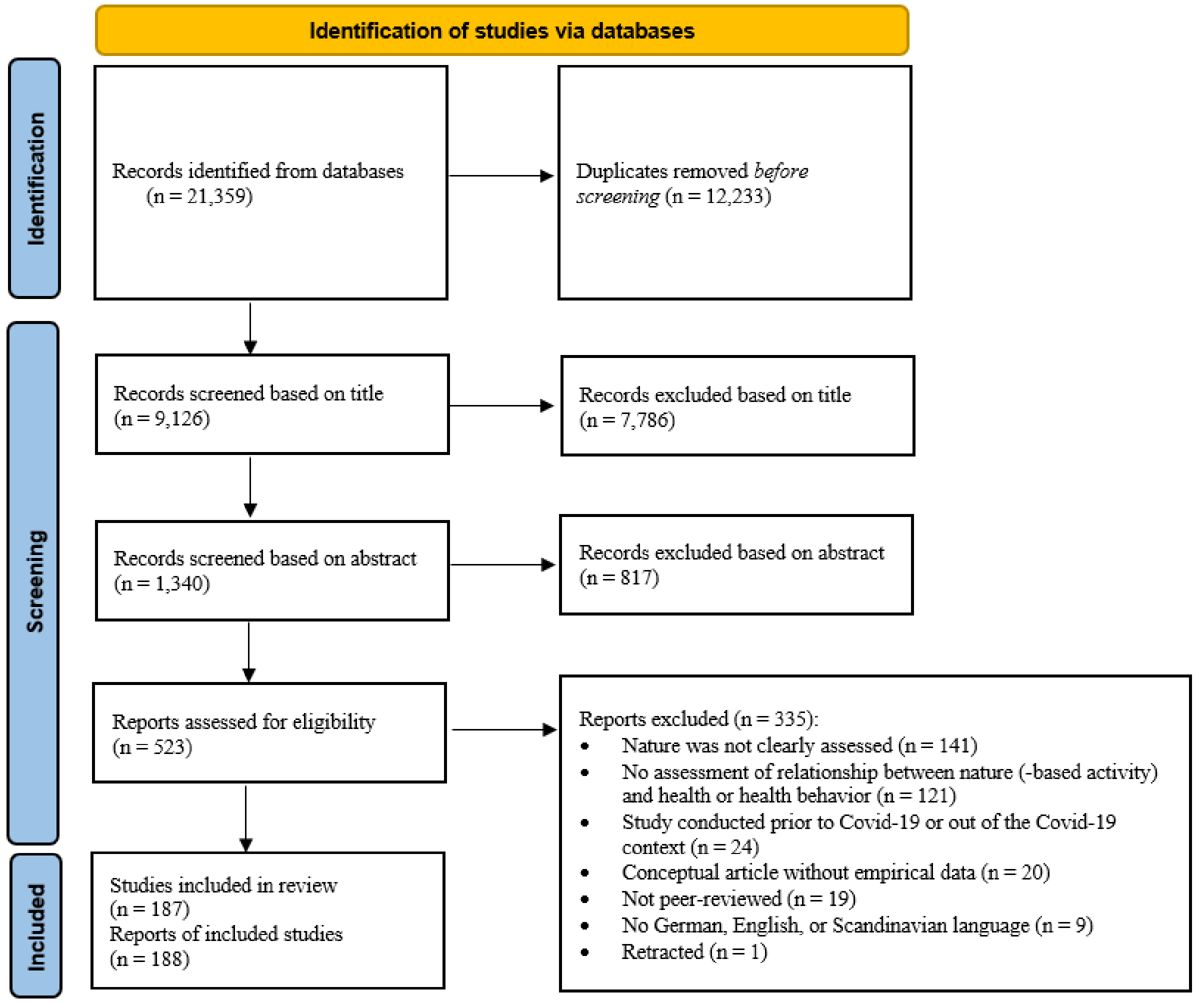
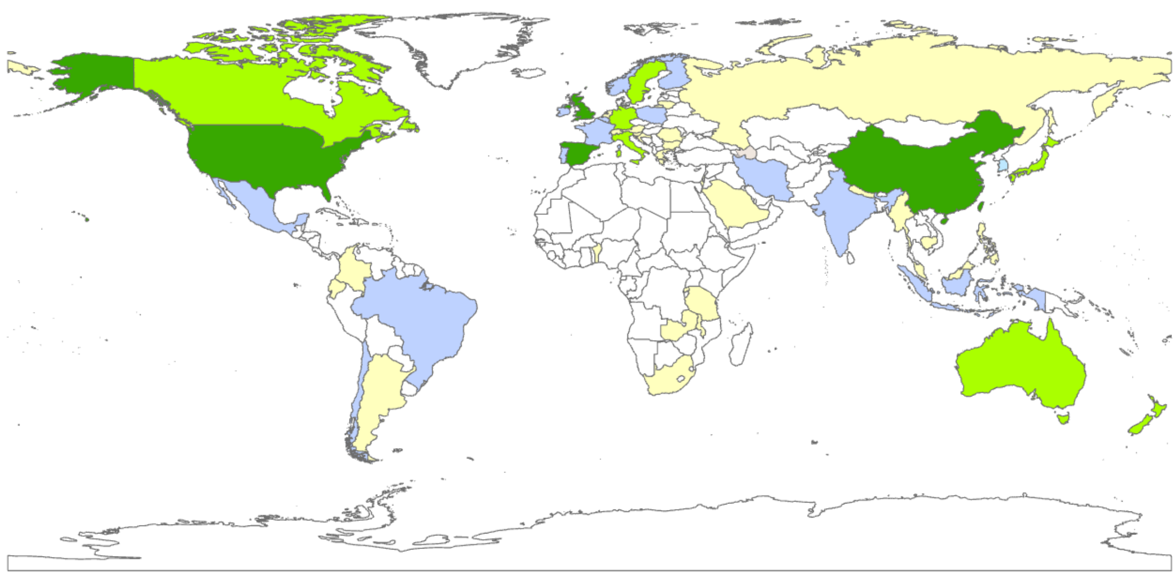


Figure 2. The frequency of studies based on the geographical location of the sample.



Please note: In large-scale multi-country studies, we only included countries with 100 or more responses if country participant information was available (n = 4).

Table 1. Methodological characteristics of the included studies (N = 188 articles, N = 187 studies)

Characteristics	***Categories***	***n***
Methodological approach	Quantitative	132
	Qualitative	30
	Mixed-Methods	25
Study design	Cross-sectional	150
	Longitudinal	32
	Intensive longitudinal	2
	Case-study	5
Study type	Observational	171
	Experimental	16
	Participatory action research	1
Data collection methodology	Online survey	132
	Other survey forms	22
	Qualitative interviews	24
	Geospatial methods	20
	Device-based health outcome assessment methods	7
	Analysis of audio-visual material	6
	Ethnographic approaches	4
	Social media analysis	4
	Fitness app analysis	3
	Participating writings	3
	Observation	2
	Other[b]	3
Nature assessment	Self-report	150
	Objective[c]	30
	Nature visitation or exposure in real-life[c]	15
	Digital nature exposure	8
Study population / sample	General population	84
	Urban residents	42
	University students	15
	Gardeners and farmers	8
	Families	8
	Park and forest visitors	7
	People with physical health problems	6
	Fitness app and social media post analysis	6
	People engaging in nature-based physical activity	5
	Health care workers	5
	People with mental health problems	4
	Greenspace experts	3
	Employees	2
	People in nursing homes	2
	Other[d]	9
Sample age [e]	Children	20
	Adolescents	24
	Adults	158
	Older adults	128
Sample size	≤ 10	6
	11-100	36
	101-500	47
	501-1000	34
	1,001-5,000	47
	5,001-10,000	6
	> 10,000	4

Please note: Some studies applied multiple study designs, data collection methodologies, and nature assessments and included multiple age groups. Thus, it is possible that the sum of the categories exceeds the number of studies and included articles. The sample size category does not include sample information about social media (i.e., number of posts). [a] *Intensive longitudinal study design refers to study designs with repeated measurements within one unit (e.g., a person) to investigate changes within this unit (Bolger & Laurenceau, 2013).* [b] *"Other" refers to data collection methods that did not fit into any of those categories and were only applied once across the studies included, e.g., health impact assessment.* [c] *"Objective" refers to methods where nature is identified via geospatial approaches, such as creating buffers around residential addresses, while "nature visitation or exposure in real-life" refers to studies that investigated people in natural environments, e.g., park visitors or intervention studies exposing participants to nature.* [d] *"Other" refers population groups investigated that did not fit into any of those categories and were only investigated once across the included studies, e.g., prisoners or webcam travelers.* [e] *Children were defined as participants up to nine years, adolescents from ten 10 to 17 years (Sacks, 2003), adults 18 – 64 years, and older adults 65 years and older (Orimo et al., 2006).*

Identified main and sub-categories

As introduced in the methods sections, we identified three main categories, with the first two main categories being deductively obtained based on the two research questions and the third main category being obtained through a data-driven inductive process in our analyses: 1) Nature type investigated during COVID-19, 2) Health outcomes and health behaviors investigated during COVID-19, and 3) Heterogeneity in the nature–health association during COVID-19. A summary of the main- as well as first- and second-level sub-categories is presented in *Table 2*, and a table with a detailed description can be found in *Appendix F Table A2*.

Nature type investigated during COVID-19

Within this main category, three first-level sub-categories were distinguished, including the geographic dimension, the characteristics of nature, and nature-based activities. From a geographical point of view, both public and private nature were investigated during COVID-19. Public nature was the domain that received the greatest interest (*n* = 102 codes), specifically parks (*n* = 29 codes), and urban natural areas (*n* = 28 codes). Private nature was less investigated (*n* = 28 codes) and concentrated on gardens and garden access (*n* = 22 codes). Regarding the characteristics of nature, most studies looked at greenspace and vegetation (*n* = 24 codes) and general nature (*n* = 21 codes), followed by views on nature from the window (*n* = 12 codes), and blue space, such as general blue space and beach areas (*n* = 11 codes). Less investigated were digital nature in forms of webcam travel, videos, and virtual nature experiences (*n* = 8 codes), nature quality (*n* = 6 codes), and nature sounds (*n* = 3 codes). Regarding nature-based activities, gardening was most frequently investigated (*n* = 17 codes, followed by nature-based physical activity, such as general physical activity in natural environments or adventure sports participation (*n* = 11 codes).

Health outcomes and health behaviors in relation to nature during COVID-19

Within this second main category, three first-level sub-categories were distinguished: psychological health, health behaviors, and social health. Within each of these sub-categories, outcomes were categorized into favorable associations and no or unfavorable associations. Across all sub-categories, the majority of health outcomes and health behaviors were favorable related to nature (*n* = 423 codes), with only a few studies reporting null results or a negative association between nature and psychosocial health or health behaviors (*n* = 72 codes). In the following, we report the number of codes including both favorable and no/unfavorable associations, for a stratified overview, please see *Table 2*.

Table 2. Overview about identified main- and sub-categories.

Main category	First-level sub-category	Second-level sub-category
Nature assessed (269)	Geographic dimension (143)	Public nature (111) Private nature (32)
	Characteristics of nature (88)	Green space and vegetation (24) Nature general (21) Window view on nature (12) Blue space (11) Digital nature (8) Nature quality (6) Nature sounds (3) Other (3)
	Nature-based activities (38)	Gardening (17) Nature-based physical activity (11) Unspecified nature-based activities (3) Active and passive nature-based activities (2) Nature-based tourism (2) Other (3)
Health outcomes and behaviors (495)	Psychological health (325) – favorable associations (282)	Well-being (97) Stress (67) Mood and emotions (49) Depression and anxiety (26) Recovery (13) Coping (12) Perceived break from pandemic (11) Food security (4) Other (3)
	Psychological health (325) – no and unfavorable associations (43)	Depression and anxiety (16) Stress (12) Well-being (11) Mood and emotions (2) Other (2)
	Health behaviors (102) – favorable associations (82)	24-hour movement behaviors* (71) Diet (6) Play (5)
	Health behaviors (102) – no and unfavorable associations (20)	24-hour movement behaviors* (17) Dietary behaviors (2) Other (1)
	Social health (68) - favorable associations (59)	Social health general (26) Social health regarding the family (13) Social health regarding friends and neighbors (10) Community health (5) Loneliness (4) Other (1)
	Social health (68) - no and unfavorable associations (9)	Social health general (4) Loneliness (3) Other (2)
Heterogeneity in the nature–health relationship (131)	Heterogeneity based on human characteristics (56)	Socio-demographic inequalities (34) Nature access (9) Time spent in nature (3) Time spent on the university campus (2) Other (8)
	Heterogeneity based on nature and nature-based activity characteristics (19)	Nature type (13) Vegetation (2) Crowdedness of the natural area (2) Other (2)
	Heterogeneity based on geographic region (11)	Country-based variability (4) City-based variability (4) COVID-19 related variability (2) Other (1)

*Please note: The numbers in brackets represent the number of codes in the respective main-/sub-category. For the second-level sub-category, "other" refers to the number of codes that did not fit into any second-level sub-category. Some second-level sub-categories were further divided into third-level sub-categories. For a detailed overview regarding all the categories, we refer the reader to the coding file accessible on the Open Science Framework (https://osf.io/ad2sx/). * 24-hour movement behaviors refer to physical activity, sedentary behavior, and sleep (Stevens et al., 2020).*

Psychological health was most extensively investigated (*n* = 325 codes) in relation to nature during COVID-19. Within this first-level sub-category, the greatest interest was in well-being, including general well-being, happiness, and life satisfaction (*n* = 108 codes), followed by stress (*n* = 79 codes), mood and emotions (*n* = 51 codes), as well as depression and anxiety (*n* = 42 codes). Constructs relating to resources and restoration, including recovery (*n* = 13 codes), coping (*n* = 12 codes), were less investigated. Two sub-categories specific to the COVID-19 context were the perceived mental break from the pandemic (*n* = 11 codes), with participants indicating that nature allowed them feelings of escape from the ubiquitous pandemic life situation, as well as food security (*n* = 4 codes), which was mainly investigated in the gardening context and referred to people producing their own food.

Health behaviors received the second most frequent interest in relation to nature during COVID-19 (*n* = 102 codes). Most of interest were behaviors of the 24-hour movement cycle (*n* = 89 codes), especially physical activity, including walking, exercising, doing sports, general physical activity, and meeting the physical activity guidelines (*n* = 80 codes). Other behaviors of the 24-hour movement cycle, including sleep (*n* = 5 codes) and sedentary behavior (*n* = 3 codes), were less investigated. Lastly, some interest was given to dietary behaviors (*n* = 8 codes) and play (*n* = 5 codes).

Social health was least investigated in relation to nature in the COVID-19 context (*n* = 68 codes). Codes in this sub-category referred to general social health (*n* = 30 codes), social health regarding the family (*n* = 13 codes), and social health regarding neighbors and friends (*n* = 10 codes). Codes referring to loneliness (*n* = 7 codes) and community health (*n* = 5 codes) were less common.

Heterogeneity in the nature–health association during the COVID-19 pandemic

While the first two main categories synthesized codes referring to type of nature and the health outcomes/behaviors investigated during COVID-19, this third main category synthesized codes that refer to the nature–health relationship varying across populations and locations. Within this main-category, three first-level sub-categories were distinguished: Heterogeneity based on human characteristics, based on nature (activity) characteristics, and based on geographic regions.

Most articles targeted the variation between nature and health based on human characteristics (*n* = 56 codes), with most prominent variations occurring across sociodemographic characteristics (*n* = 34 codes), such as age, gender, and socio-economic status. In addition, some articles reported that the relationship between nature and health varied by access to nature (*n* = 9 codes), especially by garden access. Less investigated were other human characteristics, such as ethnicity (*n* = 2 codes) and characteristics more specific to the COVID-19 pandemic, e.g., being in a high-risk group (*n* = 1 code), working from home (*n* = 1 code), and social interactions during the pandemic (*n* = 1 code).

Heterogeneity was less frequently examined regarding nature characteristics (n = 19 codes). Most common variations were reported based on nature type (*n* = 13 codes), such as indoor compared to outdoor nature or park type, including variations based on nature types (*n* = 4 codes), such as forest or park type, and nature quality (*n* = 2 codes). The sub-category crowdedness (*n* = 2 codes) was rarely investigated, but especially relevant in the pandemic context, describing variations based in the relationship if the natural area was crowded.

Regarding geographic heterogeneity, the association between nature and health varied depending on the country or city where the participants lived (*n* = 4 codes, respectively), as well as the specific COVID-19 situation at the participant's location, such as public space closures and case severity (*n* = 2 codes).

Discussion

This article presents the findings of a scoping review conducted to examine the current research natural environments, psychosocial health, and health behaviors in the COVID-19 context as a public health crisis. While research on natural environments and psychosocial health as well as health behaviors has strongly increased over the last decade (Zhang et al., 2020), to this point, the role of nature in a public health crisis, such as the COVID-19 pandemic, has been unclear. The overall trend of the literature included in our scoping review suggests that nature holds the potential to mitigate the negative effects of COVID-19 on psychological health and physical activity during COVID-19 pandemic. However, this relationship is complex and varies regarding specific population characteristics, nature type, and geographic location.

We first extracted descriptive characteristics about the studies included in the review. Next, applying systematic thematic analysis, study content was coded into three main categories: a) the nature types investigated during the COVID-19 pandemic, b) health and health-related behaviors, and c) heterogeneity and variability regarding the association between nature and health. The descriptive characteristics revealed that most studies applied a cross-sectional study design, which is consistent with studies that have been conducted prior to COVID-19 (Collins et al., 2020; Zhang et al., 2021). Most studies were conducted in high-income countries, and the ethnic background of the participants was rarely reported. The most common samples comprised the general population, typically adults, while vulnerable populations were less commonly included in the sampling. This finding highlights a research gap since acute and long-term mental and social health consequences of this pandemic had and have the most severe impact on people already struggling with mental health challenges (Kola et al., 2021; O'Connor et al., 2021; Quittkat et al., 2020; Ting et al., 2021). As previous research supports that people who are psychologically vulnerable benefit most from green space interaction (Tost et al., 2019), more research on the role of nature to mitigate acute effects as well as to promote well-being amongst those most affected by the pandemic is warranted. Furthermore, people with vulnerability risk specific to the COVID-19 pandemic should be considered. For example, the imposed restrictions are expected to have exacerbated the "modern epidemic" of loneliness (Hwang et al., 2020; Jeste et al., 2020), while a study conducted prior to COVID-19 showed that green space could decrease the risk for loneliness (Astell-Burt et al., 2022). Hence, more research among vulnerable groups regarding the relationship between nature and psychosocial health and health behaviors in crisis situations and their aftermath is warranted. In addition, a group that was barely included in our review were people suffering from long-term effects of a COVID-19 infection. Recent systematic reviews indicate that 43% to 53% report long-term health effects of a COVID-19, including fatigue, general pain, or mental disorder symptoms (Chen et al., 2021; Domingo et al., 2021; Lopez-Leon et al., 2021), thus affecting a considerable number of people. For this population, exposure and interactions with natural environments may be a way to mitigate the negative long-term consequences (Kolbe et al., 2021).

Type of nature investigated

We found that public nature was primarily investigated, with the greatest interest in parks, while private nature was mostly investigated in terms of gardens with gardening activity being the most frequent form of nature-based activity. Green space and vegetation were the most common investigated nature characteristics. The thematic focus on general green space and vegetation cover is consistent with previous reviews (Frumkin et al., 2017; Hartig et al., 2014). Other types of nature, including blue space, such as rivers or lakes (Britton et al., 2020) or green infrastructure, referring to a network of open space or vegetation within a certain area that are specifically planned for ecosystem services (Matsler et al., 2021; Nieuwenhuijsen, 2021), have been neglected. Regarding gardens and gardening activity, the beneficial effects for mental health and well-being have been shown in studies prior to the pandemic (Howarth et al., 2020), but the intensity of research and their importance seem to have increased during the pandemic: A systematic review conducted pre-dominantly prior to the pandemic regarding green space exposure and mental disorder prevention showed that out of 201 included studies, only four and two studies investigated specifically community and private gardens, respectively, whereas 81 studies investigated urban green space and nature exposure or contact (Reece et al., 2021). In contrast, in our review, 34 studies investigated the health benefits of gardens or gardening activity. The reason for the focus on gardens during COVID-19 is probably due to gardens facilitating contact with nature while adhering to stay-at-home orders (e.g., lockdowns). Also, a study in Brazil showed that having a home garden was most important to mitigate mental distress during COVID-19, while visiting urban parks was deemed less relevant (Marques, Silva, Quaresma, Manna, De Magalhães Neto, et al., 2021). Thus, especially during a crisis like this pandemic, both practitioners and researchers should consider private and public nature as resources, if available.

An additional gap in the literature emerges regarding research in digital and virtual nature experiences, an area that has generated some interest prior to COVID-19, suggesting that virtual nature experiences can promote human–nature interactions and connections (Litleskare et al., 2020). This research area also seems to have experienced increasing interest during the pandemic: A systematic review regarding nature experience via virtual reality and psychological well-being prior to the COVID-19 pandemic included only 21 studies (Frost et al., 2022), compared to 153 studies included on a review on public urban green space and human well-being (Reyes-Riveros et al., 2021). In our review, elven studies investigated digital nature. Especially during COVID-19, the benefits of digital nature experiences became visible, specifically for places where leaving the house for recreational purposes was prohibited or if there was no nature access in the neighborhood. Beyond this pandemic, research on digital and virtual nature experiences should be expanded to facilitate people's contact with nature that may not have the opportunity to visit nature in real-life. For example, a study with incarcerated men showed that virtual nature exposure led to decreased stress (Nadkarni et al., 2021). Hence, benefits of digital nature should also be investigated in other settings with limited nature access, such as elderly care homes, clinical care settings, or areas of urban degradation. This could also be a chance to investigate different nature types, which may illuminate our understanding of which natural features provide the strongest psychosocial health benefits for different public subgroups (Bratman et al., 2019).

Regarding nature operationalization, in self-reported measures, a common approach was to ask participants about the frequency of nature visits or the role of nature for health, without further specification of the nature type (e.g., Anderson et al., 2022; Beckmann-Wübbelt et al., 2021; Berdejo-Espinola et al., 2021; Kang et al., 2022; Soga et al., 2021; Ugolini et al., 2021). Regarding objective assessment, a common approach was the Normalized Difference Vegetation Index (NDVI) (Cheng et al., 2021; Larson et al., 2022; Lõhmus et al., 2021; Reid et al., 2022; Robinson, Brindley, et al., 2021; Soga et al., 2021; Yang et al., 2021), which has been commonly used in pre-COVID-19 studies (Ekkel & De Vries, 2017) to assess vegetation. However, none of those measures enables conclusions regarding which nature characteristics are relevant for a health in such a crisis. This is a major gap in the research, considering that some studies included in this review indicate that the nature–health relationship differs based on nature type characteristics (e.g., Cheng et al., 2021; Dzhambov et al., 2020; Khalilnezhad et al., 2021; Larson et al., 2022; Marques, Silva, Quaresma, Manna, Neto, et al., 2021; Maury-Mora et al., 2022; Trevino et al., 2022; see also discussion about the third main category). In addition, previous studies proposed the use of nature quality indicators in explaining health outcomes and behaviors (Knobel et al., 2021; Van Dillen et al., 2012), as well as nature characteristics, such as biodiversity (Knobel et al., 2021; Marselle et al., 2021; Sandifer et al., 2015). Beyond nature type and quality, characteristics of the human–nature interaction should be considered further. For example, in physical activity, the FITT-principle is used for developing exercise prescriptions, referring to the description of physical activity frequency, intensity, time, and type (Reed & Pipe, 2016). Such a principle regarding human–nature interactions would be valuable to inform urban planners and practitioners, which may then refer to frequency, time (duration), type, and level (e.g., viewing a lake vs. swimming in a lake) (Bratman et al., 2019; Masterton et al., 2020).

Psychosocial health outcomes and health behaviors investigated

Psychological health received the most interest in relation to nature during COVID-19. This seems plausible as the COVID-19-related restrictions had a strong impact on mental health worldwide (Bu et al., 2021; Kola et al., 2021; O'Connor et al., 2021; Xiong et al., 2020). More specifically, our analysis showed that the topics of most interest among researchers included well-being and general mental health, stress, mood and emotions, as well as depression and anxiety. In that sense, nature is considered a resource to prevent mental illness and disease. However, what has been less examined were psychological constructs in a salutogenic paradigm (Antonovsky, 1987), that is nature as a resource to empower people to promote their own health, reflected through few codes regarding coping and recovery and fewer investigations regarding associations between nature and social health in the COVID-19 pandemic context. Considering that nature exposure has been shown to have similar strong effects on well-being as social interactions (Killingsworth & Gilbert, 2010; Tost et al., 2019), we suggest that future research should go beyond a deficit-based approach and should focus instead on nature as a resource for mental health promotion both through real-life and digital nature experiences, termed a strength-based approach. Although social health was still the psychosocial health sub-category experiencing the least interest compared to psychological health and health behavior with 68 codes out of 495 codes (14%) in the main category health outcomes and behaviors, it seems that there was increasing interest in this health benefit: A systematic review prior to the pandemic about health benefits of urban green space showed that less than five out of 153 studies (3%) investigated social relations as health benefit (Reyes-Riveros et al., 2021).

Regarding health behaviors, the role of nature regarding physical activity received the most interest from researchers in the field. This is not surprising, given the numerous health benefits of physical activity (Bull et al., 2020; Chaput et al., 2020) and its decline during COVID-19 (Paterson et al., 2021; Stockwell et al., 2021). Based on the studies included in our review, conclusions about whether specific features of the natural environment were relevant to the motivation of people to go to natural places in a crisis or whether physical activity in natural environments displaced other types of physical activity that were not possible due to the pandemic restrictions cannot be drawn. Both in the context of COVID-19 and beyond, it would be worthwhile to examine which features of the natural environment provide affordances for physical activity, given that nature-based physical activity may be a resource that promotes mental health to a greater extent than physical activity in other non-natural settings (Lahart et al., 2019; Mnich et al., 2019). Device-based assessment of physical activity combined with geolocation tracking technology could be valuable to obtain detailed insights on physical activity in natural environment contexts (Jankowska et al., 2015). Other health behaviors (e.g., sleep) were rarely investigated. However, from a conceptual point of view, investigations between specific types of nature or nature-based activity and health behaviors could be valuable in the context of COVID-19. For example, in two studies, most participants reported negatively changing their eating behaviors during the COVID-19 lockdown (Deschasaux-Tanguy et al., 2021; Robinson, Boyland, et al., 2021). In contrast, gardening activity was related to improved dietary intake (Beavers et al., 2020; Davis et al., 2011). Hence, as home gardening received increased interest during COVID-19 in some areas (Giraud et al., 2021), there may be sustained effects on healthy eating behaviors, which warrants further study.

Heterogeneity in the nature–health relationship

The third main category indicated that the nature–health relationship may vary across different characteristics. Most common were variations based on gender and age differences, with no clear direction. For example, while one study reported that feelings of solace and respite and feelings of reconnection were more likely to be reported by men (Astell-Burt & Feng, 2021), another study reported that shorter distance to the nearest parks mitigated a step decline in older women, but not older men (Hino & Asami, 2021). The underlying mechanisms for these differences remain to be investigated and are essential for the planning of effective nature-based solutions and interventions that promote health and well-being across specific population groups. For instance, in a qualitative study, women indicated that fear of violence hinders positive well-being experiences when visiting an urban park in Mexico during COVID-19 (Huerta & Cafagna, 2021). A recent review summarized the evidence regarding mechanisms of green space interventions for mental health and investigated which mechanisms work for whom (Masterton et al., 2020). For example, they found that green space improves mental health via the mechanism "escape/getting away", works particularly well for people with an existing mental health diagnosis, while the mechanism "shared experiences" was important across study populations (Masterton et al., 2020). Hence, future endeavors should focus on identifying the underlying reasons for disparities in the nature–health association and provide interventions that facilitate an inclusive approach to ensure safe and positive nature experiences for all citizens.

Furthermore, heterogeneity has not only been investigated regarding population characteristics, but also with regards to nature types, indicating that different nature types may have differing importance for different health outcomes. For example, indoor green space, such as house plants, were weaker related to improved mental and social health outcomes than outside green space (Dzhambov et al., 2020; Maury-Mora et al., 2022; Trevino et al., 2022). Another study found that national and state parks, but not local parks or vegetation cover were related to less emotional distress (Larson et al., 2022), which was similar to other studies showing that restorativeness was highest in national parks compared to urban forests in South Korea (Lee et al., 2021). Two studies highlighted the importance of gardens for mental health compared to public green space (Khalilnezhad et al., 2021; Marques, Silva, Quaresma, Manna, Neto, et al., 2021). These results indicate that the relationship between nature and health may be difficult to generalize across nature types. For example, a recent article showed that associations between the natural environment and mental health, physical fitness, and physical activity varied dependent on the geospatial configuration of the environment, with these different configurations representing different concepts of the natural environment (Nigg et al., 2022). Hence, to create effective nature-based solutions, it is important to understand which nature types are most effective in promoting health and health behaviors (Bratman et al., 2019).

Finally, heterogeneity was investigated regarding geographic regions, with most attention being paid to variability in the nature–health relationship between different countries, which may result from the diverse COVID-19 restrictions implemented across locations. We recommend that future reviews apply a comparison of WEIRD (Western, Educated, Industrialized, Rich, and Democratic) vs. non-WEIRD countries to explore the bias in sampling, favoring the former (Henrich et al., 2010) and to consider the human-environment interactions are embedded into cultural context, with WEIRD populations not necessarily representing the norm for human behavior (Milfont & Schultz, 2016; Tam & Milfont, 2020). Furthermore, future research is warranted regarding the urban-rural differences in the nature–health relationship. For example, one study included in this review showed that an increasing number of parks was related to less depression in urban, but not in rural areas (Bustamante et al., 2022), mirroring some research results prior to the pandemic showing an urban-rural gradient in the nature–health relationship (Dennis & James, 2017). Since the effects of the pandemic also differed across the urban-rural gradient, such as differing effects on physical activity (Hino & Asami, 2021; Nigg et al., 2021), the role of nature along the urban-rural gradient in crisis situations requires more research.

Limitations

To the best of our knowledge, this is the first scoping review summarizing a wide range of research regarding the nature type and health outcomes and behaviors investigated during COVID-19, hence providing a comprehensive overview about the research area in a time constituting a public health crisis. However, there are some limitations that should be considered. In the first step, due to the large number of studies and available resources, the study screening process was conducted based on title only, followed by abstract screening in a second step, before full texts were obtained in the third step. Thus, it cannot be ruled out that some eligible studies were overlooked in this process. However, in the title screening, both reviewers only excluded titles that were with a very high chance irrelevant for the review topic. Concurrently, or if the title was not informative enough to decide about its relevance, it was included for abstract screening. Also, both reviewers conducted the title screening independently from each other and if a title was deemed appropriate for abstract screening by only one reviewer, both reviewers screened the abstract. We only included articles published in German, English, or Scandinavian languages, thus, studies published in other languages were not included, which may have enhanced the bias regarding WEIRD countries. However, only nine studies were excluded in the stage of full-text screening based on language restrictions, with five studies from Europe, one from Brazil, one from Turkey, one from China, and one from Honduras. Except from Honduras and Turkey, all countries that were excluded are represented by other studies in this review. Regarding the systematic thematic analysis, it must be considered that the analysis was only conducted by one person, with the analytic angle may be being influenced by the person's prior knowledge. At the same time, it should be considered that there were regular meetings in the research team, where the person conducting the thematic analysis presented the codes and categorizations as well as the considerations behind the codes and categorizations, leading to re-structuring and re-categorizations.

Furthermore, we focused on psychosocial health and health behaviors based on the emerging literature that consistently demonstrated that psychosocial health and health behaviors deteriorated during COVID-19. We also focused on the benefits that humans gain from the natural environment but did not consider the impact of humans on the natural environment based on a planetary health understanding (Whitmee et al., 2015). Additionally, given the nature of a scoping review, we did not assess study quality and did not conduct an analysis to investigate publication bias (Devito & Goldacre, 2019). Together with the lack of reporting characteristics about human-nature interactions (e.g., nature exposure duration, frequency or type) that may impact health benefits, any conclusions about favorable and null or unfavorable results must be treated with caution.

Hence, for future reviews investigating associations between nature and health or health behaviors, it would be useful to also investigate associations between nature and physiological health and to assess the quality of the included articles. In addition, a comprehensive review that also considers the positive and negative impact of human–nature interactions on the natural environment, such as wildlife rebounding and increases in illegal nature activities such as hunting (Bates et al., 2021), as well as potential co-benefits (Inauen et al., 2021), would be valuable to obtain a holistic planetary health understanding (Whitmee et al., 2015).

Conclusion

The COVID-19 outbreak had a significant impact on people's psychosocial health and health behaviors. This study synthesized a wide range of available evidence regarding the types of nature and health outcomes and behaviors investigated during the COVID-19 pandemic. The available research suggests that nature may mitigate the negative impact of COVID-19 on well-being and mental health while facilitating physical activity during the pandemic, which replicates findings prior to the pandemic (Bratman et al., 2019; Remme et al., 2021; White et al., 2020). The replication of the results of non-pandemic times during pandemic times may indicate that natural environments are an important public health resource that not only promote well-being in normal circumstances, but particularly mitigates the negative effects of crisis on human's well-being. Comparing the type of conducted research included in this review to research on the nature–health relationship prior to the pandemic, we find that the focus on mental health and physical activity as research topics, the main origin of research being in high income countries, and the negligence of vulnerable groups are similar (Zhang et al., 2020). At the same time, it seems that the pandemic has intensified research on specific aspects of the nature–health relationship, including intensified research about the role of private green space in forms of gardens and digital nature, as well as the role of nature for social health (Zhang et al., 2020). Research gaps in the COVID-19 context were identified regarding I) nature types and characteristics that promote psychosocial health and health behavior, II) the impact of digital and virtual nature, III) psychological constructs relating to mental health promotion, such as resilience, IV) health-promoting behaviors other than physical activity, V) underlying mechanisms regarding heterogeneity in the nature–health relationship based on the study population, type of nature, and geographic characteristics, and VI) research focusing on vulnerable groups. Beyond the identified research gaps, future studies should ideally apply longitudinal designs and follow-up on participants to investigate possible long-term associations between nature's impact on health and health-behavior outcomes in the COVID-19 context.

The COVID-19 pandemic serves as an example of a crisis on the societal level that are relevant for global public health. Gathering knowledge and learning from it is critical. Crisis on the societal level have occurred in the past, such as the global financial crisis 2008-2009, are currently happening, such as rising energy prices and inflation in Europe threatening welfare (Commission, 2022; eurostat, 2022), and have a high potential to occur again in the future, for example, caused by other zoonotic diseases (Quammen, 2012; Walsh et al., 2020) or extreme events such as heatwaves as a consequence of climate change (Thiery et al., 2021). Therefore, natural environments may be a valuable resource to build resilience before, mitigate the negative impact during, and allow individuals to promote their health during the societal crisis impacting psychosocial health and health behaviors.

Author contributions

CN: Conceptualization, Methodology, Data Curation, Investigation, Formal analysis, Writing – Original Draft; **EP**: Conceptualization, Data curation, Writing – Review & Editing; **TM**: Funding acquisition, Writing – Review & Editing

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CHAPTER 9

Physical activity as a sustainable behavior

Slightly modified version of the 8th published article:

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Introduction

As a result of the Society of Behavioral Medicine's Provocative Question Initiative, Diefenbach (2019) reported that behavioral scientists consider climate change, sustainable development, and health as one of the most important future topics for behavioral medicine.

In the health area, the concept "planetary health" has recently been established, which simply expressed describes both human's health and the state of the earth's natural systems which human's health depends on (Whitmee et al., 2015). However, current health concepts do not consider at which ecological costs those health benefits are gained, thus posing a threat to human's future (Horton & Lo, 2015). Although planetary health emphasizes human and ecological systems interdependence, ecological systems do not exist without people, and people do not live in isolation from ecological systems (Whitmee et al., 2015). Thus, when promoting health behavior, such as physical activity (PA), which is an essential part of behavioral medicine, the impact on social and ecological systems needs to be considered. In its *Global Action Plan for Physical Activity*, the World Health Organization (WHO) (WHO, 2018) posits how PA can contribute to the United Nations' (UN) Sustainable Development Goals (SDG) (UN, 2015) on the structural level, focusing less on conceptualizing PA as individual sustainable behavior (SuB) and how this might lead to other individual SuBs. However, to achieve sustainable development, political actions and individual behavior change are necessary (IPCC, 2018; Whitmee et al., 2015; WHO, 2018).

Thus, this article conceptualizes PA as a SuB on the behavioral level of individuals and how PA impacts other SuBs that promote sustainable development. First, for a common understanding PA and SuB are defined. Second, it is explained how PA can be conceptualized as a promoter of SuB within the SDG framework plus we discuss examples how PA may counteract SDGs. Third, a future research agenda is presented regarding sustainable PA and PA's contribution to sustainable development on the behavioral level of individuals.

Understanding the concepts

Physical activity

PA refers to any bodily movement produced by muscles leading to energy expenditure, including exercise and sports as subdomains (Caspersen et al., 1985; Jenny et al., 2016). For health benefits, the WHO recommends 60 minutes daily for youth and 150 weekly minutes for adults of moderate-to-vigorous PA (WHO, 2010).

Not all PA behaviors can be conceptualized as sustainable or will have a positive impact on SuB. For example, certain sport types have recently been criticized for its ecological impact, such as environmental damage and energy consumption (Abu-Omar & Gelius, 2019). To consider the impact of PA and sports on predominantly ecological sustainability, Bjørnarå et al. defined sustainable PA as health-promoting PA activities that have a low environmental impact and that are culturally and economically accessible and accepted (Bjørnarå et al., 2017).

Sustainable behavior

Sustainable development is broadly defined as humans ensuring that current and future generations can meet their needs through their own actions (Brundtland et al., 1987). Illustrating this as a "sustainability donut", humans' actions are limited by planetary boundaries, describing ecological threshold values (ecological sustainability dimension, e.g. climate change), and by socio-economic boundaries (socio-economic sustainability dimension; e.g. income, education) (Leach et al., 2013). These aspects are found in the UN's 17 SDGs which is a global call for action to promote sustainable development socio-economically (e.g. end poverty, promoting health and economic growth) and ecologically (e.g. conserving nature, combating climate change) (UN, 2015). Thus, sustainable development goes beyond climate change and ecological sustainability. The SDGs are interdependent, which, similar to planetary health (Whitmee et al., 2015), indicates that social goals and ecological goals can not be achieved if regarded separately (Scharlemann et al., 2020; UN, 2015).

Considering the broad context of sustainable development, SuB also goes beyond pro-environmental behavior and refers to all actions intended to protect the planet's socio-physical resources (Corral-Verdugo et al., 2010). Thus, SuB describes both ecological actions to protect the physical environment (ecological sustainability) and social actions (socio-economic sustainability) (Bonnes & Bonaiuto, 2002; Corral-Verdugo et al., 2015).

The relationship between physical activity (PA) and sustainable behavior (SuB)

In this section, PA is conceptualized as a SuB within the SDG framework (UN, 2015) and evidence of PA being related to other SuB types will be described (see *Figure 1*). We will also outline the SDG interdependency with PA based on a SDG interaction framework (Scharlemann et al., 2020).

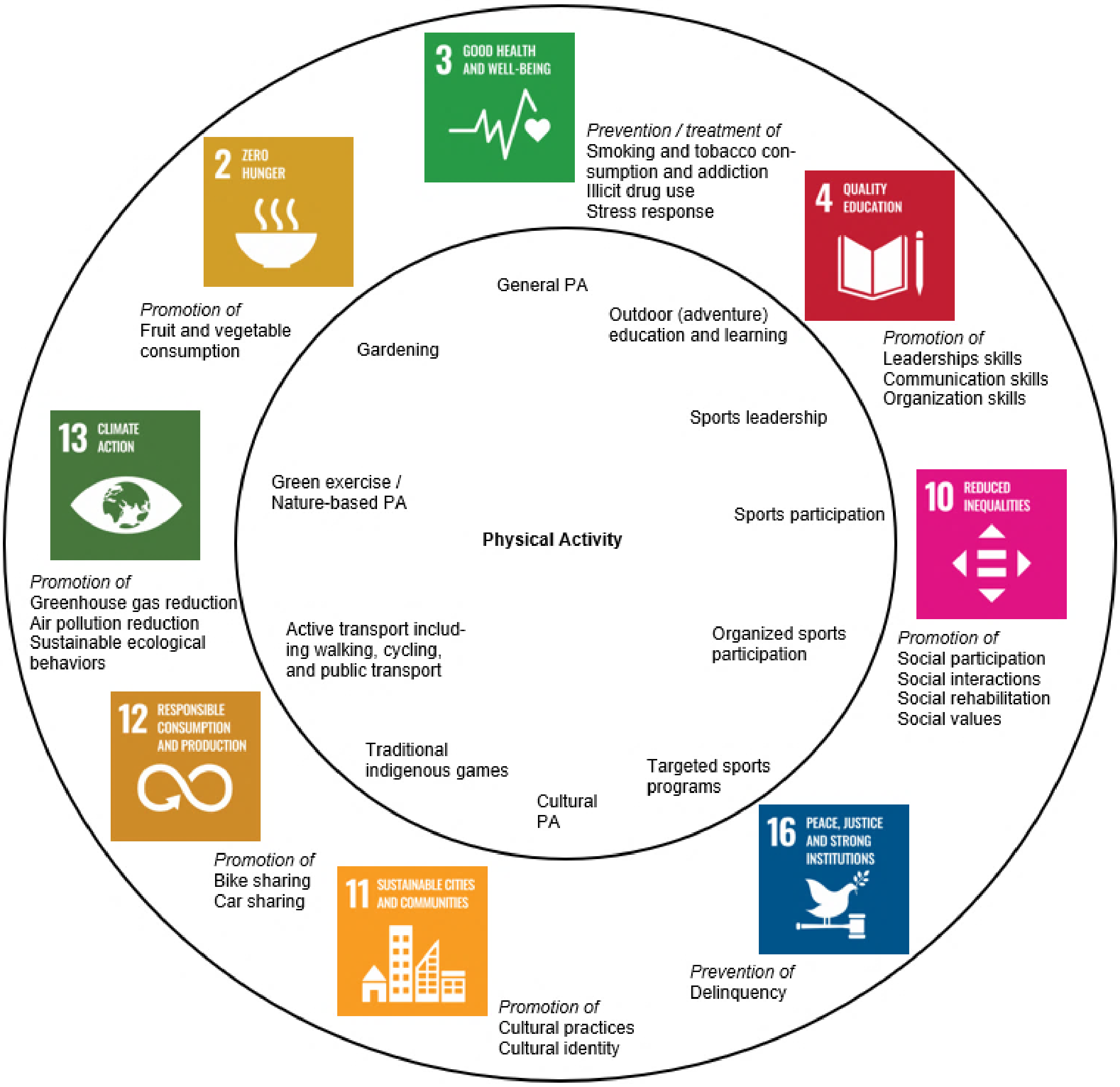
Physical activity, social capital, skills, and cultural sustainability

The UN aim to promote social inclusion and empowerment of all people, irrespective of the individual's characteristics, such as sex or ethnicity (SDG 10). Empowerment means to enable people to access materialistic and non-materialistic resources such as knowledge, skills, social networks, and social capital, with PA having the very real potential to promote social inclusion and empowerment (Lawson, 2005). A key construct is social capital – networks, norms, values, and trust in social organizations resulting from social interactions (Putnam, 1995). Sports participation has been related to social capital, resulting in increased social connectedness (Kay & Bradbury, 2009), civic engagement (Schüttoff et al., 2018), and valuable resources through connecting with the special needs community (Darcy et al., 2014).

Thus, vulnerable people can build resilience and resources, thus having a strong, indirect influence on ending poverty (SDG 1) (Harrison et al., 2019) and improving and maintaining health (Scharlemann et al., 2020; Sun et al., 2009).

PA also promotes life skills relevant for employment and social interactions, contributing to quality education and life-long learning (SDG 4). Life skills describe, amongst others, behavioral skills acquired in PA settings and transferred to non-PA settings (Gould & Carson, 2008). Involvement in organized sports provides opportunities to develop life skills such as leadership, communication, and values (Darcy et al., 2014; Kay & Bradbury, 2009) as do PAs in the outdoor education context through mastering challenging opportunities (Cotterill & Brown, 2018). If life skills can be successfully obtained through PA, it is also expected to positively impact social and economic inclusion (SDG 10), women's participation for leadership (SDG 5), employment, education and training (SDG 8), as well as ending poverty (SDG 1) (Scharlemann et al., 2020).

Figure 1. The relationship between physical activity and with sustainable behavior.



Please note: The SDG icons have been downloaded from the communication materials of the United Nations (UN, n. D.).

Another SDG is to promote peace and to end all forms of violence (SDG 16). PA and sports participation are one way to prevent and decrease delinquent behavior, e.g. through sports programs for juveniles at risk for delinquency (Spruit et al., 2018). In addition, prison-based sports programs promote resettlement, attitudes regarding communication and tolerance, and desistance of future offenses, thus contributing to social rehabilitation and inclusion of former offenders (Meek & Lewis, 2014), which is interrelated with improving social inclusion and empowerment (SDG 10) (Scharlemann et al., 2020).

Beyond promoting inclusive societies, sustainable development also aims to protect cultural heritage (SDG 11). Culture-based PA is a way to connect people and cultural practices that support to maintain a culture, e.g. through improving cultural values and identities, connecting community members, and passing on cultural aspects (Macniven et al., 2019). For some cultures (e.g., youth in Norway), practicing culture is to some extent being physically active (Green et al., 2013). Beyond this, culture-based PA may also contribute to learning skills and cultural appreciation (SDG 4), as well as social inclusion of cultural diversity (SDG 10).

These examples illustrate the tremendous potential of PA and sports participation regarding SuB, promoting social inclusion and empowerment (SDG 10), skill acquisition and lifelong learning (SDG 4), peace (SDG 16), as well cultural identity, practices, and skills (SDG 11), which may indirectly promote gender equality (SDG 5) or ending poverty (SDG 1) (Scharlemann et al., 2020).

Physical activity, greenhouse gases, and air pollution

UNs' SDG 13 refers to climate change mitigation, a most urgent area (IPCC, 2018), which individuals have a large potential to contribute to through active transport. An evaluation of bike sharing program participants in eight US cities showed that participants saved 287-353 g CO_2 per mile travelled, resulting in annual emission reductions of 41 to 5,147 tons of CO_2-equivalents (Kou et al., 2020). Beyond saving emissions, bike sharing programs have the potential to save valuable resources, as private bikes owned by one person are mostly locked when not in use, while a shared bike can be used by many, protecting valuable resources (SDG 12) and contributing to sustainable transport (SDG 11).

In addition, replacing car driving through walking and cycling reduces air pollution. For example, increasing cycling and public transport by 40% would reduce particulate matter (air pollutant resulting from vehicle driving) by 26% in Australia (Xia et al., 2015). Also, an economic analysis showed that each car driven kilometer results in € 0.11 external costs, whereas each cycled kilometer results in a € 0.18 benefit and each walked kilometer in a € 0.37 benefit (Gössling et al., 2019). Thus, active transport contributes to combating climate change, and indirectly may also contribute to protecting and restoring plants and life below the water (SDG 14) and on land (SDG 15) (Scharlemann et al., 2020).

When avoiding car use is impossible, participating in a car sharing program is more sustainable and results in increased PA (Kent, 2014), less private car-ownership, and less cars on the road (Martin et al., 2010), contributing to less resource consumption (SDG 12) and sustainable transport (SDG 11).

Summarized, active transport engagement has tremendous potential to increase PA and SuB simultaneously, contributing not only to combat climate change (SDG 13), but also creating sustainable cities (SDG 11), and saving valuable resources via bike and car sharing (SDG 12), which indirectly may also contribute to protecting and maintain terrestrial and water-based resources (SDGs 14 and 15) (Scharlemann et al., 2020).

Physical activity, sustainable diet, and sustainable agriculture

SDG 2 aims to end all forms of malnutrition by 2030, which includes malnutrition leading to overweight and obesity (WHO, 2018). PA and a healthy diet, especially in combination, contribute to weight loss and maintenance (Katz et al., 2008), with fruit and vegetable consumption being one part of a healthy diet (Epstein et al., 2001). Fruit and vegetable consumption is also recommended to protect planetary resources (Willett et al., 2019), thus contributing to sustainable consumption (SDG 12) and mitigating climate change (SDG 13) (Reynolds et al., 2014; Scharlemann et al., 2020). Looking at multiple health behavior change research, PA is a potential "gateway behavior", which when changed, also positively impacts other health behaviors through transfer mechanisms (Nigg et al., 2009). PA has been positively related to higher fruit and vegetable intake cross-sectionally (Cavadini et al., 2000; Keller et al., 2008; Plotnikoff et al., 2009), while longitudinal and intervention studies showed that increased PA predicted higher fruit and vegetable consumption (Fleig et al., 2011; Maher et al., 2020).

Another goal is to ensure sustainable food production systems that help to maintain ecosystems (SDG 2). Gardening as an individual behavior contributes to this goal (Johnson, 2012), which also allows individuals to comply with the PA guidelines (Park et al., 2008) and which is interrelated with other SuBs and SDGs, including a healthy diet (SDG 2) through home gardening (Berti et al., 2004), as well as skill acquisition (SDG 4) and social involvement (SDG 10) through community gardening (Ohmer et al., 2009).

These examples show that PA can contribute to a sustainable diet (SDG 2), and that engaging in sustainable diet behavior provides opportunities to enhance PA. In addition, looking at the example of gardening, behaviors contributing to a sustainable diet also have the potential for skill acquisition (SDG 4) as well as social inclusion (SDG 10).

Physical activity and health behaviors

SDG 3 aims to promote people's physical and mental health. PA effectively promotes physiological and physical health (Janssen & Leblanc, 2010), psychosocial and mental health (Biddle et al., 2019; Rebar et al., 2015; Wu et al., 2017), as well as reduces chronic disease risk (Lee et al., 2012; Reiner et al., 2013). In addition, PA is related and leads to other health behaviors, such as increased fruit and vegetable consumption (see previous section). PA also leads to a healthier way of coping with stress and more physically active people experience less stress (Mücke et al., 2018). In addition, PA is a means of nicotine addiction and illicit drug use prevention and treatment (Kwan et al., 2014; Zschucke et al., 2012). Good health through PA also contributes to other SDGs, as health is important to reduce vulnerability (SDG 1) and for social inclusion (SDG 10) (Scharlemann et al., 2020).

Physical activity, nature exposure, and sustainable ecological behavior

By 2030, all people should have the awareness to implement a sustainable lifestyle and a life in harmony with nature (SDG 12). PA and sports in nature could be one way to promote ecological SuB, contributing to this goal. PA and sports in nature have been conceptualized as outdoor (adventure) education and learning (Allison, 2016), and PA in natural environments or "green exercise" (Pretty et al., 2003). In these conceptualizations, nature plays a crucial role with PA being a means to experience and interact with the natural physical environment. This exposes people to nature that has been positively related to ecological SuB (Rosa & Collado, 2019), which is likely occurring through improving individual's connectedness to nature (Whitburn et al., 2019). Furthermore, PA in nature actually has additional benefits versus PA in the built environment or indoors, especially for mental health (Lahart et al., 2019; Mnich et al., 2019), thus promoting SDG 12 and improving individual's well-being (SDG 3).

In summary, nature-based PA enhances nature connectedness, which is related to several ecological SuB actions, thus increasing awareness and capability of people to live in harmony with nature (SDG 12).

The unsustainable, “dark” side of physical activity

We need to caution, however, that PA also has the potential to contribute and reinforce socio-cultural and ecological unsustainability. Although sports participation provides a great potential for social inclusion, it may also reinforce social exclusion. For example, discrimination and exclusion are still common for women engaging in socially characterized masculine sports, both at the school (McSharry, 2017) and elite level (Kipnis & Caudwell, 2015). Also, stigmatization for minorities may be reinforced, e.g. through physical education (Fitzgerald & Stride, 2012; Hargie et al., 2017). In addition, sports participation has been related to increased alcohol use and violence (Sønderlund et al., 2014). These examples counteract social inclusion (SDG 10), peace (SDG 16), and gender equality (SDG 5).

PA also has the potential to reinforce existing ecological problems. For example, sports centers and swimming pools require an annual energy consumption of 210-1,750 kWh/m^2 (Boussabaine et al., 1999). PA engagement may raise sports equipment and clothing consumption, increasing the use of ecologically problematic materials (Aall et al., 2011). Regarding PA-related nutrition behavior, it is recommended that 10-35% of the daily calorie intake consists of proteins, with meat being one of the richest protein sources (Bushman & Medicine, 2017). However, ecological protein consumption should only include small amounts of meat (Willett et al., 2019). Thus, sports-related nutrition, clothing and equipment, as well as sports facilities may counteract responsible consumption and production (SDG 12) and indirectly increase greenhouse gas emission, counteracting SDG 13.

Although not exhaustive, these examples demonstrate that PA not only has a tremendous potential as SuB, but also potentially counteracts SuBs and sustainability. Thus, PA and SuB requires an own research agenda that investigates PA as a SuB, unravels conflicts between PA, SuB, and sustainability, and investigates solutions for PA.

Physical activity and sustainable behavior – a field for future research

Considering global ecological and social challenges, and broader health concepts such as planetary health (Whitmee et al., 2015), we strongly recommend expanding the research focus of PA beyond individual and public health to consider effects of PA within planetary health and the SDG framework (UN, 2015). Research about the contribution of PA to sustainable development on a behavioral level is, to our best knowledge, scarce or non-existent. Thus, we present a future research agenda to investigate sustainable PA and to connect PA and SuB (topics displayed in *Table 1*).

Expanding the concept of sustainable PA

Bjørnarå et al. conceptualized sustainable PA, however, they focussed on ecological sustainability (Bjørnarå et al., 2017). Thus, we present an adjusted and expanded definition:

> Sustainable physical activity includes those activities that are conducted with sufficient duration, intensity and frequency for promoting health, yet without excessive expenditure of energy for food, transportation, training facilities or equipment. Sustainable physical activities have low environmental impact and they are […] economically acceptable and accessible. **Sustainable physical activities also promote social inclusion, empowerment, and the maintenance of cultural heritage and practices**.

This adapted definition contains both the ecological and social dimension. The evidence so far indicates that physical activities in daily life are more related to ecological SuB (e.g. decreasing greenhouse gas emissions through active transport), while sports participation is related to social and cultural outcomes (e.g. improving social interactions). This implies that PA is either related to ecological SuB or to social SuB. The challenge is to adapt PA to promote both ecological and social SuB simultaneously or at least that enhancements in one dimension are not detrimental to the other. Further, future research should investigate if sustainable PA has less, the same, or superior health effects versus PA that does not consider sustainability.

Table 1. Future research areas and questions for sustainable physical activity and the connection between physical activity and sustainable behavior.

Topic	Research questions
Expanding sustainable PA	• Which types of PA can be characterized as sustainable? • How can sustainable PA be implemented to promote both socio-cultural and ecological sustainability simultaneously? • How can unsustainable types of PA be adapted to be characterized as sustainable PA? • Do sustainable und unsustainable types of PA differ in their effect on physical and mental health?
Promoting sustainable PA	• What are determinants of sustainable PA? • Are determinants different between sustainable versus unsustainable PA? • How can interventions promote sustainable PA? • How can local sports clubs promote SuB? • What role do professional sports teams/athletes have in promoting sustainable PA?
Measurement of sustainable PA	• Which aspects must be considered for a sustainable PA behavior scale? • Which types of sustainable PA have the strongest direct and indirect impact on sustainable development? • Which types of PA have the strongest direct and indirect impact on other types of SuB? • How can device-based approaches inform sustainable PA?
Multiple behavior change	• Are there transfer or compensation effects on SuB when increasing individual’s PA? • Does engagement in SuB lead to increased PA? • Does individuals’ PA impact SuB that is related to more distal SDGs? • Are there gateway behavior effects of PA to SuB?
Common psychosocial constructs of PA and SuB	• Are there common underlying psychosocial constructs of PA and SuB? • How can common underlying psychosocial constructs be changed? • Are the constructs underlying sustainable PA different from underlying constructs for general PA?
Differentiating state- and trait-variables in psychosocial constructs and contextual factors	• Are there common underlying state variables for PA and SuB? • Are there common contextual factors underlying PA and SuB? • How to trait- and state variables differ regarding PA and SuB? • How to psychosocial variables and contextual factors interact regarding the relationship between PA and SuB?
Time, type, and setting of PA and its impact on SuB	• Which types of PA do promote ecological and / or socio-cultural SuB? • Does nature-based PA enhance ecological SuB? • Is there a does-response relationship between PA and SuB?
Incorporate technology to assess and promote sustainable PA	• How can technology be used to assess SuB objectively? • Can technology contribute to accurate estimates of prevalence rates of PA and SuB across populations and cultures? • How can eHealth/mHealth interventions be created that promote sustainable PA?

Promote sustainable PA

PA guidelines (WHO, 2010) should also consider global challenges and recommend sustainable PA types with low ecological and a high social impact as guidance for PA programs. To promote sustainable PA, local sports organizations are a valuable resource that can contribute to both ecological and social SuB on the behavioral level. Through role modelling and sustainable actions, instructors of sport organizations together with their sports participants and their social support groups can be valuable to promote ecological SuB, whilst promoting social SuB through a mastery climate in the sports organization.

Measurement of sustainable PA

A major challenge is to establish a scale to measure sustainable PA and its impact on SuBs. Specific SuB scales already exist, e.g. for food and clothing purchasing behavior (Fischer et al., 2017). For developing a sustainable PA scale, the process and framework applied by Geiger et al. is recommended (Geiger et al., 2017). To develop behavioral items, they suggest a hierarchical approach that includes sustainability dimensions, theoretical approaches, criteria, indicator, and the concrete single behavior. For sustainable PA, the criteria would consist of the SDGs. Examples for sustainable PA are presented in Table 2.

Table 2: Hierarchical approach to develop items for a sustainable physical activity scale.

Sustainability dimension	*Ecological*	*Social*
Theoretical approach	Planetary boundaries	Empowerment
Criteria	Climate change	Education
Indicator	CO_2	Life skills
Behavioral item	I usually walk or cycle distances up to 5 km.	When I am physically active, I cooperate with others.

Based on Geiger et al. (2017)

The scale should not only consider the PA behavior itself, but also related areas noted in the sustainable PA definition, including PA-related diet, commuting distance, modes of transport to sports and exercise destinations, training facilities, and equipment. Furthermore, the different PA settings such as school, leisure, transport, and work should be considered. When possible items are created, it needs to be identified which PA-related behaviors contribute most to the SDGs. While several scenarios outline the contribution to ecological sustainability (Gössling et al., 2019; Kou et al., 2020), assessing the impact on social sustainability is more challenging, and will require an interdisciplinary approach. Creating a PA-related interaction framework regarding the SDGs may be useful in such efforts. While PA and specific SuBs connections are presented in *Figure 1*, research needs to investigate the magnitude of the influence to those SuBs and SDGs, considering both direct and indirect influences, for example using an influence matrix (Scharlemann et al., 2020).

Going beyond multiple health behavior change to multiple behavior change

Multiple health behavior change research investigates how changes in one health behavior relate to changes in another health behavior. Research should expand beyond health behaviors and include SuBs (e.g. how increased fitness center attendance relates to person's greenhouse gas emissions). In addition, it's worth investigating whether PA or SuB precedes the other to identify intervention points.

Investigating underlying psychological constructs that connect PA and SuB

Several determinants differ for PA and SuB (Klöckner, 2013; Nigg et al., 2012). However, to motivate behavior change that has a positive impact on both PA and SuB, it is necessary to identify common underlying factors and constructs. For example, health consciousness has been related to health behavior, such as regular exercise, a vegetarian lifestyle (Espinosa & Kadić-Maglajlić, 2018; Hoek et al., 2004), and ecological SuB (Shimoda et al., 2019; Ture & Ganesh, 2012). Higher level goals also link different health behaviors (Lippke, 2014), which may also link PA and SuB.

Furthermore, future studies should investigate if the underlying constructs for sustainable PA are unique and differ from unsustainable PA types. For instance, nature-exercisers were motivated through the nature experience and convenience (e.g. starting near home), while gym exercisers through physical health benefits (e.g. reducing body weight) and sociability (e.g. being with friends) (Calogiuri & Elliott, 2017). Another study investigating active transport reported convenience, speed, cost and reliability as motives, while PA was only a side effect (Jones & Ogilvie, 2012).

Differentiating trait and state variables to investigate underlying constructs and contextual factors for sustainable PA and the relationship between PA and SuB

For both PA and SuB, theories based on psychosocial trait factors (such as self-efficacy) explain only about 30% of the behavioral variance, respectively (Klöckner, 2013; Young et al., 2014). Valuable insights could be gained if future studies investigated how psychosocial constructs and contextual factors interact regarding PA and SuB. The physical environment has been related to PA and SuB (Li et al., 2019), but, it is less clear how the environment interacts with psychosocial constructs.

When studying psychosocial constructs, contextual factors, and their relation to PA and SuB momentary states (time-varying characteristics) and trait variables (time-invariant characteristics) should be distinguished (Cushing et al., 2018). For example, when investigating how living in rural or urban areas is related to PA and SuB, it is reasonable to operationalize the residential place as trait variable as this usually does not have a high fluctuation. However, when investigating how the current environment (e.g. being in busy street, in a forest) impacts subsequent PA or SuB, it should be operationalized as a state variable as geolocations of individuals vary frequently. This allows to investigate dynamic relationships between behavior, context, and psychosocial constructs, and to gain an understanding of unconscious processes which possibly are more important for behavioral decisions than trait-related psychosocial constructs (Marteau et al., 2012; Whitmee et al., 2015).

Investigate time, type, and setting of PA and its impact on SuB

Not all PA contributes to SuB, but may even counteract sustainability. Thus, future studies investigating the relationship between PA and SuB should clearly specify the type and setting of PA and outcome of interest. For example, when investigating the contribution of PA to individuals' social connectedness, it could be helpful to investigate PA in organized settings such as sports clubs, or informal groups like impromptu basketball at a neighborhood park. In addition, even if targeting one specific social SuB like in the example, the ecological dimension should always be part of the assessment to account for any detrimental ecological effects, such as increased car driving. This also applies when targeting ecological SuB – the social dimension should always be part of the assessment to account for any detrimental social effects, e. g. exclusion of minorities.

Examining nature-based PA, which includes outdoor adventure education programs and green exercise, is a promising research avenue. For example, in children and adolescents, greening of a school playground increased PA and reduced antisocial interactions (Raney et al., 2019), but no studies investigating effects on ecological SuB were found.

Incorporate technology to assess and promote sustainable PA

As self-reported data is prone to bias (Wanner et al., 2017), big data and wearables could be one solution to obtain device-based data on PA and SuB. For instance, when investigating active modes of transport, smartphone geolocation tracking allows to investigate individual's movement trajectories together with time, distance, and setting (Reichert et al., 2019). Beyond assessment, future research should also explore ways how sustainable PA can be promoted through eHealth and mHealth interventions. For example, one mHealth healthy eating intervention successfully promoted both healthy eating and regional grocery shopping through featuring food products and discounts in local grocery stores (Gilliland et al., 2015). Such interventions based on everyday technology might be also applied to promote sustainable PA.

Conclusion

Global ecological and social challenges require interdisciplinary solutions. Health sciences, behavioral medicine, and exercise science should expand their research to investigate PA in the SDGs and planetary health contexts. This means to acknowledge that behavior, health, social, and ecological aspects are intertwined and that changes in one construct impact the other constructs. Thus, it is necessary to identify and promote sustainable PA that has a low environmental impact while promoting social inclusion, empowerment, and cultural heritage. Although there is currently a strong focus on the ecological dimension of sustainability, the impact of PA on the social dimension needs to be incorporated as sustainable development is more than combating climate change and ecological problems. In this way, PA can be more than "just" a health behavior of an individual, but a behavior that allows each person to contribute to planetary health and sustainable development.

Author contributions

CN: Conceptualization, Methodology, Writing – Original Draft; **CRN**: Conceptualization, Writing – Review & Editing

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CHAPTER 10

General discussion

10.1 Main findings

The environment is considered a crucial determinant of physical activity and health (Hartig et al., 2014; Sallis & Owen, 2015; UNICEF, 2022; WHO, 2012, 2015, 2016, 2019, 2023). Over the last two decades, research has intensified to understand the role of the built environment and green space on physical activity and health as well as potential co-benefits regarding a healthy and sustainable development in the light of increasing urbanization and climate change (Bratman et al., 2019; Cerin et al., 2022; Frumkin et al., 2017; Giles-Corti, Moudon, Lowe, Adlakha, et al., 2022; Giles-Corti, Moudon, Lowe, Cerin, et al., 2022; Romanello et al., 2022; Romanello et al., 2021; UN, 2018). However, research gaps existed regarding (A) child and adolescent physical activity prevalence and trends across urban and rural areas during and beyond Covid-19; (B) the conceptualization and importance of natural environments for physical activity and health across urban and rural areas during and beyond Covid-19, (C) child and adolescent health benefits of nature-based physical activity, and (D) physical activity's potential to serve as and lead to individual-level behaviors that contribute to the sustainable development goals.

This dissertation addressed these research gaps in eight articles, showing that:

a) Children and adolescents in **rural areas** show *detrimental trends* in physical activity across the last two decades and engage in *less MVPA*. In contrast, children and adolescent in **cities** show *no decline* in physical activity across the last two decades and engage in *more MVPA* than their rural counterparts (Nigg, Weber, et al., 2022; Reichert et al., under review).
(Research gap A)

b) During **Covid-19**, the *physical activity increase* of Germany's child and adolescent population was predominantly due to enhanced physical activity engagement of children and adolescents living in *less densely populated areas* (Nigg, Oriwol, et al., 2021).
(Research gap A)

c) **Green space** has the potential to *enhance physical activity* for child and adolescent *sub-groups living in cities*. In contrast, in *rural areas*, green space is related to *less physical activity*. The choice of the geospatial and conceptual configuration should be carefully considered when operationalizing green space and the natural environment via geographic information systems (Nigg et al., under review; Nigg, Niessner, et al., 2022).
(Research gap B)

d) During **Covid-19**, *natural environments* had the potential to *mitigate* the negative impact of the pandemic on *mental health* and *physical activity*. At the same time, there remain several large research gaps regarding the health-(behavior)-enhancing potential of natural environments which would be important to explore for specific practical implications. This includes more research on children and adolescents beyond physical activity (Nigg et al., 2023).
(Research gap B)

e) **Nature-based physical activity** does mostly not show enhanced health effects for children and adolescents compared to non-nature based physical activity based upon current evidence. Few studies and weak study quality do not allow robust conclusions (Mnich et al., 2019).
(Research gap C**)**

f) Physical activity can be conceptualized as an **individual-level sustainable behavior** that has the potential to *lead to other individual-level behaviors* that *contribute* to various United Nation's social and ecological *sustainable development goals* (Nigg & Nigg, 2021).
(Research gap D**)**

10.2 The findings in the context of previous results and theoretical considerations

Regarding **urbanicity and physical activity**, results are partially comparable with previous findings. *Declining physical activity trends* in rural areas are comparable to one of the few studies investigating children's physical activity trends across urban and rural areas, and which also found that children in rural areas showed the strongest physical activity decrease (Corder et al., 2015). Findings are also in line with adult physical activity trends across the European Union, showing stronger declines in rural areas (Moreno-Llamas et al., 2021). The trend findings of this dissertation also translated to *lower accelerometer-assessed MVPA* of children and adolescents in *rural areas* compared to cities. Here, the picture is less clear regarding when comparing these results to other studies with accelerometer-assessed MVPA: Moore et al. (2013) also found that urban youth in the US engage in more MVPA than rural youth, whereas a study in Scotland reported no MVPA differences between urban and rural youth (McCrorie et al., 2020). In contrast, studies in Portugal (Machado-Rodrigues et al., 2014) and the US (Moore et al., 2014) found that that rural girls showed enhanced MVPA compared to urban girls.

Summarized, the results from this dissertation regarding declining physical activity trends in rural areas support previous findings and seem to apply across age groups, which may reflect the detrimentally changing infrastructure in Germany's rural areas for physical activity based upon socio-ecological models (Federal Ministry of Food and Agriculture, 2020; Sallis & Owen, 2015). However, when measuring urban-rural physical activity differences with accelerometers, findings are heterogenous and may depend on the specific study site and sample characteristics, such as gender, indicating a more complex relationship. During the Covid-19 pandemic, rural areas may have benefited from characteristics that are usually considered detrimental for physical activity, such as lower density (Cerin et al., 2022), but that may have provided an opportunity for safe physical activity and outdoor play while adhering to physical distancing measures.

Regarding associations between **green space, physical activity, and health**, this dissertation found that associations between natural environments and children's and adolescent's MVPA, physical fitness, and mental health depend on the *geospatial and conceptual configuration*, i.e., the chosen buffer type, buffer size, and nature definition. These heterogenous findings are in line with previous identified methodological issues in predominantly adult studies (Browning & Lee, 2017; Davis et al., 2021; Klompmaker et al., 2018). This dissertation extends previous findings by showing that the variability in the nature-health association based upon different buffer sizes and types is also observed in children and adolescents, and takes it one step further by employing different GIS-based nature operationalizations and showing the variability also across socio-demographic sub-groups. These heterogeneity depending on the geospatial configuration has been previously addressed with the modifiable aerial unit problem (MAUP), referring to the outcome of interest being dependent on the (arbitrary) choice of the spatial unit (Clark & Scott, 2014; Jelinski & Wu, 1996). In addition, it is unclear if the spatial area used for the study also represents the geographically relevant context for the participant, also known as the uncertain geographic context problem, with previous studies showing that the immediate neighborhood is not necessarily the relevant one for physical activity and health (Basta et al., 2010; Kwan, 2012; Schipperijn et al., 2010).

When investigating *green space and MVPA across urban and rural areas*, this study showed that boys and younger children living in cities show enhanced physical activity levels across in the second compared to the first (lowest) green quartile. In contrast, children and adolescents with more green space in rural areas showed lower levels of physical activity. However, in cities, green space was detrimental for children's and adolescent's physical activity with a low socio-economic status. These results contradict previous findings, indicating that green space was associated with more MVPA in rural areas on one study site, but not on the other, while no or negative associations were observed in urban areas (Markevych et al., 2016). The favorable green space-MVPA associations for city boys are conceptually supported by previous findings showing that boys spend in general more time outdoors and engage in more independent mobility than girls (Klinker, Schipperijn, Kerr, et al., 2014; Stone et al., 2014). Hence, boys may be more exposed to the potential affordances of green space (Araújo et al., 2019; Gibson, 1979; Heft, 1988, 1989, 2010), which may translate to differently actualized affordances in urban and rural areas. During *Covid-19*, natural environments showed the potential to promote physical activity and mental health during stressful events. However, children and adolescent received in comparison to adults little research interest in relation to natural environments, especially not beyond physical activity and play.

In summary, results of this dissertation are in line with previous studies indicating the importance of a considerate choice regarding the geospatial and conceptual configuration of the natural environment when investigating green space in relation to health. In addition, the relevant activity space may be different for sub-groups in population-based studies, making a one-size-fits all approach difficult. Considering associations between green space and physical activity across urban and rural areas in the context of previous findings is difficult due to a lack of research in child and adolescent populations. However, the results of this dissertation indicate that green space in cities showed both beneficial and detrimental associations across sub-populations, which supports Hartig's model of nature and health, which specifies that associations are modified by socio-demographic characteristics (Hartig et al., 2014). The Covid-19 pandemic provided a natural experiment opportunity to investigate the natural environments as a resource during a public health crisis, with positive implications, but very little research focused on children and adolescents.

Regarding associations between **nature-based physical activity** and children's and adolescent's health parameters, the amount, heterogeneity, and quality of the evidence do not allow reliable or robust conclusions. Currently, based upon the evidence synthesis in this dissertation, there is very little evidence of enhanced health effects of nature-based physical activity compared to non-nature based physical activity in children and adolescents. This contrasts findings in adults, where nature-based physical activity showed positive effects on mental health outcomes, including improved affective states, reduced anxiety and depression, as well a reduced stress-related brain activities (Coventry et al., 2021; Lahart et al., 2019; Sudimac et al., 2022; Thompson Coon et al., 2011; Wicks et al., 2022).

Regarding the potential of **physical activity as a sustainable behavior**, the presented approach complements previous conceptualizations regarding physical activity as a behavior that contributes to sustainable development on the structural level (Bernard et al., 2021; Salvo et al., 2021; WHO, 2018). The concept presented in this dissertation focuses on physical activity as an individual-level sustainable behavior that has the potential to foster other individual-level behaviors that contribute to the sustainable development goals on an individual level, therewith intertwining political and structural approaches (IPCC, 2018; Whitmee et al., 2015; WHO, 2018) and empowering individuals to contribute to a sustainable development through a bottom-up approach. In multiple health behavior change, the compensatory carry-over action model assumes that engagement and changes in one health behavior also change other health behaviors through carry-over mechanisms and compensatory cognitions driven by higher-level goals (Lippke, 2014). The adopted health behavior leading to engagement in another health behavior is also called “gateway behavior” (Nigg et al., 2009), e.g., eating more fruit and vegetables leading to eating less unhealthy snacks (Nigg, Amrein, et al., 2021). In the climate change context, behaviors that benefit both human and environmental health have been conceptualized as behaviors with co-benefits (Paul et al., 2016). While in the context of the compensatory carry-over action model, it is assumed that behaviors are driven by higher-level goals (e.g., staying healthy; Lippke, 2014), the concept of co-benefits emphasizes the opportunity that a person must be only convinced in one area (e.g., engaging in active transport due to the importance of physical activity) to engage in a relevant behavior, even though the co-benefit may not be deemed relevant (e.g., believing that climate change does not exist; Paul et al., 2016). Combining these two approaches – common cognitions and goals as well as behavior-specific cognitions and goals – may provide a chance to intervene upon physical activity as a gateway behavior to other sustainable behaviors, with this potential to be further investigated in the future.

10.3 Methodological considerations and critical appraisal of this dissertation

This multi-method dissertation applied different research designs, which were selected based upon their suitability to answer the research question as well as upon available resources. The decisions for these methods will be elaborated on in the following together with a critical appraisal.

To answer the research questions relating to children’s and adolescent’s physical activity and health in Germany, **original quantitative research grounded in empirical observations** was deemed as an appropriate method, with the MoMo Study being a nationwide study recruiting a representative sample of children and adolescents from kindergarten age to adolescence and collecting data with regards to physical activity, physical fitness, and health (Woll et al., 2021). This provided a unique opportunity to investigate urbanicity and green space in relation to physical activity and health using empirical observations. The nationwide recruitment of participants of the MoMo Study allows to generalize results across Germany’s child and adolescent population and to derive nationwide practical and policy implications. This is especially relevant for the analysis of physical activity trends across urban and rural areas using repeated cross-sectional, weighted data to ensure representativeness. During the MoMo Study 2018-2022, it was for the first time possible to obtain participant’s address data, therewith enabling the objective GIS-based assessment of the physical environment, in particular green space, for the study population.

While the MoMo Study provides a unique opportunity to investigate the environment in relation to children’s and adolescent’s physical activity and health, there are some **limitations** that should be considered. Most empirical studies were based upon cross-sectional data from one time point, which does not allow causal inference. While urbanicity was operationalized using common measures (e.g., the European Degree of Urbanization; eurostat)) and green space through intertwining conceptual and geospatial configurations based upon current urban planning models (Allam et al., 2022; Millward et al., 2013) and considerations regarding comparability with other studies (Cain et al., 2021; Nordbø et al., 2020), it is uncertain if the relevant spatial context for participant’s physical activity was captured (Kwan, 2012). This also implies that this work could only consider green space as potential, but not actualized affordance for physical activity (Gibson, 1979; Heft, 2010). In addition, this work focused on the assessment of green space quantity (i.e., green space percentage within a certain buffer), but neglected green space type and quality aspects, which may also play a role in the green space, physical activity, and health association (Edwards et al., 2015; Hunter et al., 2019). Furthermore, from a theoretical perspective, environmental correlates should be behavior-specific (e.g., active travel, leisure-time physical activity; Sallis & Owen, 2015) and have also been shown to differ across physical activity domains (Findholt et al., 2011; Hennessy et al., 2010; Oreskovic et al., 2014). While this work was able to distinguish physical activity domains based upon self-report data for investigations regarding physical activity trends in urban and rural areas, accelerometer data for the cross-sectional studies was only available for MVPA without domain specification.

Regarding the potential of nature-based physical activity for children's and adolescent's health, a **systemic review approach** was chosen. This decision was due to the available literature having been synthesized in systematic literature reviews for adults (Lahart et al., 2019; Thompson Coon et al., 2011), while there was no synthesis on this topic for children and adolescents. An empirical investigation with the MoMo Study was not possible since to date, no data has been collected that would allow conclusions about children and adolescent's physical activity in natural environments. The critical appraisal follows in the next paragraph.

A **scoping review** in combination with a **thematic analysis** was employed to synthesize the research regarding nature types, health outcomes, and health behaviors investigated in the Covid-19 context and to identify recurring themes. The decision for this approach was chosen since at the time of starting this study, there were no other reviews found that had synthesized the research on this topic in the pandemic context. Scoping reviews have the objective of comprehensively examining key concepts, types of evidence, and research gaps within a particular field of study through a systematic search and synthesis of knowledge (Colquhoun et al., 2014). One key characteristic that sets scoping reviews apart from systematic reviews is their ability to apply a broader scope (Munn et al., 2018), enabling researchers to be more inclusive of various methodological study approaches. Since the main goal was to systematically synthesize and map the available evidence regarding natural environments, psychological and social health, and health behaviors in the context of the Covid-19 pandemic, considering academic research across diverse nature types, populations, and outcomes, inclusiveness was of particular importance. In contrast, systematic reviews typically involve certain restrictions, such as focusing on specific study designs (Sucharew, 2019), and prioritize the assessment of the significance or effectiveness of treatments to derive practical implications (Munn et al., 2018). Hence, the strength of this work is that it provides a comprehensive and inclusive overview and evidence map of the research regarding nature types, health outcomes, and health behaviors investigated during the global Covid-19 public health crisis, providing insights into research gaps and opportunities.

The strength of both reviews was that they were pre-registered; the systematic review in the review database PROSPERO and the scoping review on the Open Science Framework since scoping reviews cannot be registered on PROSEPRO. Both reviews were conducted using a comprehensive and systematic approach, with the systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA; Moher et al., 2009) for evidence synthesis and quality assessment, and the scoping review following the extended PRISMA statement for scoping reviews (Tricco et al., 2018) together with the established five-step scoping review framework introduced by Arksey and O'Malley (2005).

However, there are some **limitations** that should be considered for both the **systematic and scoping review**. Inherent to a scoping review, there was no critical appraisal of the evidence, limiting practical guidance and recommendations regarding the effectiveness of natural environments for psychosocial health and health behaviors in the pandemic context (Munn et al., 2018). For both reviews, the screening was conducted based upon title only first due to the available resources, which may have led to eligible studies being overlooked. However, records based upon title were only excluded if it was most likely that the record was irrelevant for the review topic. If the title did not provide enough information to make a decision, it was included for abstract screening. In addition, in both reviews, inclusion was limited to peer-reviewed literature. Considering grey literature may have broadened the scope and provided a more balanced evidence perspective regarding null and negative findings (Mahood et al., 2014). While the systematic review focused only on publications available in English, the scoping review considered publications in German, English, or Scandinavian language based upon the authors' language skills. The consideration of articles limited to the authors' language skills may have reinforced the already existing research bias with a focus on high-income western countries regarding human-environment interactions, neglecting potential research in non-western cultural contexts (Milfont & Schultz, 2016; Tam & Milfont, 2020).

Finally, this work included a **conceptual** article regarding physical activity as a sustainable behavior. The strength of this work is that it complements previous approaches focusing on physical activity and sustainable development on a structural level (WHO, 2018) with an individual-level perspective, drawing upon associations between physical activity and behaviors relevant for the sustainable development goals. However, so far, this is **limited** to a conceptualization with no empirical data.

10.4 Implications for future research

This dissertation sheds light on some important issues regarding urbanicity, green space, and children's and adolescent's physical activity and health. In the following, for the three major themes of the dissertation, opportunities that may be interesting to look at for future research are discussed. A summary of the research recommendations is provided in *Table 1*.

Table 1. Summary of recommendations for future research

Research area	Research recommendations
Urban-rural areas and children's and adolescent's physical activity	• Investigate physical activity-facilitating environmental characteristics across urban and rural areas to guide the creation of active environments in both settings. For those investigations, apply a framework that facilitates both country-specific guidance and conclusions as well as international comparison. • Use device-based assessment methods (GPS, GIS, and accelerometers) to determine relevant physical activity domains and locations across urban and rural areas • Develop and evaluate physical activity promotion programs specifically tailored to children and adolescents living in rural areas • Monitor children's and adolescent's physical activity across urban and rural areas at a minimum of every five years
Green space and children's and adolescent's physical activity	• Reach consensus regarding the geospatial assessment of green space in physical activity and health studies • Use device-based assessment methods (GPS, GIS, and accelerometers) to determine relevant activity spaces and investigate associations between green space and domain-specific physical activity of children and adolescents • Evaluate existing green space recommendations regarding their impact on children's and adolescent's physical activity and/or determine threshold values for green space to facilitate physical activity • Identify green space characteristics that can afford children's and adolescent's physical activity and health using qualitative and participatory research methods • Evaluate the impact of green space changes on children's and adolescent's physical activity and health as part of natural experiment and quasi-experimental studies or conduct health impact assessments to allow for more rigorous conclusions
Nature-based physical activity and health effects on children and adolescents	• Use theories to define the outcomes for rigorously designed and implemented randomized controlled trials to investigate the health benefits of nature-based physical activity in children and adolescents • Use ambulatory assessment methods (GPS, GIS, accelerometers, and e-diaries) to investigate momentary health effects of nature-based physical activity in real-world settings • Include adolescents in clinical populations in trials

Future research area 1
What are environmental factors and physical activity domain differences driving urban-rural physical activity differences?

Although the prediction is that by 2050, 84% of Germany's population will be living in urban areas (UN, 2018), this means that 16% of Germany's population, equaling about 13 million people based upon current population levels, will still be living in rural areas. To support health equity efforts, it crucial to understand **physical activity-facilitating environmental characteristics in urban and rural areas** to create active environments in both settings. However, to date, it is not well understood which environmental characteristics are similar across settings and which ones differ. For example, for children in Greece, in both urban and rural areas, neighborhood personal safety was associated with more physical activity, while play opportunities were unrelated. However, road safety concerns were related to more physical activity in urban, but less physical activity in rural children (Salmon et al., 2013). This pattern of common and distinct associations for urban and rural settings was also found in a study with US adolescents (Moore et al., 2013). A study with children and adolescents in Spain showed that both macro-scale environment (e.g., intersection density, residential density) and micro-scale environment (e.g., number of traffic lanes, aesthetics) walkability characteristics showed distinct associations with active school commuting between urban and rural youth (Molina-García et al., 2020). In a study on children's physical activity barriers in Canada, compared to urban areas, personal safety and traffic worries were less likely to be reported as barriers in rural areas, whereas distance to destinations and lack of walking infrastructure were more likely to be reported as barriers in rural areas (Taylor et al., 2018). These examples show that it is necessary to enhance our understanding about environmental correlates of physical activity in Germany's urban and rural areas to provide urban-rural specific guidance for interventions and policies to create active environments.

To investigate these correlates, it would be useful to **apply a framework as foundation and adapt it to the specifics of urban and rural settings**. That would allow to derive country-specific recommendations, but also to use the findings for international comparisons to support investigations regarding generalizability across geographic locations and culture. Such a framework could be the "11-D" framework that was published as part of the *Lancet Urban Design, Transport, and Health series*, specifying transport planning and design intervention features that are assumed to enhance physical activity as well as health and well-being (Giles-Corti, Moudon, Lowe, Cerin, et al., 2022; Giles-Corti et al., 2016). Although this framework was not specifically developed for children and adolescents, relevant environmental features for children and adolescents can be incorporated (see *Table 2*). Also, this framework focuses urban areas. While some features are also relevant in rural areas (e.g., destination proximity; Molina-García et al., 2020), it should be acknowledged that it may be sensible to conceptualize some indicators differently in rural compared to urban settings. This includes, for example, walkability (Molina-García et al., 2020), or public transport (Nobis & Kuhnimhof, 2018). Taking the latter one as an example how to change it setting-specific, instead of assessing access to high-frequency public transport – something that is rare in Germany's rural areas (Nobis & Kuhnimhof, 2018) – one option could be to replace or additionally assess if the available public transport is tailored to support access to destinations for daily living, e.g., extra bus services for schools. Hence, applying the 11D framework to rural areas, exploring in how much the associations are generalizable across urban and rural settings, and adapting associations setting-specific where needed, would be useful to provide an evidence-based model for both urban and rural community planning. Combining use of this framework with openly accessible geospatial data to investigate environmental correlates would further facilitate international comparison and data harmonization (Boeing et al., 2022).

Table 2. Urban transport planning and design characteristics to create active environments for healthy and sustainable development.

Category	Features	Examples applicable to children and adolescents
Destination proximity	Distance to local destinations	*Proximity to school, sports clubs, parks, playgrounds*
Distance to public transport	Short walking distance to public transport opportunities (e.g., bus, tram) from home	*Distance to nearest train station*
Destination accessibility	Conveniently accessible, high-quality, and age-appropriate locations and destinations	*Shopping center fitting the needs of adolescents; no- or low-cost recreational facilities; playground or park safety*
Demand management	Parking supply and pricing policies enhancing attractiveness of active transport and public transportation use while decreasing attractiveness of motorized vehicle use (e.g., cars)	*Prohibited car parking in front of schools; provision of bicycle racks*
Diversity	Mix of recreational and commercial areas and buildings with residential dwellings	*Land use mix combining relevant locations; e.g., residential housing, schools, playgrounds etc.*
Density	Density sufficient to support frequent, accessible public transport and maintenance of local businesses	*Number of multi- and single housing units within a certain area*
Design	Street-networks facilitate proximate and connected destinations for daily living and home; lot layouts are designed to increase residential density, public open space, safe walking and cycling and surveillance, while reducing traffic exposure	*Street connectivity; few cul-de-sacs; walking paths; separate cycling lanes*
Desirability	Comfortable, convenient, and safe neighborhood design with safe, accessible, and attractive public transport	*Crime safety, traffic safety, neighborhood aesthetics*
Distribution of employment	Adequate employment mix	*Appropriate job-housing balance*
Disaster mitigation	Mitigation and adaptation measures to adapt to the consequences of climate change	*Green infrastructure, such as tree canopies and shade*
Distribution of interventions and resources	Features and policies that prevent gentrification and facilitate promote equal access to health-enhancing environments	*Affordable housing*

Adapted from Giles-Corti, Moudon, Lowe, Cerin, et al., 2022; Giles-Corti et al., 2016

Different environmental correlates of children's and adolescent's physical activity may also reflect in **differing physical activity locations and domains across urban and rural areas**. For example, previous work in New Zealand and Canada showed that compared to rural areas, adolescents in urban areas accumulated more MVPA minutes through engagement in active transport (Rainham et al., 2012; White et al., 2021), while physical activity in school was an important contributor to MVPA for both urban and rural adolescents, but less important for sub-urban adolescents (Rainham et al., 2012). Understanding which locations and domains are important for children's and adolescent's daily physical activity across geographical contexts is important to develop effective physical activity interventions. While one article of this dissertation investigated self-reported physical activity domains (Nigg, Weber, et al., 2022), future research would benefit from complementing this self-reported data with device-based assessments. In particular, combining accelerometers for device-based physical activity assessment with global positioning systems (GPS) and geographic information systems (GIS) provides a valuable opportunity to assess absolutive and relative time in physical activity intensities for specific locations and domains without the bias inherent to self-reported physical activity (Jankowska et al., 2015). For example, in a study with city children and adolescents in Copenhagen combining GPS, GIS, and accelerometers, both girls and boys as well as children and adolescents spent the highest proportion in MVPA during active transport, while the proportion of MVPA during school and leisure-time was lower, and the lowest proportion of MVPA was observed at home (Klinker, Schipperijn, Christian, et al., 2014). Employing this approach in a population-based study, such as the successor project of MoMo (MoMo 2.0), would provide a valuable opportunity to not only generate knowledge specific to physical activity promotion of Germany's child and adolescent population, but also to extend our understanding of physical activity locations and domains that have been focused on urban areas and cities (Cain et al., 2021; Klinker, Schipperijn, Christian, et al., 2014) to children and adolescents in rural communities.

Based upon environmental and other factors responsible for differing physical activity levels in urban and rural areas, it is necessary to **identify how physical activity of children and adolescents living in rural areas can be promoted**. This dissertation showed that physical activity developed similarly across urban and rural areas in the school settings in Germany. Theoretically, schools have a large potential for physical activity promotion in both urban and rural areas (Heath et al., 2012; Hills et al., 2015; Pate et al., 2006) since neighborhood environmental barriers to physical activity, such as a lack of recreational facilities or long distances to destinations are typical barriers in rural communities (Taylor et al., 2018), are less relevant in the school setting. However, school-based physical activity interventions have not been shown effective to enhance in MVPA in children and adolescents (Neil-Sztramko et al., 2021), and when stratified by urban-rural status, there was a marginal effect for urban and sub-urban schools, but not for schools in rural settings (Pfledderer et al., 2021). While schools may be one promising setting, other strategies specific to the rural setting should be employed and evaluated. For example, e- and mHealth physical interventions (Van Sluijs et al., 2021) or sports programs delivered remotely using digital media (Mutz et al., 2021) could be one option to be further explored in the rural setting to tackle physical inactivity. Since there is currently little knowledge regarding effective physical activity interventions tailored to children and adolescents in rural areas in Europe (Bhuiyan et al., 2019; Pelletier et al., 2020; Walsh et al., 2017), developing, implementing, and evaluating such approaches would be useful to create an evidence-based "intervention menu" that could be employed by practitioners in rural settings. However, following an socio-ecological model approach (Sallis & Owen, 2015), approaches are expected to be most effective when physical activity is targeted across multiple settings and domains, for example, integrating active breaks throughout the school day (Wilson et al., 2017) while offering age- and gender-appropriate physical activity and sports programs at the community level for children, adolescents, and their families.

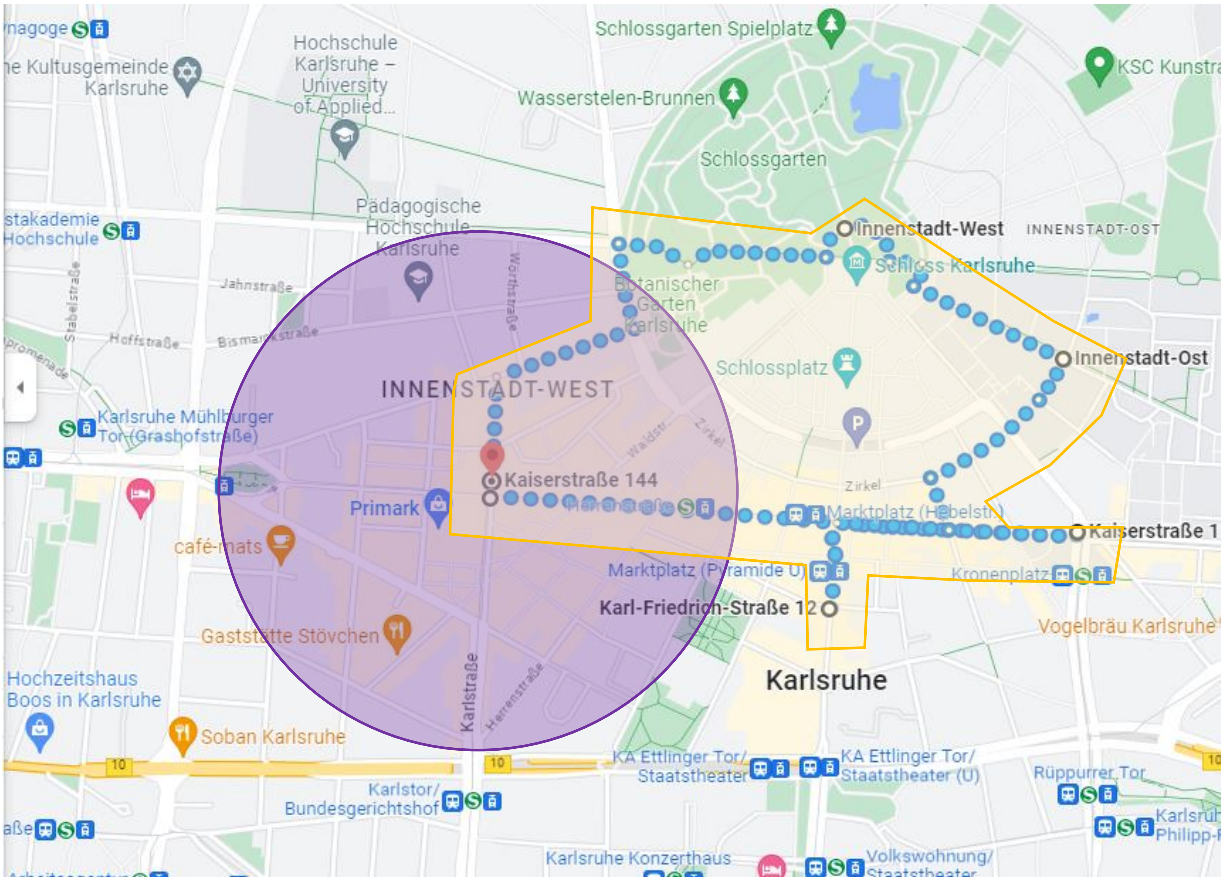
Finally, children's and adolescent's **physical activity trends and prevalence across urban and rural areas should be further carefully monitored in future studies**. The Covid-19 pandemic has reinforced sub-urbanization trends in Germany that have already started prior to the pandemic (Rink et al., 2021). In this context, Germany's future institute is also referring to "rurbanization" – areas with rural structures are experiencing urbanized characteristics, large cities are experiencing structures similar to rural areas (Horx, 2022; Zukunftsinstitut, 2021). Concepts such as the 15-minute city (Allam et al., 2022; Millward et al., 2013) and superblocks (Mueller et al., 2020), constituting person-centered approaches to (urban) planning, are more and more implemented, resolving the urban-rural dichotomy. However, in both urban-rural studies in this dissertation (Nigg, Weber, et al., 2022; Reichert et al., under review), clear physical activity trends were only observed for the extremes – large cities or highly densely populated areas and rural communities or very sparsely populated areas. Trends for small towns and medium-sized towns were less clear. Hence, with structural changes occurring along the urban-rural continuum in Germany, it is necessary to monitor how physical activity develops with these changes, with repeated cross-sectional assessments at a minimum of every five years (Van Sluijs et al., 2021).

Future research area 2
How can natural environments and green space be assessed and designed to facilitate children's and adolescent's physical activity and health?

So far, there have been large variations regarding the operationalization of GIS-assessed natural environments and green space based upon residential locations, including varying buffer types, buffer sizes, and green space definitions (Nordbø et al., 2018). This greatly limits a sensible synthesis of available research due to methodological limitations, such as the modifiable aerial unit problem (MAUP; Kwan, 2012), as well as clear recommendations for (urban) planners and policy makers regarding green space planning. Hence, **finding consensus regarding green space assessment in terms of operationalization, scale, and zone for physical activity and health-related outcomes** would benefit both future research studies as well as practitioners. Since a one-size-fits all approach is not deemed appropriate due to different conceptual considerations linking green space and various health-behaviors or health-related outcomes (Nigg, Niessner, et al., 2022), defining potential green space assessments for specific behaviors, such as physical activity, and specific health outcomes, such as mental health, would be more suitable. One potential approach is to use, if existent, leading international studies across cultural contexts as an orientation for future research. For example, for physical activity, the 15-country International Physical Activity Environment Network (IPEN) Adolescent study has specified street-network buffers for 500m and 1000m for all environment variables, together with a description and calculation for each GIS construct, which includes parks as a measure of green space (Cain et al., 2021). In absence of large international studies that can provide guidance, conceptual considerations, such as the 15-minute city (Allam et al., 2022; Millward et al., 2013), may be considered to decide for a useful measure. Another potential approach would be more data-driven: In a study on green space and mood in everyday life, the authors analyzed the median visibility radius to determine the spatially relevant area and based their buffer decision upon that (Tost et al., 2019).

While such a consensus would be useful to address the modifiable aerial unit problem, this does not help to resolve the issues that we cannot be sure that the defined spatial (proximate) area is actually relevant for the study participants (Basta et al., 2010; Christensen et al., 2022; Kwan, 2012; Schipperijn et al., 2010). To overcome this limitation, an approach already mentioned before is to **use GPS to determine one's actual activity space** (Jankowska et al., 2015), which, to date, has been applied little compared to single-point buffers in physical activity research (Rinne et al., 2022). Activity spaces are defined through time (duration and frequency) and space (locations) that individuals are in contact with as part of their daily routines (Golledge, 1997; Perchoux et al., 2013). Hence, instead of applying a fixed buffer that is likely irrelevant for some individuals, the buffer would be adopted based upon one's actual activity space. As exemplified in *Figure 1*, this would result in a rather different spatial area considered compared to a fixed circular buffer, allowing to identify the spatial area that the participant is actually exposed to. However, it has been criticized that such approaches introduce selective daily mobility bias and lead to spurious findings (Chaix et al., 2013; Plue et al., 2020) due individuals purposefully seeking out places for their activities, making it challenging to disentangle a the influence of a person's intentions and decisions from the influence of the environment. For example, according to Chaix et al. (2013), if a person actively chooses a park for exercise, it would not be the environment promoting physical activity, but the personal choice. Hence, they suggest truncating activity spaces to control for this bias, i.e., removing places actively chosen if they relate to the outcome (e.g., the park for physical activity). However, Plue et al. 2020 criticized this approach since this ignores the most relevant question regarding why people are actively choosing those places for certain activities. Instead, they suggest extending GPS approaches with ecological momentary assessment to understand how the characteristics of the specific place relate to the behavior.

Figure 1. Example of a fixed 500m buffer (purple round circle) compared to an activity-space based buffer (yellow ellipse).



In addition, the **identification of green space thresholds and relevant green space characteristics** would be crucial to provide guidance for (urban) planners and policy makers. This dissertation and previous research focused on quantitative green space, e.g., distance to green space or green space proportion (Nordbø et al., 2020). Interestingly, in this dissertation, both positive associations between green space and physical activity in urban areas as well as negative associations in rural areas were mostly observed for the middle and upper quartile in comparison to the lowest quartile, but not for the highest and greenest quartile. This indicates that more green space is not necessarily better for physical activity. To guide policy makers and practitioners, evidence-based threshold values would be useful, ideally thresholds that benefit both human health and physical activity and are sufficient to mitigate climate change consequences (Yu et al., 2020). While several cities in Europe have introduced minimum values regarding urban green space availability (Kabisch et al., 2016), it is unclear how these threshold values relate to physical activity. Drawing upon evidence from other areas, recently, the “3-30-300” rule was introduced for urban greening, referring to the rule that each citizen should be able to see three decent sized trees from home and school/work place, have at least 30% tree canopy in the neighborhood, and have no more than 300m distance to the nearest green space (Konijnendijk, 2023), with this latter recommendation being in line with the WHO recommendation (WHO, 2016). In health impact assessment studies, that 3-30-300 rule was associated with better mental health (Nieuwenhuijsen, Dadvand, et al., 2022) while compliance with the WHO green space recommendation was estimated to prevent up to 43,000 pre-mature deaths annually (Barboza et al., 2021). Evaluating such green space recommendations with regards to children’s and adolescent’s physical activity would be important to strengthen evidence-based green space recommendations and their practical implementation. An alternative approach would be to identify an optimum amount of green space. For example, in a recent study, using advanced statistical modeling via generalized additive mixed models, threshold values for population, intersection, public transport, and street-network density walking activity in cities were determined (Cerin et al., 2022). Such threshold values for green space, ideally for both urban and rural areas, would be useful to inform practitioners and policy makers.

While so far recommendations are purely based on quantitative measures of green space, research on qualitative green space aspects would be valuable to extend recommendations. However, to date, in comparison to studies with quantitative green space assessments, green space quality aspects have been neglected and findings are mixed. For adults, biodiversity, amenities, as well as walking and cycling infrastructure showed favorable associations with physical activity (Knobel et al., 2021; Schipperijn et al., 2013; Wang et al., 2021), while excessive green view was negatively related (Wang et al., 2021). For adolescents, findings regarding public open space characteristics, including parks, were mixed based upon qualitative and quantitative research methodologies, with adventurous playground and trails having the potential to facilitate physical activity (Van Hecke et al., 2018), while for children, playground presence may facilitate physical activity (Timperio et al., 2008). Again, these investigations were predominantly focused on urban areas in different countries, and it is unclear how much of these results are transferable to Germany and the rural context. Hence, future research investigating how green space can be designed to facilitate children's and adolescent's physical activity with a focus on Germany is important. Here, it could be valuable to not only assess green space characteristics as potential affordances objectively, but to hear children's and adolescent's voice regarding which environmental characteristics have a function or meaning for them that they perceive as affording for their physical activity (Clavering & McLaughlin, 2010; Heft, 2010).

Finally, a research gap that remains is the predominant use of cross-sectional research to investigate green space and physical activity (Nordbø et al., 2020). To allow more robust conclusions regarding the potential of green space for children's and adolescent's physical activity and health, **natural experiments or quasi-experimental studies** with rigorous control for confounding (Benton et al., 2016) are required. While several natural experiment studies evaluated the impact of greening interventions, e.g., park creations, renovations and, and infrastructure improvements, with positive implications for physical activity, few investigated effects on children's and adolescent's physical activity (Hunter et al., 2019). In addition, results were mostly from Australia and the US and again focused on urban green space interventions (Hunter et al., 2019). An alternative approach to natural experiments and quasi-experimental studies are **health impact assessment studies**, i.e., studies using structured methods to evaluate health consequences of a (planned) intervention or policy at a population level, with the primary goal of this intervention or policy not necessarily targeting health (Harris-Roxas et al., 2012; Lock, 2000). Especially in the context of urban and transport planning, quantitative health impact assessment has experienced increasing interest across the last decade and is considered a highly powerful tool to integrate health in all policies and evidence in decision-making processes (Nieuwenhuijsen et al., 2019). In essence, quantitative health impact assessment follows a comparative risk approach, including a baseline ("as is") assessment of a disease burden or risk factor (e.g., mortality rate, physical inactivity) and then assesses the impact on the disease burden if a certain scenario (e.g., following green space access recommendations; WHO, 2016) would be implemented applying exposure-response functions (Mueller et al., 2017; Nieuwenhuijsen et al., 2019). Such assessment studies can be implemented on a more local level, e.g., when investigating the expected impact of the people-centered Superblock city planning model in Barcelona, Spain on mortality via physical activity and green space (Mueller et al., 2020) or when investigating the impact of breaching the physical activity, heat, green space, noise, and air pollution guidelines on mortality in Bradford, UK (Mueller et al., 2018) and Vienna, Austria (Khomenko et al., 2020). Simultaneously, this assessment type can be scaled up to country- or multi-country level, such as within the *European Urban Burden of Disease Project* (Barboza et al., 2021; Nieuwenhuijsen, Barrera-Gómez, et al., 2022). While these health impact assessment studies have been focused on cities so far, their potential for rural areas has not been explored yet and remains to be further investigated.

Future research area 3
Are there enhanced health effects of nature-based compared to non-nature based physical activity for children and adolescents?

Regarding enhanced health effects when being active in natural environments compared to non-natural environments, the evidence to date does not allow robust conclusions for children and adolescents. When looking at the randomized controlled trials in the systematic review included in this dissertation, beyond the need for rigorously designed and conducted randomized controlled trials, there are some specific recommendations.

Study outcomes should be based upon **theoretical considerations regarding enhanced benefits of nature-based physical activity**. Out of the five randomized controlled trials, four studies investigated the effects on self-esteem (Barton et al., 2015; Duncan et al., 2014; Wood et al., 2013; Wood et al., 2014). However, from a theoretical perspective, it is unclear why few and short physical activity bouts, such as running for 20 minutes or 10 minutes on a cycling ergometer with exposure to digital nature, are expected to impact the unspecific, global self-esteem construct (e.g., “I feel that I have a number of good qualities”, “I wish I could have more respect for myself”; Rosenberg, 2015). In addition, except for the physical self-concept, there is in general weak empirical evidence that physical activity can have a positive impact on self-esteem (Dale et al., 2019). Furthermore, enhanced health benefits from nature-based physical activity were predominantly derived from stress recovery and attention restoration theory (Kaplan & Kaplan, 1989; Ulrich, 1983), both theories arguing for the restorative benefits of natural environments, but not providing any theoretical framework why being physically active in natural environments provides enhanced health benefits. Based upon those theories, differences between sitting and walking in a forest regarding health outcomes would not be expected. Hence, for designing future intervention studies in this area, outcomes should be specified following a theoretical approach. The theory of affordances (Gibson, 1979; Heft, 2010) and the theoretical framework of Araújo et al. (2019) can provide a useful starting point. Based upon this theory and theoretical framework, the health benefits are the result of the person-environment interaction, with the person moving in the natural environment being continuously both psychologically and physically engaged or “immersed” due to the higher variability of nature compared to manufactured environments (Araújo et al., 2019). This implies that the health effects of nature-based physical activity could be the strongest during the activity, i.e., during the person-environment interaction. Hence, with the emphasis of the momentary experience, choosing a more short-lived and continuously manifested (state) health outcome may be more suitable to investigate in this context than the impact on long-lived (trait) health outcomes (Fridhandler, 1986), especially when investigating only one or few bouts of short physical activity. Based upon the assumption that nature-based physical activity requires more psychological and physical engagement and interaction with the environment, one such health outcome may be “flow”, representing a state of being completely absorbed in an activity as a result of action capabilities (skills) and action opportunities (challenges) being in balance, and which is considered key to a good life in the positive psychology paradigm (Nakamura & Csikszentmihalyi, 2021). Momentary mood and affective states are two other frequently examined mental health outcomes in physical activity research, with physical activity being associated with enhanced positive affect and decreased negative affect across age groups in everyday life (Koch et al., 2020; Liao et al., 2015). However, it is unclear if associations differ when distinguishing nature- and non-natured based physical activity. These constructs are just examples of potential health outcomes that could be investigated based upon theoretical consideration when investigated health effects nature- and non-nature based physical activity in children and adolescents.

Connected to this is the **implementation and assessment of nature-based physical activity in ecologically valid environments**. Two of the five randomized controlled trials investigated the impact of nature-based physical activity in laboratory environments, with natural environments being displayed on screens (Duncan et al., 2014; Wood et al., 2013). This seems paradox when investigating health effects of nature-based physical activity. Although digital nature has been shown to enhance positive and negative affect in adults (Pasca et al., 2022) and virtual reality for nature-based physical activity constitutes an own research area (Calogiuri et al., 2022; Litleskare et al., 2020), affordances theory emphasizes the person-environment interaction through perceiving and actualizing affordances through individual function and meaning of objects in the environment (Gibson, 1979; Heft, 2010). Based upon this, natural environments displayed on a screen (e.g., rocks) may not provide the same function, meaning, and action possibilities as in real-life (e.g., when walking through a park). Thus, when using affordances theory as a theoretical foundation, nature-based physical activity studies should be conducted in ecologically valid, i.e., real-world settings. A promising approach for this is ambulatory assessment, a state-of-the approach to investigate fluctuating state constructs, such as mood, in relation to environmental exposures and human behavior (Cushing et al., 2018; Reichert et al., 2019; Reichert et al., 2016; Tost et al., 2019). It comprises various methods to gather data in (near) real-time and in real-world settings, which incurs high ecological validity (Fahrenberg et al., 2007; Kanning et al., 2015; Trull & Ebner-Priemer, 2013). It also allows combining device-based (e.g., GPS, GIS, accelerometers) and self-report (e.g., e-diaries) methods to repeatedly assess contextual, behavioral, and psychological aspects in daily life, therefore also facilitating investigate within-person investigations (Trull & Ebner-Priemer, 2013). Hence, this is a promising approach to assess health effects of nature-based physical activity in children and adolescents ecologically valid and in line with theoretical considerations.

Finally, **investigating the impact of nature-based physical activity interventions in adolescents and clinical child and adolescent populations with existing mental health issues** may be worthwhile. So far, intervention studies were largely conducted with children up to twelve years (e.g., Barton et al. (2015); Duncan et al. (2014); Wood et al. (2014)), missing out adolescents. However, adolescence is a sensitive development period with crucial changes, making adolescents susceptible to poor mental health (Blakemore, 2019; Patel et al., 2018) Across the last years, there has been an increase in psychiatric disorders in adolescence (Collishaw, 2015). Thus, the *Lancet Commission on global mental health* stated that it is important to identify both individual and contextual factors to positively influence mental health during this developmentally sensitive period (Patel et al., 2018). Nature-based physical activity, combining both physical activity as beneficial lifestyle behavior and nature as contextual factor, could be a promising resource to promote mental health during this sensitive development period. Furthermore, nature exposure may be especially promising for children and adolescents experiencing mental health challenges. The potential of physical activity as adjunctive treatment for mental disorders has been increasingly recognized (Stubbs et al., 2018) as has the potential of green space for the prevention of mental disorders (Bratman et al., 2019), with especially psychologically vulnerable people benefiting from green space in their everyday life (Tost et al., 2019). While studies investigating treatment effects of nature-based physical activity on psychopathological symptoms are lacking across age groups in the clinical population (Nigg, Schipperijn, et al., 2022), first results in adults with depression (Berman et al., 2012) and schizophrenia (Ryu et al., 2020) are promising, while positive results for children with attention-deficit-hyperactivity disorder could not be replicated (Faber Taylor & Kuo, 2009; Stevenson et al., 2021). The potential of natural environments in the clinical context has also been recognized by policymakers, for example with the recent Horizon Europe funding call to develop nature-based therapies for health and well-being to, amongst others, strengthen the evidence for nature prescriptions through investigating the causal nature-health relationship (EU, 2021). Hence, future research is warranted to investigate potential treatment and health effects of nature-based physical activity in the clinical population together with the underlying mechanisms (Masterton et al., 2020).

10.5 Implications for policy

Beyond future research opportunities, there are two major practical implications that can be derived from this dissertation.

Recommendations

- **Target specifically rural areas to tackle physical inactivity**
- **Design equitable green spaces that fulfill the needs of youth sub-groups, especially girls, adolescents, and socially disadvantaged youth**

While physical activity interventions should be spread across both urban and rural areas due to the large majority of children and adolescents failing to comply with the WHO (2020) guidelines (Burchartz, 2023), **rural areas should be specifically targeted to tackle physical inactivity** on multiple levels. Since children and adolescents increased school-based physical activity across the last 15 years, schools have a large potential to take on a leadership role for physical activity (Heath et al., 2012; Hills et al., 2015; Pate et al., 2006). The transport domain should be differently conceptualized for rural compared to city youth: Instead of mainly focusing on active transport, which is often unrealistic due to long distances, engaging in community partnerships (Kellstedt et al., 2021) and providing infrastructure and opportunities to access physical activity destinations are more sensible approaches (Yousefian et al., 2009). Examples of this could be privately organized carpools or community-organized buses later in day that facilitate staying longer in areas with more physical activity opportunities after school as well as when going for organized physical activity programs (e.g., sports clubs) in the evening. While this approach focuses on making urban destinations accessible, rural areas should offer some physical activity infrastructure and programs on the community level. This would be especially relevant for younger children that may not yet be allowed to travel alone into the city. Such programs and infrastructure may be especially promising when targeting the whole family (Yousefian et al., 2009) and when providing opportunities for outdoor play (Nigg, Niessner, et al., 2021). Integrating physical activity promotion in the rural health care setting, including tracking progress and counseling by local health care professionals, is another promising strategy (Pelletier et al., 2022). At the same time, the Covid-19 pandemic showed that digital media for sports programs has especially potential for younger people (Mutz et al., 2021), which could also be utilized in rural contexts together with e- and mHealth approaches (Van Sluijs et al., 2021). Providing public health funding specifically allocated to implement such interventions in rural areas and evaluate their effectiveness would facilitate combating physical inactivity in rural areas and learning from it. While each of these suggestions may be promising, the most can be expected when measures are taken on multiple levels across settings (Van Sluijs et al., 2021), such as one program sending frequent physical activity reminders via text messages, social support in physical activity groups, and physical activity events utilizing physical activity-facilitating characteristics of the rural environment, such as trails (Beck et al., 2019).

Regarding **green space design, policy makers (urban) planners should ensure to design equitable green spaces and natural environments**. The WHO recommends high-quality green space across urban and rural areas for all age groups (WHO, 2018). Focusing on the age group of children and adolescents, options are to incorporate both playgrounds for younger children as well as more adventurous and challenging playgrounds and trails for older children and adolescents in green space (Timperio et al., 2008; Van Hecke et al., 2018). At the same time, green space should be designed and maintained to make children, adolescents, and their parents feel safe (Findholt et al., 2011; Hennessy et al., 2010). Hence, when implementing green space projects, ensuring that all stakeholder groups are included – especially socially disadvantaged and minority populations that are hard to reach – is important to ensure physical activity promotion and health benefits across age and socio-demographic groups. Forming community partnerships with stakeholders than can reach those groups is essential (Bonevski et al., 2014). Since in general especially socially disadvantaged and vulnerable people seem to benefit from green space (Rigolon et al., 2021), targeting areas with little green space and social disadvantages may be promising (Mueller et al., 2018). Simultaneously, policy makers and landscape planners should work together to avoid that greening projects result in green gentrification (Triguero-Mas et al., 2022), i.e., greening projects leading to enhanced neighborhood investment and development so that mostly socially advantaged people benefit, while socially disadvantaged people cannot afford housing or have to relocate due to increased costs of living (Anguelovski et al., 2019; Hwang & Lin, 2016; Sax et al., 2022). Hence, the focus should be on inclusive, accessible, and equitable greening projects that are accompanied by anti-displacement and anti-gentrification strategies and policies (Oscilowicz et al., 2022; Triguero-Mas et al., 2022). A helpful resource for this is the *Policy and Planning Tools for Urban Green Justice* report (BCNUEJ, 2021), which suggests several anti-gentrification and anti-displacement strategies. This includes, for example, prioritizing the needs of vulnerable populations above developer and market demands as well as supporting resident-driven and community-based green space projects (BCNUEJ, 2021). Other measures include allocating resources to affordable housing, social and ethnic integration, as well as fair and affordable access to public facilities (Altrock, 2022; BCNUEJ, 2021).

10.6 Conclusion

The environment is crucial to promote physical activity and health in children and adolescents. This dissertation investigated the environment in form of urban and rural areas as well as green space as a specific environment characteristic in relation to child and adolescent physical activity and health both before and during the Covid-19 pandemic. This dissertation contributes to these research fields in several ways: It a) examined child and adolescent physical activity trends and engagement across Germany's urban and rural areas, showing the potential or city living for physical activity, while demonstrating that need to especially target physical activity promotion in rural areas; b) showed that in Germany, urban green space can potentially benefit youth sub-groups' physical activity, while rural green space may be detrimental for physical activity; c) showed the health- and physical activity-enhancing potential of natural environments during crisis times, with a lack of research on children and adolescents; d) demonstrated the need for theory-guided interventions and health effects of nature-based physical activity in children and adolescents, and e) conceptualized physical activity as a sustainable behavior that may lead to other sustainable behaviors that allow individuals to contribute to the sustainable development goals of the United Nations.

This work is a small step to better understand the associations between urban-rural living, natural environments, and physical activity in children and adolescents, with a focus on Germany. However, there is more research required to understand how active environments can be created, especially in rural settings, and to further monitor physical activity developments in urban and rural areas. This also includes to investigate how natural environments and green spaces can be effectively designed to enhance physical activity, and, taking it one step further, which impact nature-based physical activity has on child and adolescent health and well-being. Enhancing our understanding of this will allow to create active environments that can foster children's and adolescent's health and well-being and a sustainable development.

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Appendix A: Supplement Chapter 2

S1. Statistical analysis

We used a multiple-group structural equation modeling framework as implemented in M*plus* 8 (Muthén & Muthén, 1998-2017) to analyse change in the outcome variables over time and across urbanicity groups. In detail, we simultaneously estimated linear trends over T1, T2 and T3 for each urbanicity group as follows:

$Y^G = b_0^G + b_{lt}^G Time + \sum b_M^G X_M + e^G$, *for urbanicity group G = 1, 2, 3, 4.*

Where *Y* is an outcome variable (e.g., total physical activity), *Time* is an ordinal time variable (T1 = 0, T2 = 1, T3 = 2) and b_{lt} represents the linear trend (i.e. the average change in the outcomes between two consecutive time points). X_M corresponds to a set of *M* covariates and b_M represents the associated regression coefficients. We used gender, BMI, socio-economic status, age and the squared age term (age^2)[2] as covariates which have been previously associated with physical activity and screen time (Carson et al., 2016; Guthold et al., 2020; Janssen & Leblanc, 2010; Lämmle et al., 2012) in order to account for differences in the outcome variables which might be due to socio-demographic differences between urbanicity levels. Moreover, we used a Wald-χ^2-Test (MODEL TEST command in M*plus*) to test whether linear trends differ across groups. This was supplemented by testing pair-wise differences (e.g. $diff^{G12} = b_{lt}^{G=1} - b_{lt}^{G=2}$) against 0 using a z-Test via the MODEL CONSTRAINTS command.

Although a linear trend is a simple summary measure that could reduce noise (e.g. induced by sampling), it also might be biased due to constraining a nonlinear trend to be linear (Parker et al., 2018). Thus, we additionally tested for nonlinear trends by constraining the change between T1 and T2 (b_{T1T2}) to be equal to the change between T2 and T3 (b_{T2T3}) in a model, where we converted *Time* to two dummy variables, *Time12* and *Time23*. Significant differences between b_{T1T2} and b_{T2T3} indicate nonlinear trends and thus, we also report single change estimates b_{T1T2} and/or b_{T2T3} in such cases.

In order to facilitate the interpretation of the trend estimates (b_{lt}, b_{T1T2}, b_{T2T3}), we calculated effect size estimates (standardized mean differences *d*) by dividing the unstandardized estimates (b_{lt}, b_{T1T2}, b_{T2T3}) by the outcome standard deviation pooled across time and groups. We consider d-values of at least 0.1 as substantially important. For linear trends, this cut-off corresponds to a small effect (Cohen, 1992) across the whole period under investigation. For example, if the linear trend estimate is 0.1, this must be multiplied by two (i.e. 2 × 0.1 = 0.2) to obtain the effect size for the trend between T1 and T3.

Due to well-known physical activity differences regarding gender and age (Konstabel et al., 2014) we investigated whether trends are moderated by age and gender. This was accomplished by including the interaction terms *Age* × *Time* and *Gender* × *Time* in the linear trend models, and *Age* × *Time12, Age* × *Time23, Gender* × *Time12* and *Gender* × *Time23* in the nonlinear trend models. Following (Aiken et al., 1991), we plotted significant interactions and estimated simple slopes (b_{ss}), i.e. the expected trends for particular values of the moderator variables, and the corresponding p-values.

In the study, data was collected using a complex sample design (Kamtsiuris et al., 2007; Schmidt & Woll, 2017). Thus, beside of using weights (see above), it is necessary to adjust standard errors for clustering. This was accomplished by using TYPE = COMPLEX and the PSUs as cluster variable. TYPE = COMPLEX applies a sandwich estimator, that adjusts for biased standard errors due to clustering,

[2] We included the age^2-term as physical activity increases around the age of 10 years before it decreases again Schmidt, S. C. E., Anedda, B., Burchartz, A., Oriwol, D., Kolb, S., Wäsche, H., Niessner, C., & Woll, A. (2020). The physical activity of children and adolescents in Germany 2003-2017: The MoMo-study. *PloS One, 15*(7), 21780. https://doi.org/10.1371/journal.pone.0236117

provided that there are at least 25 PSUs (Huang, 2018). This requirement is met in the study. PSUs range from 57 (cities) to 87 (small towns).

Missing data ranged from 0.3% (total physical activity) to 3.1% (computer and gaming time) for the outcome variables and from 0.0% (age, gender) to 15.1% (BMI) for the covariates. The MCAR-Test of (LittleLittle, 1988) suggests that the variable means differ significantly between missing data patterns, $\chi^2 = 415.71$ (201), $p < 0.001$. For example, children and adolescents with missing BMI are about one year older, report less outdoor play and more computer and gaming time than children with non-missing BMI. These results suggest that missing data is the consequence of a missing at random (MAR; see e.g. Enders (2010)) mechanism, i.e. missingness depends on other study variables. To appropriately deal with the missing data, we used a full information maximum likelihood (FIML) estimation, what is an appropriate treatment of missing data under the MAR mechanism (Rioux & Little, 2021).

Finally, most outcome variables are skewed (< 4.15) and highly kurtotic (< 24.03) what is, amongst others, due to extreme outliers. To mitigate the impact of outliers, we exclude cases where the respective outcome variable was three standard deviations above the mean. This also reduces non-normality (skewness < 3.00 and kurtosis < 8.01). Moreover, we use a maximum likelihood estimation (MLR) with standard errors that are robust to the non-normality of observations, which is also capable of dealing with missing data (i.e. FIML-estimation).

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S2a. Descriptive statistics for the outcome variables. Time spent in the physical activity and screen time domains at each time point and for each urbanicity area (weighted estimates and outliers +/- 3 SD excluded).

	Total physical activity (minutes/week)	**Sports club physical activity (minutes/week)**	**Leisure physical activity (minutes/week)**	**Outdoor play (days/week)**	**Physical education (minutes/week)**	**Extracurricular physical activity (minutes/week)**	**TV watching (minutes/day)**	**Computer time (minutes/day)**
	M (S.E.)	*M* (S.E.)	*M* (S.E.)	*M* (S.E.)	*M* (S.E.)	*M* (S.E.)	*M* (S.E.)	*M* (S.E.)
Rural								
T1 (2003-2006)	243.49 (8.32)	80.27 (4.08)	77.96 (4.20)	4.85 (0.11)	66.02 (1.70)	4.34 (0.85)	79.97 (3.04)	44.67 (3.28)
T2 (2009-2012)	239.81 (7.28)	102.00 (6.03)	47.52 (3.09)	4.40 (0.14)	68.27 (1.72)	9.76 (1.49)	71.01 (2.96)	58.13 (4.17)
T3 (2014-2017)	212.94 (8.35)	87.75 (5.54)	37.94 (4.41)	3.89 (0.15)	72.00 (2.64)	9.47 (1.36)	89.03 (4.29)	80.36 (5.91)
Small town								
T1 (2003-2006)	228.94 (6.90)	91.37 (4.88)	57.47 (3.03)	4.32 (0.13)	65.30 (1.45)	3.36 (0.48)	83.84 (1.77)	46.56 (2.64)
T2 (2009-2012)	232.26 (6.90)	100.50 (5.03)	50.14 (3.50)	4.33 (0.12)	67.11 (1.73)	7.07 (0.73)	73.82 (2.57)	60.78 (3.13)
T3 (2014-2017)	224.96 (10.97)	91.60 (6.66)	39.40 (4.75)	4.23 (0.13)	69.05 (1.69)	9.31 (1.17)	77.71 (2.85)	69.96 (4.96)
Medium-sized town								
T1 (2003-2006)	228.84 (7.49)	86.39 (4.06)	64.24 (5.13)	4.29 (0.13)	67.08 (1.27)	4.07 (0.66)	85.73 (2.58)	50.40 (2.81)
T2 (2009-2012)	237.97 (9.33)	97.73 (5.49)	48.17 (3.72)	4.00 (0.12)	71.11 (1.69)	7.55 (0.92)	71.95 (2.69)	72.80 (3.48)
T3 (2014-2017)	213.80 (6.93)	83.81 (4.90)	35.07 (3.33)	3.67 (0.13)	73.11 (2.39)	11.05 (1.25)	76.88 (3.90)	74.28 (5.23)
City								
T1 (2003-2006)	216.24 (7.46)	70.29 (4.46)	67.79 (6.14)	4.31 (0.17)	66.72 (1.75)	4.76 (1.01)	80.23 (3.17)	60.92 (3.66)
T2 (2009-2012)	240.35 (11.30)	103.79 (7.79)	54.15 (4.71)	3.89 (0.15)	68.20 (2.07)	9.52 (1.15)	75.04 (3.83)	69.21 (4.71)
T3 (2014-2017)	238.58 (7.10)	101.61 (6.95)	49.10 (5.11)	3.70 (0.12)	72.42 (2.42)	12.28 (1.60)	72.49 (3.66)	67.81 (5.35)

Note: M = mean, S.E. = standard error

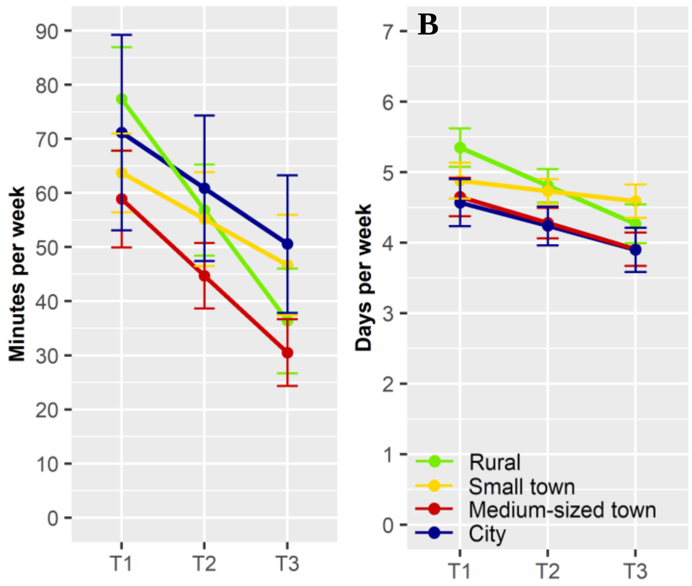
S2b. Group comparisons of the four groups at baseline (T1) and the last study wave (T3) (weighted estimates and outliers +/- 3 SD excluded).

	Rural	**Small town**	**Medium-sized town**	**City**		
	M (S.E.)	*M* (S.E.)	*M* (S.E.)	*M* (S.E.)	*Wald-χ²-Test*	*p*
Total physical activity (min/week)						
T1	288.53 (8.12)	283.56 (9.58)	266.24 (10.39)	263.98 (10.72)	5.10	0.165
T3	256.08 (9.61)	286.55 (10.86)	253.77 (8.76)	277.09 (10.60)	7.75	0.052
Sports club physical activity (min/week)						
T1	**93.50 (5.01)[a]**	**116.34 (6.37)[b]**	**110.04 (6.35)[b]**	**85.53 (7.25)[a]**	**14.75**	**0.002**
T3	100.82 (6.68)	120.69 (7.57)	109.48 (5.70)	111.38 (9.46)	4.05	0.256
Leisure physical activity (min/week)						
T1	**79.98 (5.75)[a]**	**63.51 (3.97)[b]**	**59.61 (5.01)[b]**	72.34 (9.66)	**8.14**	**0.043**
T3	40.04 (5.81)	**46.40 (5.42)[a]**	**31.40 (3.70)[b]**	**52.04 (7.23)[c]**	**9.17**	**0.027**
Outdoor play (days/week)						
T1	**5.40 (0.15)[a]**	**4.82 (0.14)[b]**	**4.64 (0.15)[b]**	**4.59 (0.18)[b]**	**17.24**	**0.001**
T3	**4.34 (0.15)[a]**	**4.52 (0.13)[a, d]**	**3.90 (0.12)[b]**	**3.93 (0.16)[c]**	**16.75**	**0.001**
Physical education (min/week)						
T1	85.21 (2.65)	83.61 (2.37)	81.92 (2.17)	81.60 (2.19)	1.37	0.712
T3	89.97 (2.54)	88.83 (2.14)	87.98 (2.90)	86.46 (3.17)	0.81	0.848
Extracurricular physical activity (min/week)						
T1	8.76 (1.25)	7.05 (0.81)	7.00 (1.01)	10.13 (1.41)	4.75	0.191
T3	13.52 (1.76)	13.34 (1.15)	13.78 (1.31)	17.26 (2.17)	2.70	0.441
TV watching (min/day)						
T1	75.26 (3.22)	82.03 (2.47)	84.25 (3.43)	80.04 (4.14)	4.19	0.242
T3	82.45 (3.61)	76.39 (3.18)	76.40 (4.34)	75.43 (3.56)	2.40	0.494
Computer time (min/day)						
T1	**37.46 (3.25)[a]**	**40.69 (2.79)**	**46.75 (3.97)[b]**	**57.56 (5.31)[b]**	**11.89**	**0.009**
T3	73.29 (4.45)	67.44 (4.73)	74.11 (5.36)	66.20 (4.03)	2.24	0.524

Note: Wald-χ^2-Test to test for differences between the four urbanicity groups. M = mean, S.E. = standard error. The intercept represents physical activity / screen time for a typical study participant (middle socio-economic status, healthy weight, age = 11.27 years, gender = 1.49). [a] is different from [b] at $p < 0.05$; [b] is different from [c] at $p < 0.05$, [c] is different from [d] at $p < 0.05$.

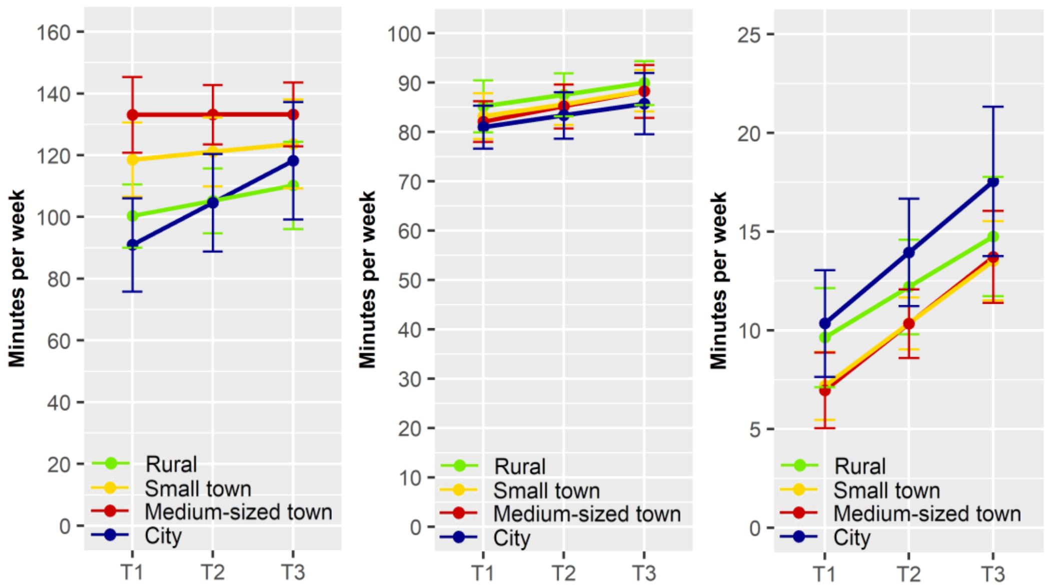
S3. Line plots for trends in physical activity domains.

Figure 2. Trends in unstructured physical activity.



Box A: Leisure physical activity; box B: Outdoor play; T1: 2003-2006, T2: 2009-2012, T3: 2014 – 2017. Error bars indicate 95% confidence intervals.

Figure 3. Trends in structured physical activity



Box A: PA sports clubs; box B: Physical education; box C: Extracurricular activities; T1: 2003-2006, T2: 2009-2012, T3: 2014 – 2017

S4. Separate change estimates between the single time points (T1-T2 / T2-T3) for physical activity and screen time domains indicating non-linear trends

	Rural				Small town				Metropolitan				City			
	B	SE	95%-CI	*d*	B	SE	95%-CI	*d*	B	SE	95%-CI	*d*	B	SE	95%-CI	*d*
Sports clubs (minutes/week)																
Intercept	119.44	6.91	105.90; 132.98		126.36	6.40	113.82; 138.90		121.05	6.53	108.25; 133.85		116.84	10.15	96.95; 136.73	
Change1	**25.95**	6.92	12.39; 39.51	0.23	10.02	5.94	-1.62; 21.66	0.09	11.01	6.30	-1.34; 23.36	0.10	**31.32**	6.84	17.91; 44.73	0.27
Change2	**-18.62**	5.65	-29.69; -7.55	0.16	-5.68	6.05	-17.54; 6.18	0.05	-11.56	7.17	-25.61; 2.49	0.10	-5.47	8.00	-21.15; 10.21	0.05
TV watching (minutes/day)																
Intercept	68.99	3.52	62.09; 75.89		71.32	2.94	65.56; 77.08		70.38	3.25	64.01; 76.75		76.01	4.23	67.72; 84.30	
Change1	-6.27	3.35	-12.84; 0.30	0.11	**-10.71**	2.76	-16.12; -5.30	0.18	**-13.87**	3.38	-20.49; -7.25	0.23	-4.04	4.55	-12.96; 4.88	0.07
Change2	**13.46**	4.06	5.50; 21.42	0.22	5.07	2.65	-0.12; 10.26	0.08	6.02	5.21	-4.19; 16.23	0.10	-0.58	4.88	-10.14; 8.98	0.01
Computer and gaming time (minutes/day)																
Intercept	38.66	3.15	32.49; 44.83		41.27	2.64	36.10; 46.44		49.44	4.01	41.58; 57.30		59.19	5.51	48.39; 69.99	
Change1	**22.33**	3.65	15.18; 29.48	0.28	**15.23**	3.39	8.59; 21.87	0.19	**22.93**	3.09	16.87; 28.99	0.29	**10.06**	4.46	1.32; 18.80	0.13
Change2	**13.51**	5.57	2.59; 24.43	0.17	**11.53**	5.12	1.49; 21.57	0.15	4.43	5.51	-6.37; 15.23	0.06	-1.42	5.25	-11.71; 8.87	0.02

Note. Change1 (B_{T1T2}) = Mean change between T1 and T2, Change2 (B_{T2T3}) = Mean change between T2 and T3. Intercept centered on T2; SE = standard error. Standardized mean difference estimate d was calculated by dividing the linear trend by the standard deviation pooled across time and groups. The intercept represents physical activity / screen time for a typical study participant (middle socio-economic status, healthy weight, age = 11.27 years, gender = 1.49) at T2.

S5. Trend estimates for age x time and gender x time interactions. Linear trend estimates for interactions age x time and gender x time

	Rural				Small town				Medium-sized town				City			
	B	SE	95%-CI	ES	B	SE	95%-CI	ES	B	SE	95%-CI	ES	B	SE	95%-CI	ES
Total physical activity (minutes/week)																
Intercept	278.95	6.84	265.54; 292.36		285.28	7.80	269.99; 300.57		264.24	6.74	251.03; 277.45		274.51	10.57	253.79; 295.23	
Linear trend (LT)	-14.62	4.88	-24.18; -5.06	0.09	1.62	5.74	-9.63; 12.87	0.01	-5.87	5.12	-15.91; 4.17	0.03	7.20	4.68	-1.97; 16.37	0.04
Age	9.73	1.52	6.75; 12.71	0.06	9.62	1.72	6.25; 12.99	0.06	10.20	1.72	6.83; 13.57	0.06	8.08	1.80	4.55; 11.61	0.05
Gender	-50.81	9.32	-69.08; -32.54	0.30	-30.71	0.25	-31.20; -30.22	0.18	-49.66	14.77	-78.61; 20.71	0.29	-61.33	0.34	-62.00; -60.66	0.36
LT*Age	-1.72	1.44	-4.54; 1.10	0.04	0.43	1.48	-2.47; 3.33	0.01	0.79	1.06	-1.29; 2.87	0.02	1.57	1.14	-0.66; 3.80	0.03
LT*Gender	-3.07	9.79	-22.26; 16.12	0.01	14.95	9.28	-3.24; 33.14	0.05	6.74	9.49	-11.86; 25.34	0.02	-2.90	11.71	-25.85; 20.05	0.01
Leisure time physical activity (minutes/week)																
Intercept	56.89	4.31	48.44; 65.34		55.51	3.44	48.77; 62.25		44.94	3.13	38.81; 51.07		60.97	6.80	47.64; 74.30	
Linear trend (LT)	-20.58	2.35	-25.19; -15.97	0.23	-8.29	2.56	-13.31; -3.27	0.09	-14.27	2.42	-19.01; -9.53	0.16	-10.25	4.11	-18.31; -2.19	0.11
Age	2.06	0.71	0.67; 3.45	0.02	3.77	0.93	1.95; 5.59	0.04	2.40	0.88	0.68; 4.12	0.03	1.97	0.24	1.50; 2.44	0.02
Gender	5.15	0.12	4.91; 5.39	0.06	-2.41	6.27	-14.70; 9.88	0.03	-0.35	6.69	-13.46; 12.76	0.00	-6.55	7.91	-22.05; 8.95	0.07
LT*Age	0.26	0.70	-1.11; 1.63	0.01	**1.62**	0.59	0.46; 2.78	0.06	0.72	0.60	-0.46; 1.90	0.03	0.74	0.99	-1.20; 2.68	0.03
LT*Gender	4.46	5.23	-5.79; 14.71	0.03	3.85	5.86	-7.64; 15.34	0.02	8.52	4.45	-0.20; 17.24	0.05	-2.02	8.04	-17.78; 13.74	0.01
Outdoor play (days/week)																
Intercept	4.82	0.11	4.60; 5.04		4.72	0.09	4.54; 4.90		4.27	0.11	4.05; 4.49		4.23	0.13	3.98; 4.48	
Linear trend (LT)	-0.51	0.08	-0.67; -0.35	0.20	-0.16	0.09	-0.34; 0.02	0.06	-0.38	0.07	-0.52; -0.24	0.15	-0.34	0.09	-0.52; -0.16	0.13
Age	-0.36	0.02	-0.40; -0.32	0.14	-0.40	0.02	-0.44; -0.36	0.16	-0.35	0.03	-0.41; -0.29	0.14	-0.46	0.02	-0.50; -0.42	0.18
Gender	-0.30	0.20	-0.69; 0.09	0.12	-0.05	0.13	-0.30; 0.20	0.02	-0.20	0.18	-0.55; 0.15	0.08	-0.20	0.18	-0.55; 0.15	0.08
LT*Age	**-0.11**	0.02	-0.15; -0.07	0.15	**-0.07**	0.01	-0.09; -0.05	0.09	**-0.10**	0.02	-0.14; -0.06	0.13	**-0.08**	0.03	-0.14; -0.02	0.10
LT*Gender	0.013	0.11	-0.20; 0.23	0.00	0.11	0.11	-0.11; 0.33	0.02	0.06	0.11	-0.16; 0.28	0.01	0.04	0.19	-0.33; 0.41	0.01
Sports club physical activity (minutes/week)																
Intercept	105.31	5.32	94.88; 115.74		120.49	5.70	109.32; 131.66		113.18	4.86	103.65; 122.71		104.45	8.12	88.53; 120.37	
Linear trend (LT)	5.01	3.05	-0.97; 10.99	0.04	2.23	3.75	-5.12; 9.58	0.02	<0.01	3.12	-6.12; 6.12	0.00	13.68	3.37	7.07; 20.29	0.12
Age	7.29	1.04	5.25; 9.33	0.06	4.90	1.01	2.92; 6.88	0.04	3.68	1.12	1.48; 5.88	0.03	5.52	1.74	2.11; 8.93	0.05
Gender	-28.90	8.28	-45.13; -12.67	0.25	-30.62	8.16	-46.61; 14.63	0.27	-1.20	9.16	-19.15; 16.75	0.01	-57.30	12.53	-81.86, -32.74	0.50
LT*Age	-0.28	0.90	-2.04; 1.48	0.01	-1.02	0.94	-2.86; 0.82	0.03	0.11	0.68	-1.22; 1.44	0.01	1.35	0.91	-0.43; 3.13	0.04

LT*Gender	-5.88	5.90	-17.44; 5.68	0.03	**12.79**	6.34	0.36; 25.22	0.06	5.60	6.07	-6.30; 17.50	0.00	-4.55	7.35	-18.96; 9.86	0.02
Physical education (minutes/week)																
Intercept	105.31	5.32	94.88; 115.74		120.49	5.70	109.32; 131.66		113.18	4.86	103.65; 122.71		104.45	8.12	88.53; 120.37	
Linear trend (LT)	5.01	3.05	-0.97; 10.99	0.04	2.23	3.75	-5.12; 9.58	0.02	<0.01	3.12	-6.12; 6.12	0.00	13.68	3.37	7.07; 20.29	0.12
Age	7.29	1.04	5.25; 9.33	0.06	4.90	1.01	2.92; 6.88	0.04	3.68	1.12	1.48; 5.88	0.03	5.52	1.74	2.11; 8.93	0.05
Gender	-28.90	8.28	-45.13; -12.67	0.25	-30.62	8.16	-46.61; 14.63	0.27	-1.20	9.16	-19.15; 16.75	0.01	-57.30	12.53	-81.86, -32.74	0.50
LT*Age	-0.28	0.90	-2.04; 1.48	0.01	-1.02	0.94	-2.86; 0.82	0.03	0.11	0.68	-1.22; 1.44	0.01	1.35	0.91	-0.43; 3.13	0.04
LT*Gender	-5.88	5.90	-17.44; 5.68	0.03	**12.79**	6.34	0.36; 25.22	0.06	5.60	6.07	-6.30; 17.50	0.00	-4.55	7.35	-18.96; 9.86	0.02
Extracurricular activities (minutes/week)																
Intercept	12.21	1.21	9.84; 14.58		3.14	0.66	1.85; 4.43		10.30	0.87	8.59; 12.01		13.94	1.39	11.22; 16.66	
Linear trend (LT)	2.80	0.69	1.45; 4.15	0.13	3.63	0.95	1.77; 5.49	0.17	3.40	0.63	2.17; 4.63	0.16	3.54	0.96	1.66; 5.42	0.17
Age	-0.04	0.22	-0.47; 0.39	0.00	0.10	0.16	-0.21; 0.41	0.00	0.06	0.20	-0.33; 0.45	0.00	-0.37	0.27	-0.90; 0.16	0.02
Gender	-1.16	0.04	-1.24; -1.08	0.06	0.65	1.60	-2.49; 3.79	0.03	-1.43	1.70	-4.76; 1.90	0.07	1.12	0.04	1.04; 1.20	0.05
LT*Age	**-0.58**	0.15	-0.87; -0.29	0.10	-0.20	0.12	-0.44; 0.04	0.03	**-0.28**	0.11	-0.50; -0.06	0.05	-0.25	0.19	-0.62; 0.12	0.04
LT*Gender	0.75	1.45	-2.09; 3.59	0.02	0.76	0.81	-0.83; 2.35	0.02	**-2.91**	1.44	-5.73; -0.09	0.07	-1.53	1.69	-4.84; 1.78	0.04
TV watching (minutes/day)																
Intercept	75.23	2.66	70.02; 80.44		76.47	2.41	71.75; 81.19		76.90	2.51	71.98; 81.82		77.26	3.06	71.26; 83.26	
Linear trend (LT)	2.95	1.75	-0.48; 6.38	0.05	-3.20	1.59	-6.32; -0.08	0.05	-4.52	2.57	-9.56; 0.52	0.08	-2.25	1.98	-6.13; 1.63	0.04
Age	4.11	0.76	2.62; 5.60	0.07	3.79	0.58	2.65; 4.93	0.06	5.40	0.65	4.13; 6.67	0.09	4.39	0.65	3.12; 5.66	0.07
Gender	-15.79	4.51	-24.63; -6.95	0.26	-15.36	3.29	-21.81; -8.91	0.26	-15.95	5.34	-26.42; -5.48	0.27	-3.12	6.74	-16.33; 10.09	0.05
LT*Age	0.50	0.38	-0.24; 1.24	0.03	-0.24	0.24	-0.71; 0.23	0.01	-0.81	0.486	-1.76; 0.14	0.05	**1.01**	0.44	0.15; 1.87	0.06
LT*Gender	**6.69**	2.80	1.20; 12.18	0.06	-0.23	2.58	-5.29; 4.83	0.00	1.12	3.21	-5.17; 7.41	0.01	-2.75	4.27	-11.12; 5.62	0.02
Computer and gaming time (minutes/day)																
Intercept	59.91	2.40	55.21; 64.61		54.71	2.39	50.03; 59.39		63.86	3.54	56.92; 70.80		63.69	3.85	56.14; 71.24	
Linear trend (LT)	17.57	1.96	13.73; 21.41	0.22	13.77	2.39	9.09; 18.45	0.17	13.97	2.75	8.58; 19.36	0.18	4.95	2.96	-0.85; 10.75	0.06
Age	10.03	0.84	8.38; 11.68	0.13	9.73	0.54	8.67; 10.79	0.12	12.00	0.84	10.35; 13.65	0.15	11.50	0.91	9.72; 13.28	0.15
Gender	-13.69	5.93	-25.31; -2.07	0.17	-12.54	4.79	-21.93; -3.15	0.16	-16.86	6.16	-28.93; -4.79	0.21	-8.51	0.20	-8.90; -8.12	0.11
LT*Age	**3.58**	0.56	2.48; 4.68	0.16	**2.00**	0.47	1.08; 2.92	0.09	**2.78**	0.57	1.66; 3.90	0.12	**1.58**	0.71	0.19; 2.97	0.07
LT*Gender	**15.29**	5.26	4.98; 25.60	0.10	**13.63**	3.81	6.16; 21.10	0.09	**14.58**	4.89	5.00; 24.16	0.09	**16.27**	4.50	7.45; 25.09	0.11

Note: Intercept: centered on T1. Linear trend = mean change between two consecutive timepoints. Effect size (ES) for linear trend = standardized mean difference estimate d, calculated by dividing the linear trend by the standard deviation pooled across time and groups.(Cohen et al., 2013) ES for age, gender and interaction effects = standardized regression coefficients. SE = standard error. The intercepts represent engagement in the respective behavior for a typical study participant (middle socio-economic status, healthy weight, age = 11.27 years, gender = 1.49) at T1.

Separate trend estimates for interactions (age x time and gender x time) between the single time points (T1-T2 / T2-T3) for PA and ST domains indicating non-linear trends

	Rural				Small town				Medium-sized town				City			
	B	SE	95%-CI	ES	B	SE	95%-CI	ES	B	SE	95%-CI	ES	B	SE	95%-CI	ES
Sports club physical activity (minutes/week)																
Intercept	119.49	6.87	106.02; 132.96		126.14	6.44	113.52; 138.76		121.07	6.50	108.33; 133.81		117.22	10.26	97.11; 137.33	
Change1	26.31	6.75	13.08; 39.54	0.23	10.04	5.87	-1.47; 21.55	0.09	10.93	6.29	-1.40; 23.26	0.10	32.03	6.74	18.82; 45.24	0.28
Change2	-18.61	5.48	-29.35; -7.87	0.16	-6.50	6.21	-18.67; 5.67	0.06	-11.73	7.30	-26.04; 2.58	0.10	-5.88	7.95	-21.46; 9.70	0.05
Age	7.29	1.04	5.25; 9.33	0.06	4.90	1.01	2.92; 6.88	0.04	3.68	1.12	1.48; 5.88	0.03	5.52	1.74	2.11; 8.93	0.05
Gender	-28.90	8.28	-45.13; -12.67	0.25	-30.62	8.16	-46.61; -14.63	0.27	-1.20	9.16	-19.15; 16.75	0.01	-57.30	12.53	-81.86; -32.74	0.50
Change1*Age	2.13	1.59	-0.99; 5.25	0.04	0.04	1.30	-2.51; 2.59	0.00	0.65	1.41	-2.11; 3.41	0.01	2.77	2.24	-1.62; 7.16	0.05
Change2*Age	**-2.89**	1.39	-5.61; -0.17	0.05	-2.19	1.39	-4.91; 0.53	0.04	-0.50	1.61	-3.66; 2.66	0.01	-0.23	2.23	-4.60; 4.14	0.00
Change1*Gender	1.84	11.93	-21.54; 25.22	0.01	8.39	10.43	-12.05; 28.83	0.02	-2.53	10.22	-22.56; 17.50	0.01	-27.51	15.80	-58.48; 3.46	0.07
Change2*Gender	14.15	16.08	-17.37; 45.67	0.04	17.79	15.11	-11.83; 47.41	0.05	14.42	13.73	-12.49; 41.33	0.04	19.18	17.50	-15.12; 53.48	0.05
TV watching (minutes/day)																
Intercept	68.75	3.30	62.28; 75.22		71.62	2.90	65.94; 77.30		70.50	3.27	64.09; 76.91		76.03	4.24	67.72; 84.34	
Change1	-6.59	3.20	-12.86; -0.32	0.11	-10.56	2.69	-15.83; -5.29	0.18	-13.78	3.38	-20.40; -7.16	0.23	-3.92	4.48	-12.70; 4.86	0.07
Change2	13.61	3.95	5.87; 21.35	0.23	4.74	2.64	-0.43; 9.91	0.08	5.29	5.19	-4.88; 15.46	0.09	-0.38	4.88	-9.94; 9.18	0.01
Age	4.11	0.76	2.62; 5.60	0.07	3.79	0.58	2.65; 4.93	0.06	5.40	0.65	4.13; 6.67	0.09	4.39	0.65	3.12; 5.66	0.07
Gender	-15.79	4.51	-24.63; -6.95	0.26	-15.36	3.29	-21.81; -8.91	0.26	-15.95	5.34	-26.42; -5.48	0.27	-3.12	6.74	-16.33; 10.09	0.05
Change1*Age	0.11	0.78	-1.42; 1.64	0.00	-0.26	0.77	-1.77; 1.25	0.01	0.64	0.83	-0.99; 2.27	0.02	0.83	0.89	-0.91; 2.57	0.03
Change2*Age	0.82	0.97	-1.08; 2.72	0.03	-0.14	0.75	-1.61; 1.33	0.01	-2.28	1.16	-4.55; -0.01	0.08	1.20	1.03	-0.82; 3.22	0.04
Change1*Gender	**-16.75**	6.27	-29.04; -4.46	0.09	**-16.01**	5.10	-26.01; -6.01	0.08	-6.42	5.93	-18.04; 5.20	0.03	-2.68	9.61	-21.52; 16.16	0.01
Change2*Gender	**33.09**	7.25	18.88; 47.30	0.16	**16.54**	5.28	6.19; 26.89	0.08	8.87	7.44	-5.71; 23.45	0.04	-2.77	9.66	-21.70; 16.16	0.01
Computer and gaming time (minutes/day)																
Intercept	59.76	3.19	53.51; 66.01		55.52	2.96	49.72; 61.32		70.21	4.12	62.13; 78.29		67.01	5.42	56.39; 77.63	
Change1	21.58	3.83	14.07; 29.09	0.27	15.10	3.46	8.32; 21.88	0.19	22.91	3.11	16.81; 29.01	0.29	9.39	4.50	0.57; 18.21	0.12
Change2	12.70	5.44	2.04; 23.36	0.16	12.34	5.23	2.09; 22.59	0.16	4.25	5.84	-7.20; 15.70	0.05	-0.27	5.36	-10.78; 10.24	0.00
Age	10.03	0.84	8.38; 11.68	0.13	9.73	0.54	8.67; 10.79	0.12	12.00	0.84	10.35; 13.65	0.15	11.50	0.91	9.72; 13.28	0.15
Gender	-13.69	5.93	-25.31; -2.07	0.17	-12.54	4.79	-21.93; -3.15	0.16	-16.86	6.16	-28.93; -4.79	0.21	-8.51	0.20	-8.90; 8.12	0.11
Change1*Age	**2.90**	1.05	0.84; 4.96	0.08	**2.16**	0.74	0.71; 3.61	0.06	**4.08**	0.99	2.14; 6.02	0.11	1.38	1.21	-0.99; 3.75	0.04

Change2*Age	**4.42**	1.30	1.87; 6.97	0.11	1.82	0.98	-0.10; 3.74	0.05	1.33	1.32	-1.26; 3.92	0.03	1.80	1.27	-0.69; 4.29	0.05
Change1*Gender	**20.11**	5.54	9.25; 30.97	0.08	**21.10**	6.76	7.85; 34.35	0.08	**21.10**	7.10	7.18; 35.02	0.08	**32.46**	9.83	13.19; 51.73	0.12
Change2*Gender	9.49	11.14	-12.34; 31.32	0.04	5.39	8.21	-10.70; 21.48	0.02	7.91	9.47	-10.65; 26.47	0.03	-1.97	10.53	-22.61; 18.67	0.01

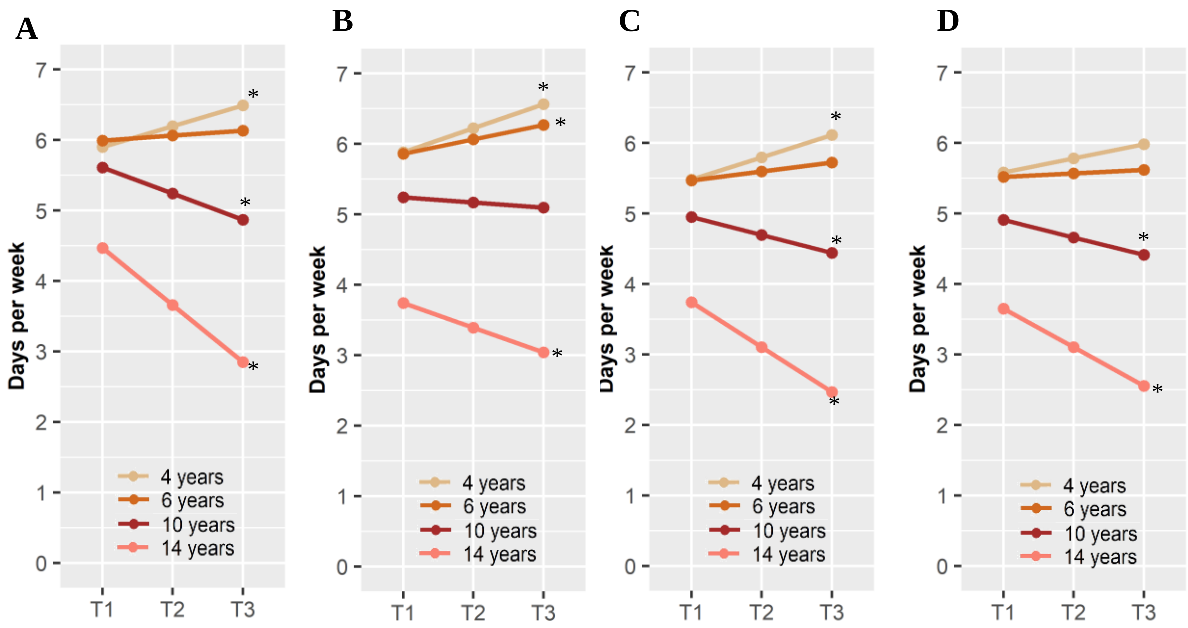
Note: Intercept: centered on T1. Linear trend = mean change between two consecutive timepoints. Effect size (ES) for linear trend = standardized mean difference estimate d, calculated by dividing the linear trend by the standard deviation pooled across time and groups.(Cohen et al., 2013) ES for age, gender and interaction effects = standardized regression coefficients. SE = standard error. The intercepts represent engagement in the respective behavior for a typical study participant (middle socio-economic status, healthy weight, age = 11.27 years, gender = 1.49) at T1.

S6. Interactions between age x time and gender x time with plots

Age x time interactions were plotted for the ages 4 (pre-school age), 6 (elementary school age), 10 (secondary school age) and 14 (adolescent age) years. Gender x time interactions were plotted for males and females.

Outdoor play. For outdoor play, the interactions indicate that 14-year-old adolescents decreased outdoor play over time in all areas (rural areas: b_{ss} = -0.81, 95%-CI [-1.01; -0.61]; small towns: b_{ss} = -.34, 95%-CI [-0.55; -0.15]; medium-sized towns: b_{ss} = -0.64, 95%-CI [-0.84; -0.44]; cities: b_{ss} = -0.55, 95%-CI [-0.82; -0.28]). Moreover, 10-year-olds decreased outdoor play in rural areas (b_{ss} = -0.37, 95%-CI [-0.53; -0.32]), medium-sized towns (b_{ss} = -.26, 95%-CI [-0.40; -0.12]), and cities (b_{ss} = -0.25, 95%-CI [-0.41; -0.09]). In contrast, 4-year-olds increased outdoor play in rural areas (b_{ss} = 0.30, 95%-CI [0.05; 0.55]), small towns (b_{ss} = 0.34, 95%-CI [0.12; 0.56]), and medium-sized towns (b_{ss} = 0.32, 95%-CI [0.12; 0.52]), and 6-year-olds showing increases in small towns (b_{ss} = 0.20, 95%-CI [0.01; 0.39]). See also *Figure 4*.

Figure S6.1. Time x age interactions for outdoor play in the different urbanicity areas.

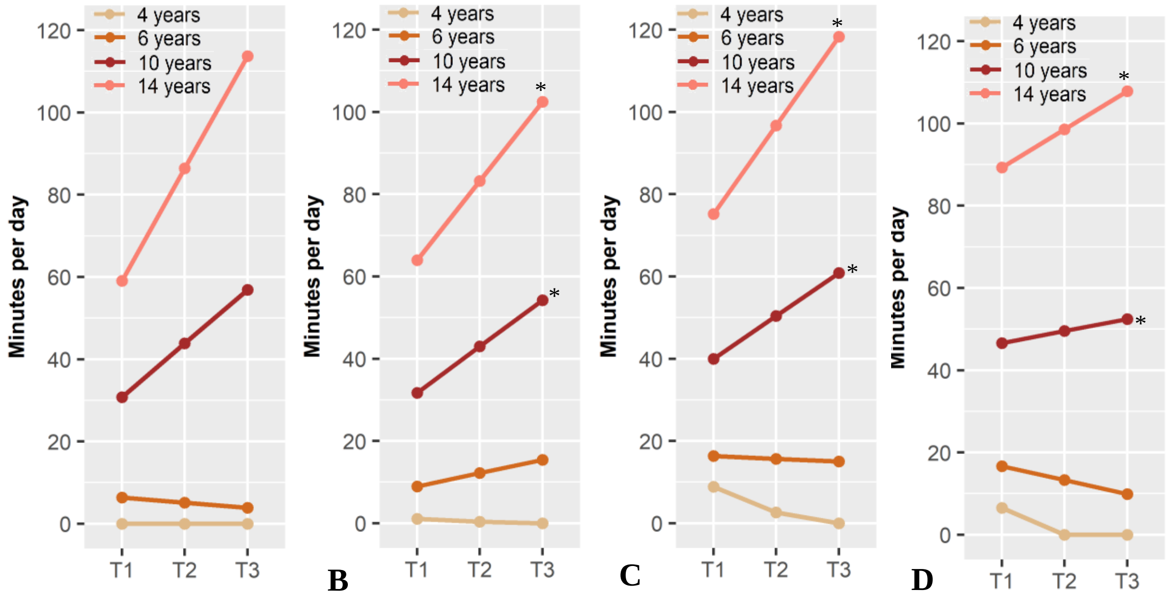


*Box A: Time X age interaction for rural areas; box B: Time X age interaction for small towns; box C: Time X age interaction for medium-sized towns; box D: Time X age interaction for cities; T1: 2003-2006, T2: 2009-2012, T3: 2014 – 2017. * 95%-CI does not include zero for the trend estimate of the respective sub-group.*

Computer and gaming time. Age x time interactions for computer and gaming showed increases for 10-year-olds in rural areas (b_{ss} = 13.04, 95%-CI [10.04; 16.04]), small towns (b_{ss} = 11.24, 95%-CI [7.26; 15.22]), and medium-sized towns (b_{ss} = 10.45, 95%-CI [5.99; 14.91]). For 14-year-olds, increases were observed across rural areas (b_{ss} = 27.34, 95%-CI [20.99; 33.69]), small towns (b_{ss} = 19.23, 95%-CI [12.57; 25.89]), medium-sized towns (b_{ss} = 21.56, 95%-CI [13.67; 29.47]), and cities (b_{ss} = 9.27, 95%-CI [0.53; 18.01]) (see also *Figure 5*).

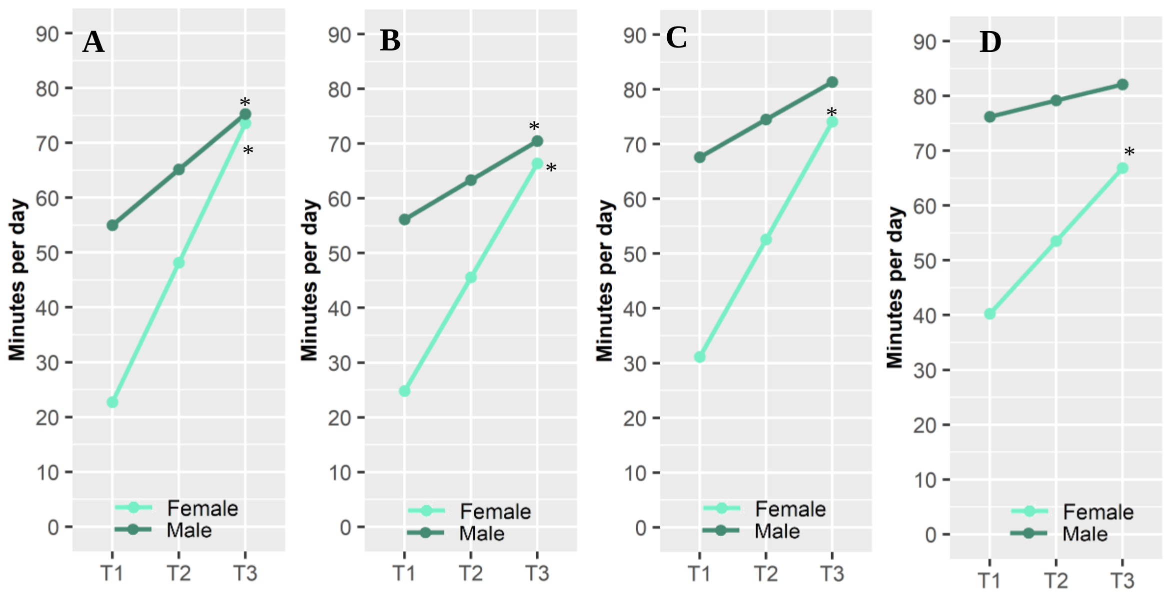
Gender x time interactions showed increases in computer and gaming time across all areas for girls (rural areas: b_{ss} = 25.43, 95%-CI [19.18; 31.68]; small towns: b_{ss} = 20.78, 95%-CI [14.23; 27.33]; medium-sized towns: b_{ss} = 21.47; 95%-CI [14.81; 28.13]; cities: b_{ss} = 13.31, 95%-CI [7.02; 19.60]). For males, there were only significant trends in rural areas (b_{ss} = 10.14, 95%-CI [3.53; 16.75]) and small towns (b_{ss} = 7.11, 95%-CI [1.72; 12.58]), which were smaller than for girls (see also *Figure 6*).

Figure S6.2. Time x age interactions for computer and gaming time in rural and urban areas.



*Box A: Time X age interaction for rural areas; box B: Time X age interaction for small towns; box C: Time X age interaction for medium-sized towns; box D: Time X age interaction for cities; T1: 2003-2006, T2: 2009-2012, T3: 2014 – 2017; * 95%-CI does not include zero for the trend estimate of the respective sub-group. Please note: If calculations for computer and gaming were below zero, they were restricted to zero.*

Figure S6.3. Time x gender interactions for computer and gaming time.



*Box A: Time X gender interaction for rural areas; box B: Time X gender interaction for small towns; box C: Time X gender interaction for medium-sized towns; box D: Time X gender interaction for cities; T1: 2003-2006, T2: 2009-2012, T3: 2014 – 2017. * 95%-CI does not include zero for the trend estimate of the respective sub-group*

Appendix B: Supplement Chapter 3

Table A.1. Discovery study's descriptive statistics stratified by urban-rural status

	Rural (N=449)	**Small town (N=822)**	**Medium-sized town (N=587)**	**City (N=332)**	*p*
Gender					.823
Boys	214 (47.7%)	395 (48.1%)	271 (46.2%)	151 (45.5%)	
Girls	235 (52.3%)	427 (51.9%)	316 (53.8%)	181 (54.5%)	
Age group					.883
6-10 years	111 (24.7%)	222 (27.0%)	162 (27.6%)	89 (26.8%)	
11-13 years	168 (37.4%)	299 (36.4%)	223 (38.0%)	128 (38.6%)	
14-17 years	170 (37.9%)	301 (36.6%)	202 (34.4%)	115 (34.6%)	
Age in years mean (SD)	12.6 (3.33)	12.4 (3.33)	12.3 (3.25)	12.3 (3.24)	.438
Socio-economic status mean score (SD)	13.1 (3.47)	13.7 (3.61)	14.6 (3.85)	15.6 (4.04)	**< .001**
BMI (based on IOTF cut points)					.708
Normal weight	39 (8.7%)	73 (8.9%)	53 (9.0%)	38 (11.4%)	
Underweight	331 (73.7%)	601 (73.1%)	437 (74.4%)	248 (74.7%)	
Overweight	62 (13.8%)	119 (14.5%)	74 (12.6%)	33 (9.9%)	
Obese	17 (3.8%)	29 (3.5%)	23 (3.9%)	13 (3.9%)	
Accelerometer wear-time mean minutes/day (SD)	804 (75.6)	815 (79.4)	803 (73.5)	804 (82.2)	**.009**
MVPA mean minutes/day (SD)	48.2 (21.8)	51.5 (24.2)	51.5 (24.7)	56.4 (22.6)	**<.001**
WHO (2020) physical activity guidelines					**<.001**
Not fulfilled	333 (74.2%)	575 (70.0%)	393 (67.0%)	201 (60.5%)	
Fulfilled	116 (25.8%)	247 (30.0%)	194 (33.0%)	131 (39.5%)	

Please note: One-way ANOVA (dimensional variables) and chi-square tests (categorical variables) were used to test differences between the urban-rural groups.

Table A.2. Replication study's descriptive statistics stratified by urban-rural status

	Rural areas (low density) (N=324)	**Suburbs and small towns (intermediate density) (N=391)**	**Cities (high density) (N=208)**	***p***
Gender				.938
Boys	164 (50.6%)	195 (49.9%)	102 (49.0%)	
Girls	160 (49.4%)	196 (50.1%)	106 (51.0%)	
Age group				.164
6-10 years	127 (39.2%)	174 (44.5%)	91 (43.8%)	
11-13 years	108 (33.3%)	127 (32.5%)	78 (37.5%)	
14-17 years	89 (27.5%)	90 (23.0%)	39 (18.8%)	
Age in years mean (SD)	11.5 (3.38)	11.0 (3.40)	11.0 (3.14)	.059
Socio-economic status mean score (SD)	14.7 (3.06)	16.0 (3.33)	16.0 (3.31)	**<.001**
BMI (based on IOTF cut points)				.511
Normal weight	236 (72.8%)	306 (78.3%)	164 (78.8%)	
Underweight	34 (10.5%)	31 (7.9%)	21 (10.1%)	
Overweight	46 (14.2%)	46 (11.8%)	19 (9.1%)	
Obese	8 (2.5%)	8 (2.0%)	4 (1.9%)	
Accelerometer wear-time mean minutes/day (SD)	823 (112)	812 (103)	827 (125)	.189
MVPA mean minutes/day (SD)	51.9 (23.8)	55.6 (24.2)	59.4 (23.6)	**.002**
WHO (2020) physical activity guidelines				**.001**
Not fulfilled	232 (71.6%)	246 (62.9%)	118 (56.7%)	
Fulfilled	92 (28.4%)	145 (37.1%)	90 (43.3%)	

Please note: One-way ANOVA (dimensional variables) and chi-square tests (categorical variables) were used to test differences between the urban-rural groups.

Table A.3. Discovery study's logistic regression analysis for compliance with the WHO physical activity guidelines stratified by gender.

	Boys (N = 1031)			**Girls (N = 1159)**		
Predictors	*OR*	*95%CI*	*p*	*OR*	*95%CI*	*p*
(Intercept)	2.72	1.82;4.09	**<.001**	0.85	0.55;1.28	.436
Urbanicity (ref. rural)						
Small town	1.15	0.78;1.71	.472	1.16	0.75;1.82	.503
Medium sized town	1.46	0.96;2.24	.076	1.33	0.84;2.12	.224
City	1.96	1.21;3.20	**.006**	2.13	1.28;3.56	**.004**
Socio-economic status	1.03	0.99;1.07	.131	0.98	0.94;1.02	.365
BMI (ref. normal BMI)						
Underweight	1.20	0.71;2.04	.494	1.37	0.87;2.14	.168
Overweight	0.55	0.35;0.85	**.008**	0.73	0.44;1.16	.196
Obese	0.74	0.35;1.53	.430	0.27	0.08;0.75	**.021**
Age group (ref. 6-10 years)						
11-13 years	0.16	0.11;0.23	**<.001**	0.21	0.14;0.30	**<.001**
14-17 years	0.08	0.05;0.11	**<.001**	0.08	0.05;0.13	**<.001**
Accelerometer wear-time	1.00	1.00;1.00	**.002**	1.00	1.00;1.00	**.025**

Table A.4. Discovery study's logistic regression analysis for compliance with the WHO physical activity guidelines stratified by age group.

	6-10 years (N = 584)			**11-13 years (N = 818)**			**14-17 years (N = 788)**		
Predictors	*OR*	*95%CI*	*p*	*OR*	*95%CI*	*p*	*OR*	*95%CI*	*p*
Intercept	2.26	1.44;3.59	**<0.001**	0.59	0.40;0.87	**.008**	0.15	0.08;0.26	**<.001**
Urbanicity (ref. rural)									
Small town	1.22	0.74;1.98	0.435	0.84	0.53;1.32	.440	1.88	1.01;3.69	.056
Medium sized town	1.67	0.99;2.84	0.054	0.98	0.61;1.60	.949	2.10	1.08;4.26	**.033**
City	1.82	0.97;3.46	0.065	1.43	0.84;2.45	.191	3.81	1.89;7.97	**<.001**
Gender (ref. boys)									
Girls	0.31	0.21;0.44	**<0.001**	0.38	0.27;0.54	**<.001**	0.34	0.22;0.52	**<.001**
Socio-economic status	1.03	0.98;1.08	0.299	1.00	0.96;1.05	.844	1.00	0.94;1.05	.926
BMI (ref. normal)									
Underweight	1.31	0.73;2.39	0.375	1.64	0.98;2.71	.056	0.72	0.28;1.57	.439
Overweight	0.89	0.52;1.54	0.670	0.41	0.22;0.70	**.002**	0.67	0.33;1.26	.244
Obese	0.32	0.12;0.79	**0.016**	0.52	0.15;1.47	.259	1.00	0.35;2.43	.993
Accelerometer wear-time	1.00	1.00;1.00	0.177	1.00	1.00;1.01	**<.001**	1.00	1.00;1.00	.159

Table A.5. Replication study's logistic regression analysis for compliance with the WHO physical activity guidelines stratified by gender.

	Boys (N = 461)			**Girls (N = 462)**		
Predictors	*OR*	*95%CI*	*p*	*OR*	*95%CI*	*p*
(Intercept)	2.21	1.42;3.50	**.001**	0.72	0.44;1.17	.195
Urbanicity degree (ref. rural areas)						
Towns	1.57	0.95;2.60	.077	1.40	0.80;2.47	.243
Cities	1.72	0.96;3.11	.069	2.09	1.11;3.98	**.023**
Socio-economic status	0.97	0.91;1.04	.374	1.05	0.97;1.13	.221
BMI (ref. normal BMI)						
Underweight	0.96	0.46;2.01	.922	0.84	0.38;1.78	.656
Overweight/Obese	0.25	0.12;0.50	**<.001**	0.39	0.16;0.86	**.027**
Age group (ref. 6-10 years)						
11-13 years	0.13	0.08;0.22	**<.001**	0.24	0.14;0.41	**<.001**
14-17 years	0.08	0.04;0.15	**<.001**	0.06	0.03;0.14	**<.001**
Accelerometer wear-time	1.00	1.00;1.01	**.006**	1.00	1.00;1.00	.319

Please note: Due to the low number of cases of the category "obesity" when stratified, we collapsed the categories overweight and obesity to avoid problems in the modeling process.

Table A.6. Replication study's logistic regression analysis for compliance with the WHO physical activity guidelines stratified by age group.

	6-10 years (N = 392)			11-13 years (N = 313)			14-17 years (N = 218)		
Predictors	*OR*	*95%CI*	*p*	*OR*	*95%CI*	*p*	*OR*	*95%CI*	*p*
(Intercept)	2.16	1.39;3.36	**.001**	0.34	0.18;0.61	**<.001**	0.12	0.05;0.33	**<.001**
Urbanicity degree (ref. rural areas)									
Towns and suburbs	1.36	0.82;2.26	.228	1.37	0.68;2.76	.382	2.48	0.80;7.76	.117
Cities	2.03	1.10;3.73	**.023**	1.70	0.80;3.61	.165	3.36	0.72;15.58	.122
Gender (ref. boys)									
Girls	0.35	0.23;0.55	**<.001**	0.56	0.32;0.97	**.040**	0.16	0.05;0.53	**.002**
Socio-economic status	1.03	0.96;1.10	.444	1.04	0.95;1.14	.399	0.86	0.74;1.00	.050
BMI (ref. normal BMI)									
Underweight	0.83	0.41;1.68	.609	0.96	0.38;2.48	.940	0.41	0.03;4.99	.486
Overweight/obese	0.19	0.09;0.41	**<.001**	0.31	0.11;0.91	**.032**	1.57	0.48;5.19	.458
Accelerometer wear-time	1.00	1.00;1.01	**.019**	1.00	1.00;1.00	.384	1.00	1.00;1.01	.665

Please note: Due to the low number of cases of the category "obesity" when stratified, we collapsed the categories overweight and obesity to avoid problems in the modeling process.

Table A.7. Sensitivity analysis with imputed data for missing values for multiple linear regression results with moderate-to-vigorous physical activity (MVPA) as outcome.

	Discovery Study (N = 2,743)				**Replication Study (N = 1,196)**			
Predictors	*B*	*SE*	*95%CI*	*p*	*B*	*SE*	*95%CI*	*p*
(Intercept)	74.77	1.31	72.20;77.34	**<.001**	72.27	1.49	69.35;75.19	**<.001**
Urbanicity discovery study (ref. rural)								
Small town	2.30	1.14	0.07;4.53	**.044**				
Medium-sized town	2.39	1.15	0.14;4.64	**.037**				
City	7.45	1.42	4.67;10.23	**<.001**				
Urbanicity replication study (ref. rural areas)								
Towns and suburbs					2.49	1.46	-0.37;5.35	.087
Cities					5.63	1.84	2.02;9.24	**.002**
Age group (ref. 6-10 years)								
11-13 years	-21.66	1.08	-23.78;-19.54	**<.001**	-19.79	1.55	-22.83;-16.75	**<.001**
14-17 years	-30.75	1.14	-32.98;-28.52	**<.001**	-26.56	1.69	-29.87;-23.25	**<.001**
Gender (ref. boys)								
Girls	-11.20	0.85	-12.87;-9.53	**<.001**	-10.03	1.23	-12.44;-7.62	**<.001**
Socio-economic status	0.14	0.11	-0.08;0.36	.188	-0.07	0.21	-0.48;0.34	.725
BMI (ref. normal)								
Underweight	-0.23	1.39	-2.95;2.49	.867	-2.89	2.32	-7.44;1.66	.214
Overweight	-3.52	1.21	-5.89;-1.15	**.004**	-8.60	1.86	-12.25;-4.95	**<.001**
Obese	-5.55	2.07	-9.61;1-49	**.007**	-10.18	4.32	-18.65;1.71	**.019**
Accelerometer wear-time	0.04	0.01	0.02;0.06	**<.001**	0.02	0.01	0.00;0.04	**.004**

Table A.8. Sensitivity analysis with imputed data for missing values for logistic regression results regarding compliance with the WHO (2020) physical activity guidelines.

	Discovery Study (N = 2,743)			**Replication Study (N = 1,196)**		
Predictors	*Odds Ratio*	*95%CI*	*p*	*Odds Ratio*	*95%CI*	*p*
(Intercept)	2.61	1.92;3.55	**<.001**	2.01	1.42;2.83	**<.001**
Urbanicity discovery study (ref. rural)						
Small town	1.19	0.88;1.60	.256			
Medium sized town	1.36	1.02;1.83	**.038**			
City	2.06	1.47;2.89	**<.001**			
Urbanicity replication study (ref. rural areas)						
Towns and suburbs				1.46	1.02;2.10	**.039**
Cities				1.89	1.24;2.88	**.003**
Gender (ref. boys)						
Girls	0.35	0.28;0.43	**<.001**	0.39	0.30;0.55	**<.001**
Socio-economic status	1.01	0.98;1.03	.612	1.01	0.96;1.05	.871
BMI (ref. normal)						
Underweight	1.23	0.89;1.71	.215	0.84	0.52;1.48	.622
Overweight	0.65	0.47;0.90	**.010**	0.29	0.22;0.65	**<.001**
Obese	0.56	0.31;0.99	**.046**	0.08	0.05;0.78	**.020**
Age group (ref. 6-10 years)						
11-13 years	0.18	0.14;0.23	**<.001**	0.17	0.12;0.25	**<.001**
14-17 years	0.08	0.06;0.10	**<.001**	0.07	0.05;0.13	**<.001**
Accelerometer wear-time	1.003	1.002;1.004	**<.001**	1.002	1.001;1.004	**.006**

Appendix C: Supplement Chapter 4

S1. Equations of the linear regression models

Moderate-to-vigorous physical activity (MVPA)

$$Y(\boldsymbol{MVPA})_j = \beta_{00} + \beta_{01} * nature\_index_j + \beta_{02} * age_j + \beta_{03} * sex_j + \beta_{04} * BMI_j + \beta_{05} * socio - economic\ status_j + r_j$$

Standing long jump distance

$$Y(\boldsymbol{Standing\ long\ jump\ distance})_j = \beta_{00} + \beta_{01} * nature\_index_j + \beta_{02} * age_j + \beta_{03} * sex_j + \beta_{04} * BMI_j + \beta_{05} * socio - economic\ status_j + r_j$$

Mental health assessed via the Strength and Difficulties Questionnaire (SDQ) score

$$Y(\boldsymbol{SDQ\ score})_j = \beta_{00} + \beta_{01} * nature\_index_j + \beta_{02} * age_j + \beta_{03} * sex_j + \beta_{04} * BMI_j + \beta_{05} * socio - economic\ status_j + r_j$$

Example interaction analysis for nature index by socio-economic status

Moderate-to-vigorous physical activity (MVPA)

$$Y(\boldsymbol{MVPA})_j = \beta_{00} + \beta_{01} * nature\_index_j + \beta_{02} * age_j + \beta_{03} * sex_j + \beta_{04} * BMI_j + \beta_{05} * socio - economic\ status_j + \beta_{06} * nature\_index_j * socio - economic\ status_j + r_j$$

Table S1. Descriptive results of the whole study sample regarding socio-demographic information, weight status, and outcome variables (N = 2,843)

	MVPA (N=923)	**Standing long jump (N = 2,493)**	**Mental health problems (N = 2,341)**
Socio-demographic information and weight status			
Age in years (mean, SD)	11.19 (3.34)	10.37 (3.96)	10.42 (3.94)
Gender			
Boys	461 (49.9%)	1294 (51.9%)	1213 (51.8%)
Girls	462 (50.1%)	1199 (48.1%)	1128 (48.2%)
BMI based on IOTF cutpoints			
Underweight	86 (9.3%)	241 (9.7%)	230 (9.8%)
Normal weight	706 (76.5%)	1887 (75.7%)	1773 (75.7%)
Overweight	111 (12.0%)	284 (11.4%)	268 (11.4%)
Obese	20 (2.2%)	81 (3.2%)	70 (3.0%)
Socio-economic status			
Low	164 (17.8%)	489 (19.6%)	447 (19.1%)
Medium	532 (57.6%)	1434 (57.5%)	1360 (58.1%)
High	227 (24.6%)	570 (22.9%)	534 (22.8%)
Circular buffer % (mean, SD)			
Nature 100m	17.71 (21.12)	16.79 (20.57)	17.02 (20.57)
Nature 250m	33.20 (23.98)	30.96 (23.22)	31.33 (23.25)
Nature 500m	46.46 (24.55)	43.59 (24.00)	43.97 (24.00)
Nature 1000m	59.27 (24.02)	56.63 (23.49)	57.05 (23.37)
Greenspace 100m	17.42 (20.99)	16.51 (20.43)	16.75 (20.42)
Greenspace 250m	32.53 (23.86)	30.31 (23.10)	30.67 (23.13)
Greenspace 500m	45.30 (24.70)	42.42 (23.99)	42.81 (23.98)
Greenspace 1000m	57.78 (24.48)	54.96 (23.81)	55.40 (23.70)
Accessible greenspace 100m	6.053 (12.37)	5.990 (12.03)	6.085 (12.20)
Accessible greenspace 250m	10.54 (13.12)	10.56 (12.48)	10.58 (12.56)
Accessible greenspace 500m	14.45 (13.89)	14.18 (12.80)	14.16 (12.87)
Accessible greenspace 1000m	18.54 (14.00)	18.09 (13.13)	18.11 (13.19)
Street-network buffer % (mean, SD)			
Nature 1000m	42.50 (23.19)	39.65 (22.73)	40.04 (22.63)
Nature 3000m	64.71 (23.21)	62.27 (22.52)	62.61 (22.48)
Nature 5000m	71.49 (20.91)	69.59 (20.24)	69.83 (20.20)
Greenspace 1000m	41.90 (23.29)	39.00 (22.77)	39.40 (22.68)
Greenspace 3000m	63.90 (23.28)	61.11 (22.81)	61.43 (22.78)
Greenspace 5000m	70.63 (21.24)	68.56 (20.57)	68.81 (20.51)
Accessible greenspace 1000m	13.89 (12.51)	13.49 (11.75)	13.54 (11.83)
Accessible greenspace 3000m	23.18 (14.34)	22.34 (13.73)	22.46 (13.82)
Accessible greenspace 5000m	26.14 (14.59)	25.14 (13.91)	25.27 (13.97)
Outcome variable (mean, SD)			
MVPA (minutes/day)	53.18 (23.50)		
Standing long jump distance (centimeters)		136.61 (37.49)	
Mental health problems (SDQ score)			9.49 (5.00)

Table S2. Results of the multiple linear regression models predicting moderate-to-vigorous physical activity.

Nature predictor in the model	*Intercept*	*SE Intercept*	*B Nature predictor*	*SE B Nature predictor*	*p*	*Adj. R^2*
Circular buffer						
Nature100m	59.52	1.14	0.00	0.00	0.968	0.287
Nature250m	59.56	1.14	-0.04	0.03	0.165	0.289
Nature500m	59.58	1.14	**-0.06**	0.03	0.023	0.291
Nature1000m	59.67	1.14	**-0.07**	0.03	0.009	0.293
Greenspace100m	59.52	1.14	0.00	0.00	0.967	0.287
Greenspace250m	59.56	1.14	-0.04	0.03	0.177	0.289
Greenspace500m	59.56	1.14	**-0.06**	0.03	0.032	0.291
Greenspace1000m	59.63	1.14	**-0.07**	0.03	0.015	0.292
AccessibleGreen100m	59.55	1.14	0.04	0.05	0.406	0.288
AccessibleGreen250m	59.58	1.14	0.07	0.05	0.160	0.289
AccessibleGreen500m	59.57	1.14	0.09	0.05	0.064	0.290
AccessibleGreen1000m	59.57	1.14	0.08	0.05	0.088	0.290
Street-network buffers						
Nature1000m	59.57	1.14	-0.04	0.03	0.130	0.289
Nature3000m	59.64	1.14	**-0.06**	0.03	0.046	0.291
Nature5000m	59.66	1.14	**-0.08**	0.03	0.011	0.293
Greenspace1000m	59.57	1.14	-0.04	0.03	0.147	0.289
Greenspace3000m	59.64	1.14	-0.03	0.03	0.263	0.288
Greenspace5000m	59.65	1.14	**-0.08**	0.03	0.012	0.292
AccessibleGreen1000m	59.59	1.14	0.06	0.05	0.254	0.288
AccessibleGreen3000m	59.56	1.14	0.03	0.05	0.546	0.288
AccessibleGreen5000m	59.50	1.14	0.02	0.04	0.720	0.288

Please note: All models were controlled for age (centered on the sample's mean), gender (ref. category: males), socio-economic status (ref. category: medium), and BMI (ref. category: normal weight. ***Bolded*** *values indicate $p < 0.05$*

Table S3. Results of the multiple linear regression models predicting long jump (centimeters).

Nature predictor in the model	*Intercept*	*SE Intercept*	*B Nature predictor*	*SE B Nature predictor*	*p*	*Adj.* R^2
Circular buffer						
Nature100m	145.77	0.75	0.00	0.02	0.893	0.669
Nature250m	145.77	0.75	0.02	0.02	0.329	0.669
Nature500m	145.76	0.75	0.03	0.02	0.078	0.669
Nature1000m	145.73	0.75	**0.04**	0.02	0.031	0.669
Greenspace100m	145.77	0.75	0.00	0.02	0.925	0.669
Greenspace250m	145.76	0.75	0.02	0.02	0.356	0.669
Greenspace500m	145.76	0.75	0.03	0.02	0.075	0.669
Greenspace1000m	145.74	0.75	**0.04**	0.02	0.024	0.669
AccessibleGreen100m	145.72	0.75	-0.04	0.04	0.228	0.669
AccessibleGreen250m	145.71	0.75	-0.06	0.03	0.069	0.669
AccessibleGreen500m	145.73	0.75	**-0.08**	0.03	0.026	0.669
AccessibleGreen1000m	145.75	0.75	**-0.09**	0.03	0.008	0.670
Street-network buffers						0.669
Nature1000m	145.73	0.75	0.04	0.02	0.067	0.669
Nature3000m	145.72	0.75	0.03	0.02	0.099	0.669
Nature5000m	145.73	0.75	0.04	0.02	0.104	0.669
Greenspace1000m	145.74	0.75	0.04	0.02	0.063	0.669
Greenspace3000m	145.75	0.75	0.02	0.02	0.308	0.669
Greenspace5000m	145.73	0.75	0.03	0.02	0.100	0.669
AccessibleGreen1000m	145.75	0.75	-0.06	0.04	0.127	0.669
AccessibleGreen3000m	145.73	0.75	0.03	0.03	0.420	0.669
AccessibleGreen5000m	145.73	0.75	-0.01	0.03	0.808	0.669

Please note: All models were controlled for age (centered on the sample's mean), gender (ref. category: males), socio-economic status (ref. category: medium), and BMI (ref. category: normal weight. ***Bolded*** *values indicate* $p < 0.05$

Table S4. Results of the multiple linear regression models predicting mental health.

Nature predictor in the model	*Intercept*	*SE Intercept*	*B Nature predictor*	*SE B Nature predictor*	*p*	*Adj. R^2*
Circular buffer						
Nature100m	9.46	0.17	-0.01	0.00	0.073	0.043
Nature250m	9.46	0.17	0.00	0.00	0.876	0.042
Nature500m	9.46	0.18	0.00	0.00	0.805	0.042
Nature1000m	9.47	0.18	0.00	0.00	0.266	0.042
Greenspace100m	9.46	0.18	-0.01	0.00	0.074	0.043
Greenspace250m	9.46	0.18	0.00	0.00	0.857	0.042
Greenspace500m	9.46	0.18	-0.02	0.00	0.593	0.042
Greenspace1000m	9.47	0.18	-0.01	0.00	0.119	0.043
AccessibleGreen100m	9.46	0.18	-0.01	0.01	0.512	0.042
AccessibleGreen250m	9.47	0.18	0.01	0.01	0.201	0.042
AccessibleGreen500m	9.48	0.18	0.01	0.01	0.156	0.042
AccessibleGreen1000m	9.46	0.18	0.01	0.01	0.095	0.043
Street-network buffers						
Nature1000m	9.47	0.18	0.00	0.00	0.398	0.042
Nature3000m	9.47	0.18	-0.01	0.00	0.166	0.042
Nature5000m	9.47	0.18	-0.01	0.01	0.289	0.042
Greenspace1000m	9.47	0.18	0.00	0.00	0.394	0.042
Greenspace3000m	9.47	0.18	-0.01	0.00	0.154	0.042
Greenspace5000m	9.47	0.18	-0.01	0.00	0.280	0.042
AccessibleGreen1000m	9.47	0.18	0.01	0.01	0.101	0.043
AccessibleGreen3000m	9.46	0.17	**0.02**	0.01	0.015	0.044
AccessibleGreen5000m	9.47	0.17	**0.03**	0.01	<0.001	0.047

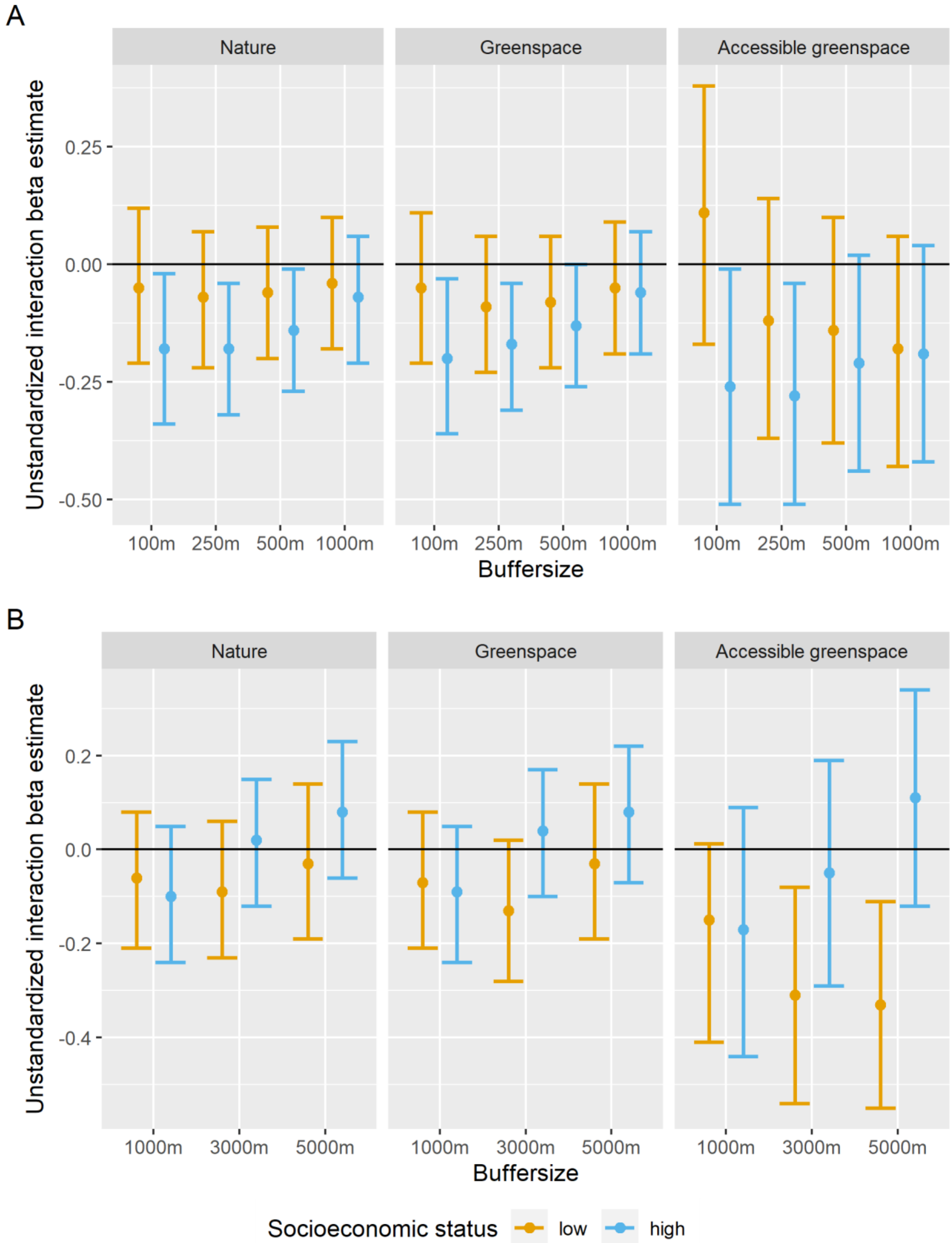
Please note: All models were controlled for age (centered on the sample's mean), gender (ref. category: males), socio-economic status (ref. category: medium), and BMI (ref. category: normal weight. ***Bolded*** *values indicate $p < 0.05$*

Table S5. Selected models including the reporting of co-variates.

	MVPA (N = 923)					SDQ score (N = 2,341)					Long jump distance (N = 2,493)				
Predictors	*B*	*95%CI*	*SE*	*β*	*p*	*B*	*95%CI*	*SE*	*β*	*p*	*B*	*95%CI*	*SE*	*β*	*p*
(Intercept)	59.67	57.43;61.90	1.14	0.08	**<0.001**	9.47	9.12;9.81	0.18	-0.05	**<0.001**	145.74	144.28;147.21	0.75	0.06	**<0.001**
Nature 1000m circular buffer	-0.07	-0.13;-0.02	0.03	-0.07	**0.009**	-0.00	-0.01;0.00	0.00	-0.02	0.266	0.04	0.00;0.08	0.02	0.02	**0.031**
Age	-3.18	-3.57;-2.79	0.20	-0.45	**<0.001**	0.09	0.04;0.14	0.03	0.07	**<0.001**	7.54	7.32;7.75	0.11	0.80	**<0.001**
Socio-economic status (ref. medium)															
Low	0.69	-2.79;4.18	1.78	0.03	0.696	1.42	0.90;1.95	0.27	0.28	**<0.001**	-4.99	-7.22;-2.75	1.14	-0.13	**<0.001**
High	-0.85	-3.96;2.27	1.59	-0.04	0.593	-0.86	-1.35;-0.36	0.25	-0.17	**0.001**	4.17	2.06;6.28	1.07	0.11	**<0.001**
Gender (ref. boys)	-9.42	-11.99;-6.85	1.31	-0.20	**<0.001**	-0.48	-0.87;-0.08	0.20	-0.05	**0.019**	-12.85	-14.54;-11.15	0.87	-0.17	**<0.001**
IOTF (ref. normal weight)															
Underweight	-4.84	-9.28;-0.40	2.26	-0.21	**0.032**	0.17	-0.50;0.85	0.34	0.03	0.617	-0.72	-3.62;2.17	1.48	-0.02	0.624
Overweight	-8.85	-12.83;-4.86	2.03	-0.38	**<0.001**	0.76	0.13;1.40	0.32	0.15	**0.018**	-11.82	-14.53;-9.11	1.38	-0.32	**<0.001**
Obese	-12.47	-21.31;-3.63	4.50	-0.53	**0.006**	2.70	1.52;3.89	0.60	0.54	**<0.001**	-25.37	-30.22;-20.53	2.47	-0.68	**<0.001**

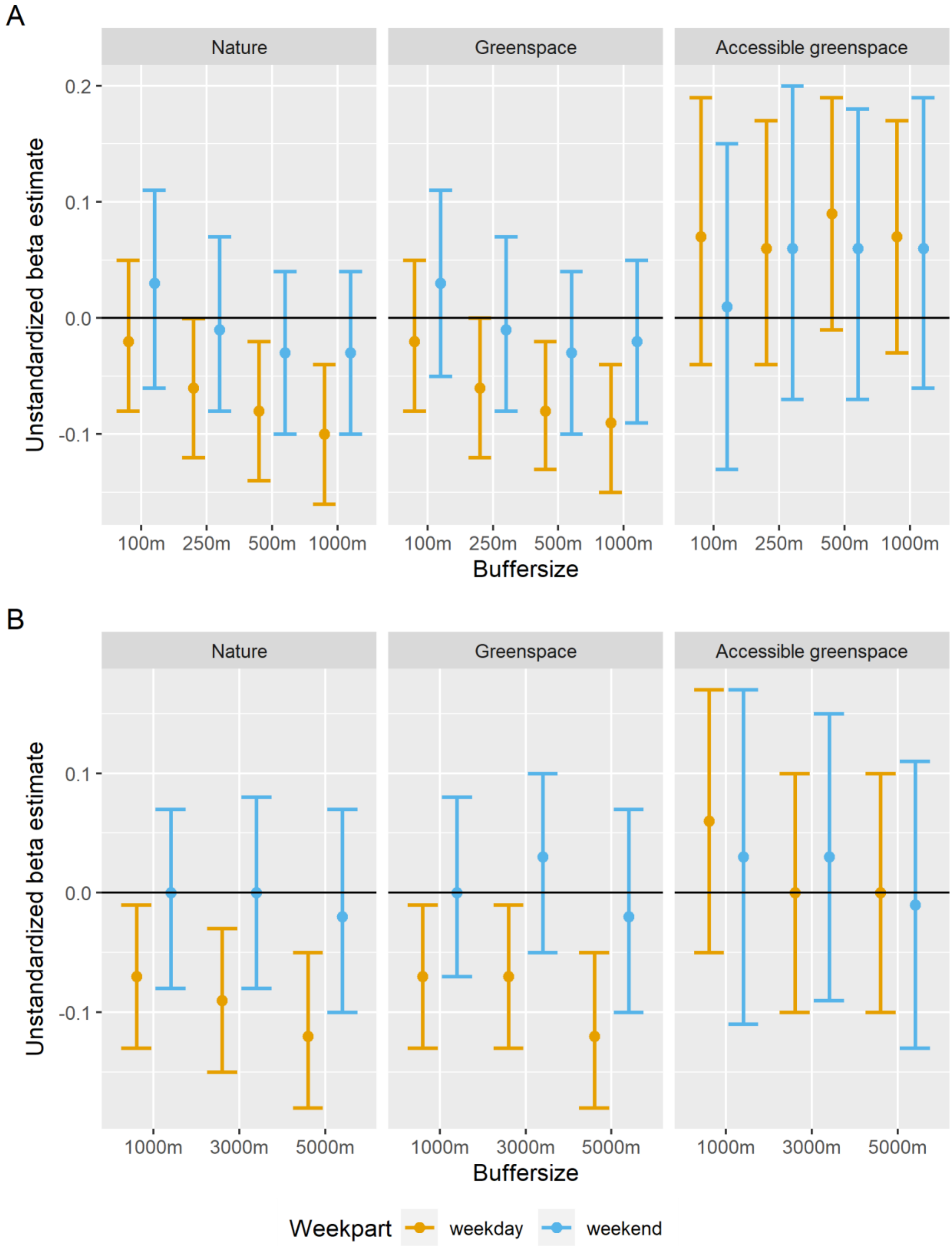
Please note: The relationship between the co-variates and health outcomes remained stable across all models with varying nature operationalizations, buffer types, and buffer sizes.

Figure S1. Variation regarding the relationship between nature indices, buffer types, and buffer distances for moderate-to-vigorous physical activity (MVPA) across youth with low and high socio-economic status compared to youth with medium socio-economic status (reference category).



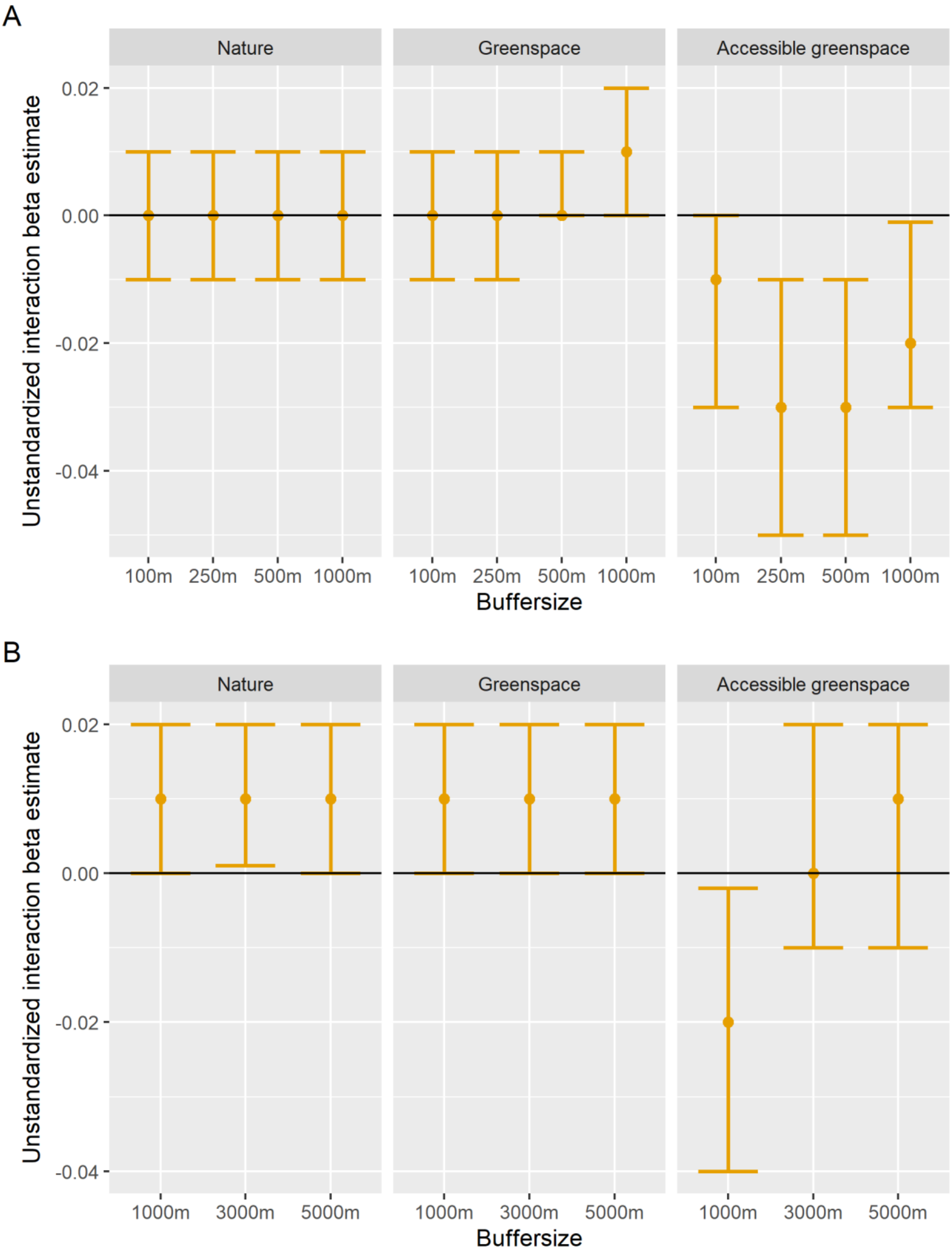
Panel A: Unstandardized beta estimates for circular buffers. Panel B: Unstandardized beta estimates for street-network buffers Sample size: N = 923. Error bars represent 95% confidence intervals. All models were adjusted for age, gender, BMI, and socio-economic status.

Figure S2. Variation regarding the relationship between nature indices, buffer types, and buffer distances for moderate-to-vigorous physical activity (MVPA) at the weekend and during the week.



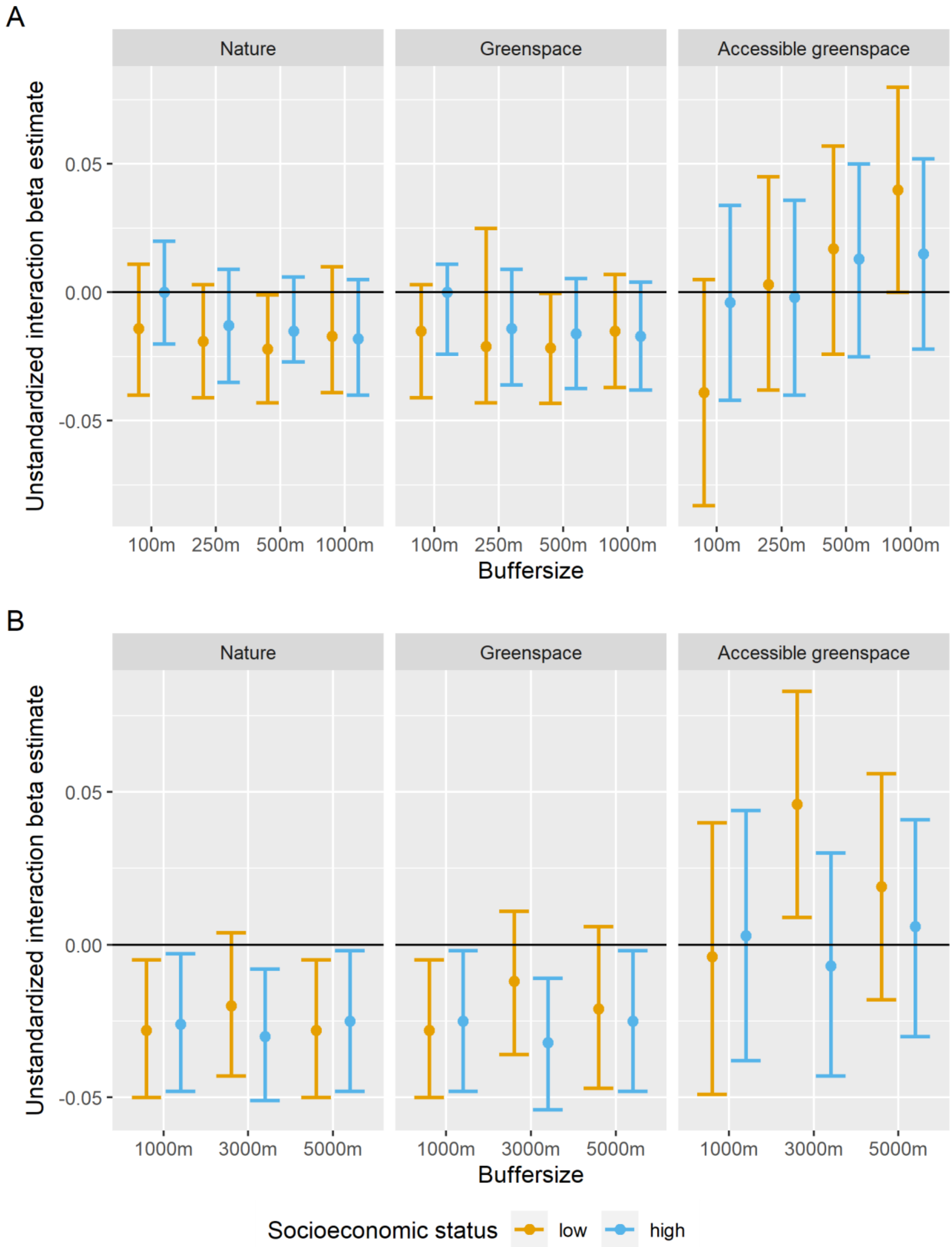
Panel A: Unstandardized interaction beta estimates for circular buffers. Panel B: Unstandardized interaction beta estimates for street-network buffers. Sample size: N = 923. Error bars represent 95% confidence intervals. All models were adjusted for age, gender, BMI, and socio-economic status.

Figure S3. Variations regarding the relationship between nature indices, buffer types, and buffer distances across age for standing long jump distance.



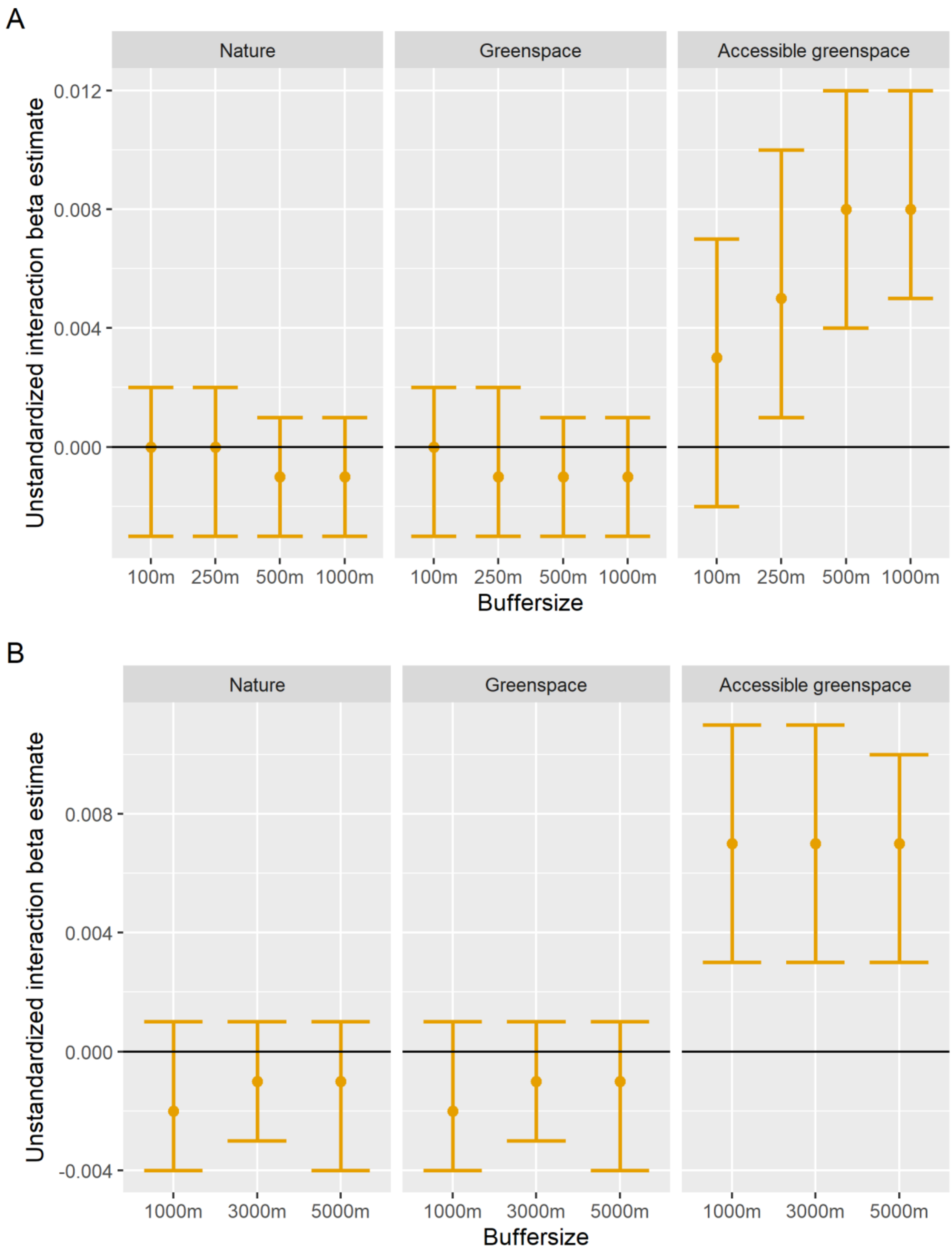
Panel A: Unstandardized interaction beta estimates for circular buffers. Panel B: Unstandardized interaction beta estimates for street-network buffers. Sample size: N = 2,493. Error bars represent 95% confidence intervals. All models were adjusted for age, gender, BMI, and socio-economic status.

Figure S4. Variation regarding the relationship between nature indices, buffer types, and buffer distances for mental health problems across youth with low and high socio-economic status compared to youth with medium socio-economic status.



Panel A: Unstandardized interaction beta estimates for circular buffers. Panel B: Unstandardized interaction beta estimates for street-network buffers. Sample size: N = 2,341. Error bars represent 95% confidence intervals. All models were adjusted for age, gender, BMI, and socio-economic status.

Figure S5. Variation regarding the relationship between nature indices, buffer types, and buffer distances across age regarding mental health problems.



Panel A: Unstandardized interaction beta estimates for circular buffers. Panel B: Unstandardized interaction beta estimates for street-network buffers. Sample size: N = 2,341. Error bars represent 95% confidence intervals. All models were adjusted for age, gender, BMI, and socio-economic status.

Appendix D: Supplement Chapter 5

Table S1. Threshold Values (%) for Green Space Quartiles

	Rural areas (*N* = 324)		**Town/suburb** (*N* = 391)		**Cities** (*N* = 208)	
	Range	*Mean (SD)*	Range	*Mean (SD)*	Range	*Mean (SD)*
1st quartile	0.00 – 0.04	0.03 (0.01)	0.00 – 0.05	0.04 (0.02)	0.00 – 0.07	0.04 (0.02)
2nd quartile	0.04 – 0.09	0.07 (0.01)	0.05 – 0.10	0.08 (0.02)	0.07 – 0.12	0.09 (0.01)
3rd quartile	0.09 – 0.18	0.14 (0.03)	0.10 – 0.18	0.14 (0.02)	0.12 – 0.20	0.16 (0.02)
4th quartile	0.18 – 0.94	0.35 (0.18)	0.18 – 0.59	0.29 (0.10)	0.20 – 0.45	0.29 (0.07)

Table S2. Multiple Linear Regression Models including Green Space – Gender Interactions to Predict MVPA (minutes/day)

	Rural areas					**Small towns and suburbs**					**Cities**				
	B	*SE*	*β*	*95%CI*	*p*	*B*	*SE*	*β*	*95%CI*	*p*	*B*	*SE*	*β*	*95%CI*	*p*
(Intercept)	73.02	4.18	0.89	64.80;81.24	**<0.001**	74.51	4.75	0.78	65.17;83.85	**<0.001**	62.14	5.08	0.12	52.12;72.17	**<0.001**
Green space (reference: Bottom [1st] quartile)															
Middle [2nd] quartile	-6.98	4.64	-0.29	-16.10;2.14	0.133	-0.84	4.33	-0.03	-9.35;7.68	0.847	14.58	5.74	0.62	3.27;25.90	**0.012**
Upper [3rd] quartile	-11.19	4.32	-0.47	-19.69;-2.69	**0.010**	0.24	4.09	0.01	-7.80;8.28	0.954	6.55	5.48	0.28	-4.26;17.36	0.233
Top [4th] quartile	-10.55	4.50	-0.44	-19.40;-1.70	**0.020**	-0.37	4.20	-0.02	-8.62;7.88	0.929	8.54	5.82	0.36	-2.93;20.02	0.143
Gender (ref. boys)	-13.76	4.48	-0.58	-22.57;-4.95	**0.002**	-12.24	4.20	-0.51	-20.50;-3.98	**0.004**	-0.87	5.56	-0.04	-11.84;10.10	0.875
Age group (ref. 6-10 years)	-23.63	2.34	-0.99	-28.24;-19.02	**<0.001**	-21.78	2.20	-0.90	-26.11;-17.45	**<0.001**	-23.44	2.83	-0.99	-29.03;-17.85	**<0.001**
Socio-economic status	-0.51	0.37	-0.07	-1.24;0.23	0.174	0.42	0.32	0.06	-0.21;1.05	0.187	-0.58	0.41	-0.08	-1.39;0.23	0.163
BMI (ref. normal weight)															
Underweight	0.74	3.73	0.03	-6.61;8.08	0.844	-4.29	3.93	-0.18	-12.02;3.44	0.276	-2.24	4.68	-0.09	-11.47;7.00	0.634
Overweight/obese	-9.11	3.10	-0.38	-15.22;-3.01	**0.004**	-11.33	3.09	-0.47	-17.41;-5.26	**<0.001**	-7.78	4.37	-0.33	-16.40;0.83	0.076
Season (ref. summer)															
Autumn	6.80	3.20	0.29	0.50;13.10	**0.034**	-3.77	4.15	-0.16	-11.93;4.39	0.364	13.09	4.38	0.56	4.46;21.72	**0.003**
Winter	1.03	3.38	0.04	-5.63;7.68	0.762	-2.56	3.84	-0.11	-10.10;4.99	0.506	7.82	4.36	0.33	-0.78;16.43	0.074
Spring	8.33	3.69	0.35	1.08;15.59	**0.025**	4.77	4.17	0.20	-3.43;12.97	0.254	5.86	4.36	0.25	-2.74;14.45	0.181
Wear time	0.02	0.01	0.09	-0.00;0.04	0.061	0.02	0.01	0.09	0.00;0.04	**0.049**	0.00	0.01	0.02	-0.02;0.03	0.787
Green quartile * gender															
Middle [2nd] quartile * gender	0.99	6.31	0.04	-11.44;13.41	0.876	1.16	5.97	0.05	-10.58;12.90	0.846	-19.96	7.60	-0.85	-34.94;-4.97	**0.009**
Upper [3rd] quartile * gender	9.64	6.33	0.41	-2.83;22.10	0.129	-1.35	5.96	-0.06	-13.07;10.36	0.821	-10.11	7.83	-0.43	-25.55;5.34	0.199
Top [4th] quartile * gender	9.03	6.33	0.38	-3.42;21.49	0.155	3.24	5.91	0.13	-8.39;14.86	0.584	-14.78	7.67	-0.63	-29.91;0.34	0.055
Observations	324					391					208				
R^2 / R^2 adjusted	0.331 / 0.299					0.310 / 0.283					0.404 / 0.357				

Note: For better interpretability of the intercept, socio-economic status and accelerometer wear time were grand-mean centered. BMI = body-mass-index; ref. = reference

Table S3. Multiple Linear Regression Models including Green Space – Age Group Interactions to Predict MVPA (minutes/day)

	Rural areas					Small towns and suburbs					Cities				
	B	*SE*	*β*	*95%CI*	*p*	*B*	*SE*	*β*	*95%CI*	*p*	*B*	*SE*	*β*	*95%CI*	*p*
(Intercept)	73.56	4.23	0.91	65.23;81.90	**<0.001**	76.05	4.72	0.85	66.77;85.33	**<0.001**	65.35	4.79	0.25	55.91;74.80	**<0.001**
Green space (reference: Bottom [1st] quartile)															
Middle [2nd] quartile	-11.74	4.83	-0.49	-21.24;-2.24	**0.016**	-1.13	4.17	-0.05	-9.32;7.07	0.787	10.13	5.01	0.43	0.26;20.00	**0.044**
Upper [3rd] quartile	-11.17	4.62	-0.47	-20.26;-2.08	**0.016**	-1.46	3.99	-0.06	-9.30;6.38	0.715	3.58	5.11	0.15	-6.51;13.67	0.485
Top [4th] quartile	-7.94	4.75	-0.33	-17.29;1.40	0.095	-2.37	4.09	-0.10	-10.41;5.67	0.563	1.53	5.18	0.07	-8.68;11.75	0.767
Age group (ref. 6-10 years)	-28.47	4.60	-1.20	-37.51;-19.43	**<0.001**	-24.60	4.23	-1.02	-32.91;-16.29	**<0.001**	-15.99	5.58	-0.68	-26.99;-4.99	**0.005**
Gender (ref. boys)	-8.87	2.29	-0.37	-13.39;-4.36	**<0.001**	-11.43	2.13	-0.47	-15.61;-7.25	**<0.001**	-12.59	2.77	-0.53	-18.06;-7.13	**<0.001**
Socio-economic status	-0.52	0.38	-0.07	-1.26;0.22	0.168	0.38	0.32	0.05	-0.25;1.01	0.240	-0.48	0.41	-0.07	-1.29;0.34	0.251
BMI (ref. normal weight)															
Underweight	1.30	3.74	0.05	-6.05;8.65	0.729	-4.74	3.93	-0.20	-12.47;2.99	0.229	-2.43	4.63	-0.10	-11.56;6.70	0.600
Overweight/obese	-9.24	3.12	-0.39	-15.37;-3.11	**0.003**	-11.43	3.08	-0.47	-17.49;-5.36	**<0.001**	-7.14	4.41	-0.30	-15.83;1.56	0.107
Season (ref. summer)															
Autumn	6.72	3.20	0.28	0.42;13.03	**0.037**	-4.21	4.13	-0.17	-12.33;3.90	0.308	13.95	4.39	0.59	5.30;22.60	**0.002**
Winter	1.01	3.40	0.04	-5.69;7.70	0.767	-3.10	3.80	-0.13	-10.57;4.36	0.414	7.61	4.42	0.32	-1.11;16.32	0.087
Spring	7.80	3.68	0.33	0.55;15.05	**0.035**	3.98	4.15	0.16	-4.18;12.15	0.338	7.45	4.36	0.32	-1.16;16.06	0.089
Wear time	0.02	0.01	0.09	-0.00;0.04	0.081	0.02	0.01	0.08	-0.00;0.04	0.066	0.00	0.01	0.01	-0.02;0.02	0.890
Green quartile * age group															
Middle [2nd] quartile * age group	8.70	6.37	0.37	-3.84;21.24	0.173	1.84	5.96	0.08	-9.88;13.56	0.758	-16.34	7.71	-0.69	-31.55;-1.12	**0.035**
Upper [3rd] quartile * age group	8.19	6.44	0.34	-4.47;20.86	0.204	2.30	6.01	0.09	-9.53;14.12	0.703	-8.29	7.60	-0.35	-23.28;6.70	0.277
Top [4th] quartile * age group	2.95	6.44	0.12	-9.71;15.62	0.647	7.85	5.98	0.32	-3.90;19.60	0.190	-4.29	7.69	-0.18	-19.46;10.87	0.577
Observations	324					391					208				
R^2 / R^2 adjusted	0.329 / 0.296					0.312 / 0.285					0.396 / 0.349				

Note: For better interpretability of the intercept, socio-economic status and accelerometer wear time were grand-mean centered. BMI = body-mass-index; ref. = reference

Table S4. Multiple Linear Regression Models including Green Space – Socio-economic Status Interactions to Predict MVPA (minutes/day)

	Rural areas					Small towns and suburbs					Cities				
	B	*SE*	*β*	*95%CI*	*p*	*B*	*SE*	*β*	*95%CI*	*p*	*B*	*SE*	*β*	*95%CI*	*p*
(Intercept)	70.23	3.67	0.77	63.01;77.45	**<0.001**	74.34	4.48	0.77	65.54;83.14	**<0.001**	66.37	4.32	0.29	57.86;74.88	**<0.001**
Green space (reference: Bottom [1st] quartile)															
Middle [2nd] quartile	-6.31	3.19	-0.27	-12.59;-0.03	**0.049**	-0.17	2.95	-0.01	-5.97;5.63	0.954	4.78	3.83	0.20	-2.77;12.33	0.213
Upper [3rd] quartile	-6.57	3.19	-0.28	-12.84;-0.30	**0.040**	-0.29	3.03	-0.01	-6.25;5.66	0.923	0.48	3.84	0.02	-7.10;8.05	0.901
Top [4th] quartile	-5.70	3.17	-0.24	-11.94;0.54	0.073	1.23	3.05	0.05	-4.77;7.22	0.688	1.54	3.87	0.07	-6.09;9.18	0.691
Socio-economic status	-1.00	0.68	-0.13	-2.33;0.34	0.144	0.94	0.67	0.13	-0.38;2.25	0.161	-2.29	0.81	-0.32	-3.90;-0.69	**0.005**
Gender (ref. boys)	-8.90	2.29	-0.37	-13.41;-4.40	**<0.001**	-11.44	2.10	-0.47	-15.57;-7.31	**<0.001**	-12.06	2.74	-0.51	-17.46;-6.65	**<0.001**
Age group (ref. 6-10 years)	-23.29	2.35	-0.98	-27.93;-18.66	**<0.001**	-21.75	2.20	-0.90	-26.07;-17.43	**<0.001**	-24.50	2.82	-1.04	-30.06;-18.93	**<0.001**
BMI (ref. normal weight)															
Underweight	0.62	3.73	0.03	-6.72;7.95	0.868	-4.84	3.95	-0.20	-12.60;2.92	0.221	-2.95	4.55	-0.13	-11.93;6.03	0.518
Overweight/obese	-8.62	3.13	-0.36	-14.78;-2.47	**0.006**	-11.61	3.09	-0.48	-17.68;-5.54	**<0.001**	-7.68	4.34	-0.33	-16.24;0.87	0.078
Season (ref. summer)															
Autumn	6.65	3.22	0.28	0.32;12.99	**0.040**	-4.13	4.16	-0.17	-12.30;4.05	0.322	15.27	4.35	0.65	6.68;23.86	**0.001**
Winter	1.39	3.44	0.06	-5.37;8.16	0.686	-2.78	3.82	-0.11	-10.29;4.73	0.467	8.81	4.39	0.37	0.15;17.46	**0.046**
Spring	7.86	3.70	0.33	0.59;15.14	**0.034**	4.69	4.18	0.19	-3.53;12.91	0.262	8.38	4.29	0.36	-0.08;16.85	0.052
Wear time	0.02	0.01	0.08	-0.00;0.04	0.095	0.02	0.01	0.09	0.00;0.04	**0.041**	0.00	0.01	0.01	-0.02;0.03	0.803
Green quartile * socio-economic status (SES)															
Middle [2nd] quartile * SES	1.82	1.00	0.23	-0.16;3.79	0.071	-0.38	0.91	-0.05	-2.18;1.41	0.675	1.14	1.17	0.16	-1.16;3.44	0.329
Upper [3rd] quartile * SES	0.20	1.01	0.03	-1.79;2.20	0.841	-0.85	0.88	-0.12	-2.58;0.89	0.339	3.40	1.13	0.48	1.18;5.62	**0.003**
Top [4th] quartile * SES	-0.02	1.05	-0.00	-2.08;2.04	0.982	-0.76	0.95	-0.11	-2.64;1.11	0.423	2.57	1.15	0.36	0.30;4.84	**0.027**
Observations	324					391					208				
R^2 / R^2 adjusted	0.332 / 0.300					0.311 / 0.283					0.413 / 0.367				

Note: For better interpretability of the intercept, socio-economic status and accelerometer wear time were grand-mean centered. BMI = body-mass-index; ref. = reference

Table S5. Multiple Linear Regression Models for City Youth with Socio-economic Status Divided into Tertiles

	B	*SE*	*β*	*95%CI*	*p*
(Intercept)	78.88	5.38	0.83	68.27;89.49	**<0.001**
Green space (reference: Bottom [1st] quartile)					
Middle [2nd] quartile	-3.75	6.28	-0.16	-16.15;8.65	0.551
Upper [3rd] quartile	-20.26	6.99	-0.86	-34.05;-6.48	**0.004**
Top [4th] quartile	-11.77	5.97	-0.50	-23.55;0.01	0.050
Socio-economic status (ref. 1st tertile / low)					
2nd tertile / medium	-16.29	5.98	-0.69	-28.09;-4.49	**0.007**
3rd tertile / high	-21.58	7.43	-0.92	-36.23;-6.93	**0.004**
Gender (ref. boys)	-12.07	2.73	-0.51	-17.46;-6.68	**<0.001**
Age group (ref. 6-10 years)	-24.93	2.85	-1.06	-30.55;-19.31	**<0.001**
BMI (ref. normal weight)					
Underweight	-2.01	4.58	-0.09	-11.05;7.03	0.661
Overweight/obese	-6.39	4.39	-0.27	-15.06;2.28	0.147
Season (ref. summer)					
Autumn	15.82	4.44	0.67	7.06;24.58	**<0.001**
Winter	9.06	4.39	0.38	0.40;17.72	**0.040**
Spring	9.07	4.31	0.38	0.57;17.56	**0.037**
Wear time	0.00	0.01	0.02	-0.02;0.03	0.746
Green quartile * socio-economic status (SES)					
Middle [2nd] quartile * 2nd SES tertile	11.16	8.88	0.47	-6.36;28.68	0.211
Upper [3rd] quartile * 2nd SES tertile	29.35	9.42	1.25	10.77;47.93	**0.002**
Top [4th] quartile * 2nd SES tertile	20.62	8.89	0.87	3.08;38.16	**0.021**
Middle [2nd] quartile * 3rd SES tertile	12.70	9.78	0.54	-6.60;32.00	0.196
Upper [3rd] quartile * 3rd SES tertile	31.18	9.97	1.32	11.51;50.86	**0.002**
Top [4th] quartile * 3rd SES tertile	19.26	9.63	0.82	0.27;38.26	**0.047**
Observations	208				
R^2 / R^2 adjusted	0.430 / 0.372				

Note: For better interpretability of the intercept, socio-economic status and accelerometer wear time were grand-mean centered.

Table S6. Descriptive Information about the Study Sample including Participants with Missing Data

	Rural areas (N = 406)	**Town/suburb** (N = 523)	**Cities** (N = 282)	**Overall** (N = 1,211)
Gender				
Boys	208 (51.23%)	271 (51.82%)	148 (52.48%)	627 (51.78%)
Girls	198 (48.77%)	252 (48.18%)	134 (47.52%)	584 (48.22%)
Missing	*0 (0%)*	*0 (0%)*	*0 (0%)*	*0 (0%)*
Age in years (Mean, SD)	11.64 (3.372)	11.29 (3.480)	11.31 (3.226)	11.41 (3.387)
Missing	*0 (0%)*	*0 (0%)*	*0 (0%)*	*0 (0%)*
Age group				
6-10 years	186 (45.81%)	268 (51.24%)	139 (49.29%)	593 (48.97%)
11-17 years	220 (54.19%)	255 (48.76%)	143 (50.71%)	618 (51.03%)
Missing	*0 (0%)*	*0 (0%)*	*0 (0%)*	*0 (0%)*
BMI				
Underweight	38 (9.38%)	39 (7.46%)	32 (11.35%)	109 (9.008%)
Normal weight	290 (71.60%)	403 (77.06%)	217 (76.95%)	910 (75.21%)
Overweight/obese	77 (19.01%)	81 (15.49%)	33 (11.70%)	191 (15.79%)
Missing	*1 (0.2%)*	*0 (0%)*	*0 (0%)*	*1 (0.1%)*
Socio-economic status (Mean, SD)	14.82 (3.08)	15.73 (3.38)	15.84 (3.43)	15.46 (3.32)
Missing	*14 (3.4%)*	*8 (1.5%)*	*9 (3.2%)*	*31 (2.6%)*
Season				
Summer	93 (22.91%)	43 (8.222%)	41 (14.54%)	177 (14.62%)
Autumn	136 (33.50%)	137 (26.20%)	84 (29.79%)	357 (29.48%)
Winter	96 (23.65%)	225 (43.02%)	74 (26.24%)	395 (32.62%)
Spring	81 (19.95%)	118 (22.56%)	83 (29.43%)	282 (23.29%)
Missing	*0 (0%)*	*0 (0%)*	*0 (0%)*	*0 (0%)*
Greenspace (%)				
Mean (SD)	0.14 (0.15)	0.13 (0.11)	0.14 (0.10)	0.14 (0.12)
Missing	3 (0.7%)	5 (1.0%)	0 (0%)	8 (0.7%)
Accelerometer wear time min/day (Mean, SD)	824.02 (111.25)	811.43 (102.60)	828.94 (128.63)	819.83 (112.07)
Missing	*67 (16.5%)*	*122 (23.3%)*	*68 (24.1%)*	*257 (21.2%)*
MVPA min/day(Mean, SD)	51.95 (23.82)	55.18 (24.09)	59.23 (23.36)	54.94 (23.96)
Missing	*67 (16.5%)*	*122 (23.3%)*	*68 (24.1%)*	*257 (21.2%)*

Table S7. Sensitivity Analysis with Imputed Data for Missing Values for Multiple Linear Regression Analysis with Green Space Stratified by Urbanicity Level Predicting MVPA (minutes/day)

	Rural areas			**Small towns and suburbs**			**Cities**		
	B	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*
(Intercept)	69.86	3.60	**<0.001**	74.18	4.42	**<0.001**	68.63	4.20	**<0.001**
Green space (reference: Bottom [1st] quartile)									
Middle [2nd] quartile	-5.48	3.24	0.090	-2.12	2.95	0.472	3.04	3.81	0.424
Upper [3rd] quartile	-6.49	3.15	**0.039**	0.29	2.98	0.926	-1.11	3.68	0.763
Top [4th] quartile	-5.70	3.22	0.077	0.96	3.04	0.752	0.09	3.68	0.980
Socio-economic status	-0.53	0.38	0.155	0.44	0.32	0.168	-0.46	0.41	0.252
Gender (ref. boys)	-9.18	2.25	**<0.001**	-10.66	2.06	**<0.001**	-12.58	2.71	**<0.001**
Age group (ref. 6-10 years)	-23.21	2.31	**<0.001**	-21.32	2.13	**<0.001**	-23.31	2.78	**<0.001**
BMI (ref. normal weight)									
Underweight	1.01	1.01	0.786	-5.53	3.85	0.151	-3.26	4.44	0.463
Overweight/obese	-7.66	3.74	**0.010**	-11.67	3.01	**<0.001**	-7.56	4.34	0.082
Season (ref. summer)									
Autumn	6.75	3.07	**0.028**	-4.40	4.09	**0.282**	14.29	4.30	**0.001**
Winter	1.43	3.27	**0.661**	-3.15	3.78	**0.404**	7.86	4.32	0.069
Spring	8.66	3.60	**0.015**	3.93	4.11	**0.339**	7.55	4.28	0.078
Wear time	0.02	0.01	0.056	0.02	0.01	**0.049**	0.00	0.01	0.930

Note: For better interpretability of the intercept, socio-economic status and accelerometer wear time were grand-mean centered. BMI = body-mass-index; ref. = reference

Table S8. Sensitivity Analysis with Imputed Data for Missing Values for Multiple Linear Regression Models including Green Space – Gender Interactions to Predict MVPA (minutes/day)

	Rural areas			**Small towns and suburbs**			**Cities**		
	B	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*
(Intercept)	72.00	4.15	**<0.001**	74.62	4.74	**<0.001**	62.95	4.84	**<0.001**
Green space (reference: Bottom [1st] quartile)									
Middle [2nd] quartile	-4.82	4.75	0.310	-4.32	4.30	0.315	13.81	5.50	**0.012**
Upper [3rd] quartile	-11.01	4.26	**0.010**	0.97	4.05	0.811	4.14	5.20	0.426
Top [4th] quartile	-10.03	4.61	**0.002**	-0.72	4.17	0.863	8.53	5.50	0.121
Gender (ref. boys)	-13.79	4.50	**<0.001**	-12.14	4.23	**0.004**	-2.17	5.17	0.121
Socio-economic status	-0.52	0.36	0.163	0.44	0.32	0.169	-0.47	0.40	0.675
Age group (ref. 6-10 years)	-23.36	2.30	**<0.001**	-21.40	2.16	**<0.001**	-23.55	2.76	**<0.001**
BMI (ref. normal weight)									
Underweight	0.77	3.73	0.836	-5.47	3.87	0.157	-2.48	4.47	0.579
Overweight/obese	-7.76	2.99	**0.009**	-11.45	3.02	**<0.001**	-7.75	4.29	0.071
Season (ref. summer)									
Autumn	7.15	3.07	**0.020**	-4.13	4.13	0.317	13.67	4.27	**0.001**
Winter	1.56	3.26	**0.631**	-2.84	3.82	0.457	8.06	4.27	0.059
Spring	9.17	3.58	**0.010**	4.11	4.15	0.322	6.49	4.25	0.127
Wear time	0.02	0.01	**0.037**	0.02	0.01	**0.042**	0.00	0.01	0.830
Green quartile * gender									
Middle [2nd] quartile * gender	-0.65	6.37	0.919	4.19	5.98	0.484	-19.69	7.49	**0.008**
Upper [3rd] quartile * gender	10.09	6.24	0.105	-1.51	5.87	0.796	-8.13	7.41	0.273
Top [4th] quartile * gender	8.76	6.41	0.172	3.50	5.92	0.555	-14.61	7.27	**0.045**

Note: For better interpretability of the intercept, socio-economic status and accelerometer wear time were grand-mean centered. BMI = body-mass-index; ref. = reference

Table S9. Sensitivity Analysis with Imputed Data for Missing Values for Multiple Linear Regression Models including Green Space – Age Group Interactions to Predict MVPA (minutes/day)

	Rural areas			Small towns and suburbs			Cities		
	B	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*
(Intercept)	72.13	4.28	**<0.001**	76.27	4.73	**<0.001**	66.26	4.62	**<0.001**
Green space (reference: Bottom [1st] quartile)									
Middle [2nd] quartile	-9.03	5.11	0.078	-5.05	4.22	0.232	9.07	4.95	0.067
Upper [3rd] quartile	-10.99	4.68	**0.019**	-0.31	3.96	0.939	1.04	4.90	0.833
Top [4th] quartile	-6.61	4.89	0.174	-3.40	4.09	0.405	1.57	4.92	0.749
Age group (ref. 6-10 years)	-27.19	4.73	**<0.001**	-25.32	4.26	**<0.001**	-17.28	5.31	**0.001**
Socio-economic status	-0.53	0.38	0.164	0.38	0.32	0.239	-0.45	0.41	0.266
Gender (ref. boys)	-9.27	2.26	**<0.001**	-10.60	2.09	**<0.001**	-12.94	2.71	**<0.001**
BMI (ref. normal weight)									
Underweight	1.38	3.75	0.713	-6.02	3.86	0.119	-2.82	4.45	0.526
Overweight/obese	-7.91	3.00	**0.008**	-11.79	3.01	**<0.001**	-7.26	4.34	0.095
Season (ref. summer)									
Autumn	7.09	3.09	**0.022**	-4.39	4.10	0.284	14.65	4.31	**0.001**
Winter	1.68	3.29	0.609	-3.33	3.78	0.379	7.68	4.32	0.075
Spring	8.74	3.58	**0.015**	3.45	4.13	0.403	8.05	4.32	0.062
Wear time	0.02	0.01	0.057	0.02	0.01	0.080	0.00		
Green quartile * gender									
Middle [2nd] quartile * age group	6.02	6.63	0.364	5.97	6.04	0.323	-14.26	7.59	0.060
Upper [3rd] quartile * age group	8.57	6.49	0.187	0.95	5.92	0.872	-5.98	7.31	0.414
Top [4th] quartile * age group	0.99	6.55	0.880	9.67	5.99	0.106	-4.33	7.42	0.559

Note: For better interpretability of the intercept, socio-economic status and accelerometer wear time were grand-mean centered. BMI = body-mass-index; ref. = reference

Table S10. Sensitivity Analysis with Imputed Data for Missing Values for Multiple Linear Regression Models including Green Space– Socio-economic Status Interactions to Predict MVPA (minutes/day)

	Rural areas			Small towns and suburbs			Cities		
	B	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*
(Intercept)	69.34	3.62	**<0.001**	73.98	4.48	**<0.001**	67.35	4.14	**<0.001**
Green space (reference: Bottom [1st] quartile)									
Middle [2nd] quartile	-4.97	3.24	0.125	-1.84	2.97	0.536	4.71	3.79	0.213
Upper [3rd] quartile	-6.34	3.15	**0.044**	0.53	3.00	0.859	-1.15	3.66	0.753
Top [4th] quartile	-5.38	3.22	0.095	1.19	3.06	0.697	1.22	3.66	0.739
Socio-economic status	-0.87	0.69	0.204	1.02	0.68	0.136	-1.99	0.75	**0.008**
Gender (ref. boys)	-9.26	2.26	**<0.001**	-10.62	2.07	**<0.001**	-12.35	2.66	**<0.001**
Age group (ref. 6-10 years)	-22.99	2.32	**<0.001**	-21.39	2.16	**<0.001**	-24.27	2.75	**<0.001**
BMI (ref. normal weight)									
Underweight	0.79	0.79	0.833	-5.67	3.89	0.145	-3.06	4.38	0.484
Overweight/obese	-7.32	3.01	**0.015**	-11.82	3.02	**<0.001**	-7.40	4.27	0.084
Season (ref. summer)									
Autumn	7.00	3.11	**0.024**	-4.53	4.14	0.274	15.01	4.24	**<0.001**
Winter	2.01	3.33	0.546	-3.09	3.81	0.417	8.37	4.27	0.050
Spring	8.76	3.61	**0.015**	4.01	4.16	0.335	8.10	4.21	0.054
Wear time	0.02	0.01	0.061	0.02	0.01	**0.042**	000	0.01	0.975
Green quartile * socio-economic status									
Middle [2nd] quartile * SES	1.48	1.03	0.148	-0.78	0.92	0.400	0.57	1.17	0.628
Upper [3rd] quartile * SES	0.21	1.02	0.836	-0.71	0.89	0.425	3.02	1.07	**0.005**
Top [4th] quartile * SES	-0.28	1.06	0.795	-0.73	0.96	0.448	2.39	1.09	**0.028**

Note: For better interpretability of the intercept, socio-economic status and accelerometer wear time were grand-mean centered. BMI = body-mass-index; ref. = reference

Appendix E: Supplement Chapter 6

Test statistics and descriptives

Author/ year	**Results**		
Barton et al. (2015)	No effects on the SE change score due to intervention type, school location or interaction of both (all p > 0.05). Pre-intervention SE score affected SE score change (F[1,77] = 25.09; p < .01).		
		SE change scores	
		Nature-based orienteering	**Playground sports equipment**
	Urban school	2.16 ± 5.81 [0.68–5.16]	2.33 ± 6.69 [-0.65–3.66]
	Rural school	0.59 ± 3.33 [-0.97-3.19]	0.78 ± 5.18 [-1.68-2.46]
Duncan et al. (2014)	No interaction effects (condition X time) or main effects (all p > 0.05) for diastolic BP. For systolic BP, no significant interaction or main effects immediately post-exercise (p > .05). Significant condition X time interaction for systolic BP 15 minutes post-exercise (F [2,26] = 3.49, p = 0.04, Pɳ2 = 0.212) with systolic BP significantly lower after green exercise. No significant condition X time interaction for heart rate, no main effect for condition (both p > .05). Significant main effect with HR being higher immediately and 15-min. post-exercise (F [2,26] = 47.19, p < .01, Pɳ2 = 0.784). Significant mood scale X time (F [2,12] = 48.6, p < .01, Wilks' Lambda = 0.11, Pɳ2 = 0.89). Post-exercise, significantly higher fatigue scores and significantly lower vigor scores (Bonferroni corrected p = 0.001). Scores for tension were not significantly different (p > 0.05).		
		Green exercise	**Control condition**
		Diastolic BP (mm Hg)	
	Pre	m=69.5 [64.2-74.8]	m=64.7 [60.4-68.9]
	Immediately post	m=68.4 [61-75.8]	m=70.6 [62.9-78.2]
	15 minutes post	m=66.6 [62.6-70.5]	m=64.4 [58.8-68.3]
		Systolic BP (mm Hg)	
	Pre	m=103.9 [99.5-108.2]	m=102.2 [98.4-105.9]
	Immediately post	m=111.2 [108.1-117.3]	m=112.7 [103-121.4]
	15 minutes post	m=97.2 [93.9-100.4]	m=102.7 [99.1-108.6]
		Heart rate (bpm)	
	Pre	m=81 [76-84]	m=83 [76-89]
	Immediately post	m=102 [95-108]	m=106 [101-109]
	15 minutes post	m=93 [89-97]	m=94 [86-101]
		Mood state	
	Fatigue pre	m=39.3 [39-42]	m=39.8 [37.8-42.2]
	Fatigue post	m=45.3 [43.5-49.2]	m=47 [44.5-50]
	Vigor pre	m=52.1 [49-55]	m=51.5 [48.6-54.6]
	Vigor post	m=45 [42.1-49]	m=44.4 [40.6-48.6]
	Tension pre	m=45.8 [43.1-48]	m=45 [42.9-47]
	Tension post	m=44.4 [42.9-46.3]	m=44.5 [43-45.6]
Faber Taylor & Kuo (2009)	DSB performance dependent on setting (F [2,16] = 4.72, p < .05). No significant DSB performance differences between neighborhood and downtown settings (p > .05). DSB scores better after park walk (Fisher's PLSD d = .71, p < .01), and downtown walk (Fisher's PLSD d = .59, p < .05). Park setting significantly higher on fun (t [13] = 2.39, p < .05). No other significant rating differences (all p > .05).		
		DSB performance mean scores after walk in each setting	
	Neighborhood	m=3.71 ± 1.21	
	Downtown	m=3.82 ± 1.07	
	Park	m=4.41 ± 1.18	
Flynn et al. (2017)	A request was sent out to the other for the exact test statistics, but no reply was obtained. No significant differences for PA self-efficacy and enjoyment. At follow-up, children reported increased frequency of someone having performed a physical activity or played a sport with them (median score, 2; range, 2–3) and that someone had provided transportation to a place where they could do physical activities or sports (median score, 2; range, 1–3).		
Gopinath, Baur et al.; Gopinath, Hardy et al. (2011)	No significant differences between the tertile groups of indoor and outdoor PA for retinal arteriolar and venular diameter and systolic and diastolic BP. Linear associations between BP and outdoor and indoor PA: No significant effect of outdoor PA on any BP measures (systolic / diastolic / mean arterial BP). Significant effect of indoor PA on diastolic BP and mean arterial BP.		

Study		Outdoor PA	Indoor PA
	Retinal arteriolar caliber (μm)		
	Low tertile	m=162.5 [160.9-164.1]	m=163.3 [161.6-164.9]
	Moderate tertile	m=163.0 [161.0-165.1]	m=164.7 [162.0-167.4]
	High tertile	m=164.7 [163-166.5]	m=162.4 [161.0-163.8]
	Retinal venular caliber (μm)		
	Low tertile	m=229.7 [227.2-230.8]	m=229.0 [227.2-230.8]
	Moderate tertile	m=228.8 [226.6-231.1]	m=228.8 [226.6-231.1]
	High tertile	m=229.3 [226.3-230.4]	m=228.2 [226.2-230.2]
	Systolic BP (mm Hg)		
	Low tertile	m=100.8 [99.1-102.4]	m=101.2 [99.6-102.8]
	Moderate tertile	m=100.8 [99.4-102.3]	m=100.8 [99.5-102.1]
	High tertile	m=100.9 [99.4-102.5]	m=99.9 [98.3-101.5]
	Diastolic BP (mm Hg)		
	Low tertile	m=63.0 [60.8-65.2]	m=62.6 [60.7-64.5]
	Moderate tertile	m=62.9 [61.1-64.6]	m=62.4 [60.2-64.5]
	High tertile	m=61.5 [59.5-65.5]	m=62.0 [60.2-63.9]
	Multiple Regression on BP outcomes (mm Hg)		
	Systolic BP	β=.38 (SE: .34), p > .05	β= -1.76 (SE: 1.26), p > .05
	Diastolic BP	β= -.80 (SE: .42), p > .05	β= -2.35 (SE: .73), p < .01
	Mean arterial BP	β= -.41 (SE: .33), p > .05	β= -2.15 (SE: .75), p < .01

Gopinath et al. (2012)

For indoor PA, the moderate- and high-PA tertiles were only presented summarized.
Higher QoL total score, physical, psychosocial, emotional, social and school scores in low tertiles of indoor PA compared to low tertiles of outdoor PA
Higher QoL total score, physical, psychosocial, emotional, social and school scores in high tertiles of outdoor PA compared to moderate-high tertiles of indoor PA

Note: The CIs were not presented in the original study but calculated by the authors of this review to allow for comparisons between outdoor and indoor PA in terms of health-related life quality. Mean differences were considered as significant when CIs were not overlapping.

Study		Outdoor PA	Indoor PA
	Quality of life total score		
	Low tertile cross-sectional (CS)	m=79.65 [79.54-79.76]	m=80.23 [80.77-80.89]
	Moderate tertile CS	m=79.84 [79.71-79.97]	m=79.40 [79.28-79.52]
	High tertile CS	m=81.84 [81.73-81.95]	
	Low tertile longitudinal (LT)	m=78.68 [78.25-79.11]	m=80.75 [80.10-81.40]
	Moderate tertile LT	m=79.30 [78.83-79.77]	m=79.66 [79.17-80.15]
	High tertile LT	m=83.12 [82.75-83.49]	
	Physical score		
	Low tertile CS	m=89.23 [89.11-89.35]	m=90.60 [90.62-90.76]
	Moderate tertile CS	m=89.61 [89.47-89.75]	m=90.33 [90.19-90.47]
	High tertile CS	m=92.72 [92.59-92.85]	
	Low tertile LT	m=89.03 [88.60-89.46]	m=94.35 [93.62-95.08]
	Moderate tertile LT	m=89.11 [88.64-89.58]	m=93.35 [92.80-93.90]
	High tertile LT	m=95.11 [94.74-95.48]	
	Psychosocial score		
	Low tertile CS	m=75.00 [74.87-75.13]	m=76.07 [76.00-76.14]
	Moderate tertile CS	m=75.04 [74.89-75.19]	m=74.05 [73.90-74.20]
	High tertile CS	m=76.56 [76.42-76.70]	
	Low tertile LT	m=89.03 [88.60-89.46]	m=73.97 [73.16-74.78]
	Moderate tertile LT	m=89.11 [88.64-89.58]	m=72.91 [72.67-73.15]
	High tertile LT	m=95.11 [94.74-95.48]	
	Emotional score		
	Low tertile CS	m=72.65 [72.48-72.82]	m=73.75 [73.65-73.85]
	Moderate tertile CS	m=72.40 [72.21-72.59]	m=71.06 [70.87-71.25]
	High tertile CS	m=73.97 [73.80-74.14]	

	Low tertile LT	m=70.16 [69.46-70.86]	m=69.46 [68.36-70.56]	
	Moderate tertile LT	m=69.61 [68.85-70.37]	m=68.00 [67.19-68.81]	
	High tertile LT	m=73.47 [72.87-74.07]		
	Social score			
	Low tertile CS	m=89.05 [88.92-89.18]	m=90.84 [90.77-90.91]	
	Moderate tertile CS	m=88.67 [88.52-88.82]	m=88.63 [88.48-88.78]	
	High tertile CS	m=92.62 [92.48-92.76]		
	Low tertile LT	m=88.21 [87.74-88.68]	m=89.98 [89.17-90.79]	
	Moderate tertile LT	m=90.08 [89.57-90.59]	m=89.43 [88.82-90.04]	
	High tertile LT	m=93.54 [93.14-93.94]		
	School score			
	Low tertile CS	m=64.11 [63.92-64.30]	m=64.41 [64.30-64.52]	
	Moderate tertile CS	m=64.99 [64.78-65.20]	m=63.56 [63.35-63.77]	
	High tertile CS	m=64.03 [63.83-64.23]		
	Low tertile LT	m=63.30 [62.54-64.06]	m=63.32 [62.14-64.50]	
	Moderate tertile LT	m=65.16 [64.33-65.99]		
	High tertile LT	m=65.64 [65.01-66.27]	m=63.00 [62.13-63.87]	
Hammond et al. (2011)	No significant correlations neither between outdoor organized activities / sports and health problems or indoor organized activities / sports (all p > .05)			
		Outdoor organized activities / sports	**Indoor organized activities / sports**	
	Body pain / discomfort	r=.05, p>.05	r= -.05, p>.05	
	Trouble sleeping	r= -.13, p>.05	r= -.01, p>.05	
	Repeated upset stomach	r= -.04, p>.05	r= -.04, p>.05	
	Feeling tired / having low energy	r= -.04, p>.05	r= -.04, p>.05	
Liu et al. (2015)	Children who took part in outdoor PA had higher proportion of good self-reported health than those without. For females, only significant health differences between frequent and infrequent outdoor PA at age 12. Participation in outdoor PA at both ages 6 and 12 years is associated with a higher likelihood of good self-reported health (OR= 1.27[1.08, 1.50]) compared with those who did not like or participate in this at only one or at neither age. OR 1.47[1.14-1.89] for persistent outdoor participation in boys, no significant different likelihood for persistent outdoor PA in girls (OR= 1.14 [.92-1.42]).			
	Good self-reported health			
		Frequent outdoor PA	**Infrequent outdoor PA**	
	Males 6 years	85.5%	79.7%	*p<.01*
	Males 12 years	86.5%	81.5%	*p<.01*
	Females 6 years	81.0%	80.5%	*p>.05*
	Females 12 years	82.5%	78.7%	*p<.05*
	Both ages	82.3%	79.1%	*p<.05*
Parsons et al. (2018)	No associations between napping, nighttime sleep duration and total sleep with PA time indoors or outdoors.			
		Outdoor PA	**Indoor PA**	
	Nighttime sleep (hours)	m=9.69 ± .97 β=.02 (SE=.04), p>.05	m=9.69 ± .97 β=.07 (SE=.05), p<.05	
	Nighttime and nap sleep (hours)	m=11.20 ± 1.03 β= -.01 (SE=.06), p>.05	m=11.20 ± 1.03 β= .10 (SE=.06), p>.05	
	Napped at center	OR 1.10 [.67-1.81]	OR .88 [.61-.125]	
	Bedtime after 9 pm	OR 1.06 [.9-1.26]	OR .81 [.7-.94]	
Raney et al. (2019)	Condition X time interaction for antisocial behavior (F[2,998]=10.28, p<0.01) with physical and verbal conflict rates decreasing below pre-greening rates after 4 months at the experimental location. Significant decrease in minutes spent alone (mean difference= −2.2 [1.7−2.7], p<0.01) and significant increase in the number of minutes spent in small groups (mean difference=1.7 [0.9-2.6], p<0.01) at experimental location.			
	Number of antisocial interactions during 20 min. recess			
		Greening location	**Control location**	
	Pre-greening	m=3.5 [2.5-4.5]	m=3.6 [3.2-4.0]	
	Post-greening	m=4.6 [3.0-6.2]	m=2.9 [1.5-4.3]	
	4 month follow-up	m=1.8 [1.0-2.6]	m=3.2 [2.6-3.8]	
Reed et al. (2013)	There was a significant main effect for exercise on self-esteem (F[1,74]=12.2, p<.01), but no main effect for exercise condition (F[1,74]=0.02, p>.05) and no interaction (F[1,74] = 0.13, p>.05). No significant differences			

<table>
<tr><td rowspan="5"></td><td colspan="4">between green and control exercise in terms of enjoyment (t[75] = 0.43, p>.05), ratings of perceived exertion (t[75] = 0.11, p>.05) or change in self-esteem (t[75] = 0.13, p>.05).</td></tr>
<tr><td></td><td>Green Exercise</td><td>Control condition</td><td></td></tr>
<tr><td>Δ Self-esteem</td><td>.9 ± 2.6</td><td>.5 ± 4.2</td><td>p>.05</td></tr>
<tr><td>Ratings of perceived exertion</td><td>m=13.5 ± 3.6</td><td>m=13.6 ± 3.6</td><td>p>.05</td></tr>
<tr><td>Enjoyment</td><td>m=89.2 ± 31.4</td><td>m=83.6 ± 34.7</td><td>p>.05</td></tr>
<tr><td rowspan="14">Wood et al. (2013)</td><td colspan="4">Significant main effect on SE due to PA (F[1]=6.10, p<.05) but not due to the environmental viewing condition (p>.05). For mood, no significant effect of viewing different environmental conditions (p>.05). Main effect for mood changes and PA participation (F[6]=5.29, p<.01). PA resulted in significant increase in fatigue (F[1]=8.11, Bonferroni corrected p<.0083) and decrease in tension (F[1]=11.56, Bonferroni corrected p<.0083). No other significant pre-post changes on other mood sub-scale (all p > .0083). No significant main effect for total mood disturbance due to participation in PA or environmental viewing condition (all p>.05).</td></tr>
<tr><td></td><td>Green Exercise</td><td>Control condition</td><td></td></tr>
<tr><td>Tension pre</td><td>m=49.7 ± 7.9</td><td>m=50.3 ± 9.3</td><td></td></tr>
<tr><td>Tension post</td><td>m=50.3 ± 9.3</td><td>m=44.7 ± 6.1</td><td></td></tr>
<tr><td>Depression pre</td><td>m=45.8 ± 4.0</td><td>m=45.0 ± 3.2</td><td></td></tr>
<tr><td>Depression post</td><td>m=45.9 ± 4.3</td><td>m=45.3 ± 3.7</td><td></td></tr>
<tr><td>Anger pre</td><td>m=46.6 ± 6.1</td><td>m=46.7 ± 5.6</td><td></td></tr>
<tr><td>Anger post</td><td>m=47.0 ± 9.4</td><td>m=46.9 ± 6.7</td><td></td></tr>
<tr><td>Vigour pre</td><td>m=53.4 ± 9.1</td><td>m=50.3 ± 8.7</td><td></td></tr>
<tr><td>Vigour post</td><td>m=49.8 ± 9.4</td><td>m=48.6 ± 9.3</td><td></td></tr>
<tr><td>Fatigue pre</td><td>m=47.6 ± 10.1</td><td>m=46.6 ± 9.5</td><td></td></tr>
<tr><td>Fatigue post</td><td>m=52.4 ± 9.5</td><td>m=52.6 ± 10.2</td><td></td></tr>
<tr><td>Confusion pre</td><td>m=46.9 ± 5.6</td><td>m=46.4 ± 5.5</td><td></td></tr>
<tr><td>Confusion post</td><td>m=45.2 ± 4.5</td><td>m=45.2 ± 5.1</td><td></td></tr>
<tr><td rowspan="5">Wood et al. (2014)</td><td colspan="4">No significant interaction for time X environmental condition for SE. No significant main effect due to the orienteering environment (all p>0.05). Significant time main effect for SE (F[1,49]= 5.24; p<.05, n_p=0.1).</td></tr>
<tr><td></td><td colspan="2">Self-esteem scores</td><td></td></tr>
<tr><td></td><td>Green Exercise</td><td>Control Condition</td><td></td></tr>
<tr><td>Pre</td><td>m=31.5 [30.2-32.3]</td><td>m=31.4 [30.1-32.1]</td><td></td></tr>
<tr><td>Post</td><td>m=31.9 [30.6-32.7]</td><td>m=32.4 [31.1-33.3]</td><td></td></tr>
</table>

Quality assessment with the EPHPP tool

Category and Global rating

Study	*Selection Bias*	*Study Design*	*Confounders*	*Blinding*	*Data Collection Methods*	*Withdrawal / Dropouts*	***Overall Rating***
Barton et al. (2015)	3	2	1	3	3	3	**3**
Duncan et al. (2014)	3	1	1	3	1	1	**3**
Faber Taylor & Kuo (2009)	3	1	1	1	1	2	**2**
Flynn et al. (2017)	3	2	1	3	2	3	**3**
Gopinath, Baur et al. / Gopinath, Hardy et al. 2011	2	3	N/A	N/A	3	1	**3**
Gopinath et al. (2012)	2	2	N/A	N/A	3	3	**3**
Hammond et al. (2011)	3	3	N/A	N/A	3	1	**3**
Liu et al. (2015)	2	2	N/A	N/A	3	3	**3**
Parsons et al. (2018)	2	3	N/A	N/A	3	1	**3**
Raney et al. (2019)	3	1	3	3	1	3	**3**
Reed et al. (2013)	3	1	1	3	3	1	**3**
Wood et al. (2013)	3	1	1	2	3	1	**3**
Wood & Smyth (2014)	3	1	1	3	2	3	**3**

Intervention Integrity and Analyses

	Intervention Integrity			*Analyses*			
	% participants receiving allocated exposure	*Consistency measured*	*Likely that subjects received an unintended intervention*	*Unit of allocation*	*Unit of analyses*	*Statistical methods appropriate*	*Analyses by allocation status rather than actual intervention received*
Barton et al. (2015)	80-100	Can’t tell	Can’t tell	Individual	Individual	No	No
Duncan et al. (2014)	80-100	Yes	Can’t tell	Individual	Individual	No	Yes
Faber Taylor & Kuo (2009)	80-100	Yes	Can’t tell	Individual	Individual	Yes	No
Flynn et al. (2017)	80-100	Yes	Can’t tell	Individual	Individual	Yes	No
Gopinath, Baur et al. 2011	N/A			Individual	Individual	No	No
Gopinath, Hardy et al. (2011)	N/A			Individual	Individual	No	No
Gopinath et al. (2012)	N/A			Individual	Individual	No	No
Hammond et al. (2011)	N/A			Individual	Individual	Yes	N/A
Liu et al. (2015)	N/A			Individual	Individual	No	No
Parsons et al. (2018)	N/A			Individual	Individual	No	N/A
Raney et al. (2019)	80-100	Can’t tell	Can’t tell	Individual	Individual	No	No
Reed et al. (2013)	80-100	Yes	Can’t tell	Individual	Individual	Yes	No
Wood et al. (2013)	80-100	Yes	Can’t tell	Individual	Individual	No	No
Wood & Smyth (2014)	80-100	Can’t tell	Can’t tell	Individual	Individual	No	No

Appendix F: Supplement Chapter 8

A1. Detailed search strategy implemented

Web of Science

TS=(“Covid 19” OR COVID-19 OR Corona OR Covid19 OR pandemic OR Sars-Cov-2 OR lockdown) AND TS=(outdoor* OR ”green space” OR “green area*” OR vegetation OR ”blue space” OR “blue area*” OR river OR lake OR ocean OR sea OR ”nature-based” OR ”natur* space” OR "natur* environment" OR "open space" OR "green infrastructure" OR park OR woodland* OR forest* OR mountain* OR beach OR wetland* OR horticulture OR “therapeutic landscape*” OR “ecosystem service*” OR friluftsliv OR wilderness OR garden* OR “digital nature” OR “planetary health”)

Scopus

TITLE-ABS-KEY(“Covid 19” OR COVID-19 OR Corona OR Covid19 OR pandemic OR Sars-Cov-2 OR lockdown) AND TITLE-ABS-KEY (outdoor* OR ”green space” OR “green area*” OR vegetation OR ”blue space” OR “blue area*” OR river OR lake OR ocean OR sea OR ”nature-based” OR ”natur* space” OR "natur* environment" OR "open space" OR "green infrastructure" OR park OR woodland* OR forest* OR mountain* OR beach OR wetland* OR horticulture OR “therapeutic landscape*” OR “ecosystem service*” OR friluftsliv OR wilderness OR garden* OR “digital nature” OR “planetary health”)

Pubmed

(COVID-19[mh] OR Covid19[tiab] OR SARS-CoV-2[mh] OR Corona [tiab] OR lockdown[tiab] OR pandemic[tiab]) AND (outdoor[tiab] OR "green space"[tiab] OR “green area*”[tiab] OR vegetation[tiab] OR "blue space"[tiab] OR “blue area*”[tiab] OR river[tiab] OR lake[tiab] OR ocean[tiab] OR sea[tiab] OR "nature based"[tiab] OR "natural environment"[tiab] OR "natural space"[tiab] OR “therapeutic landscape"[tiab] OR "park"[tiab] OR woodland[tiab] OR forest[tiab] OR mountain[tiab] OR beach[tiab] OR wetland[tiab] OR horticulture[tiab] OR “ecosystem service*”[tiab] OR friluftsliv[tiab] OR wilderness[tiab] OR garden*[tiab] OR “digital nature” [tiab] OR “planetary health” [tiab])

Embase (via Ovid)

1 Covid: Title OR Abstract OR keyword
2 Green: Title OR Abstract OR keyword
3 Year of Publication: 2020 Or 2021
1 and 2 and 3
(Covid 19 OR COVID-19 OR Corona OR Covid19 OR pandemic OR Sars-Cov-2 OR lockdown) AND (outdoor OR green space OR green area OR vegetation OR blue space OR blue area OR river OR lake OR ocean OR sea OR nature-based OR natural space OR natural environment OR open space OR green infrastructure OR park OR woodland OR forest OR mountain OR beach OR wetland OR horticulture OR therapeutic landscape OR ecosystem service OR friluftsliv OR wilderness OR garden OR digital nature OR planetary health)

CINAHL

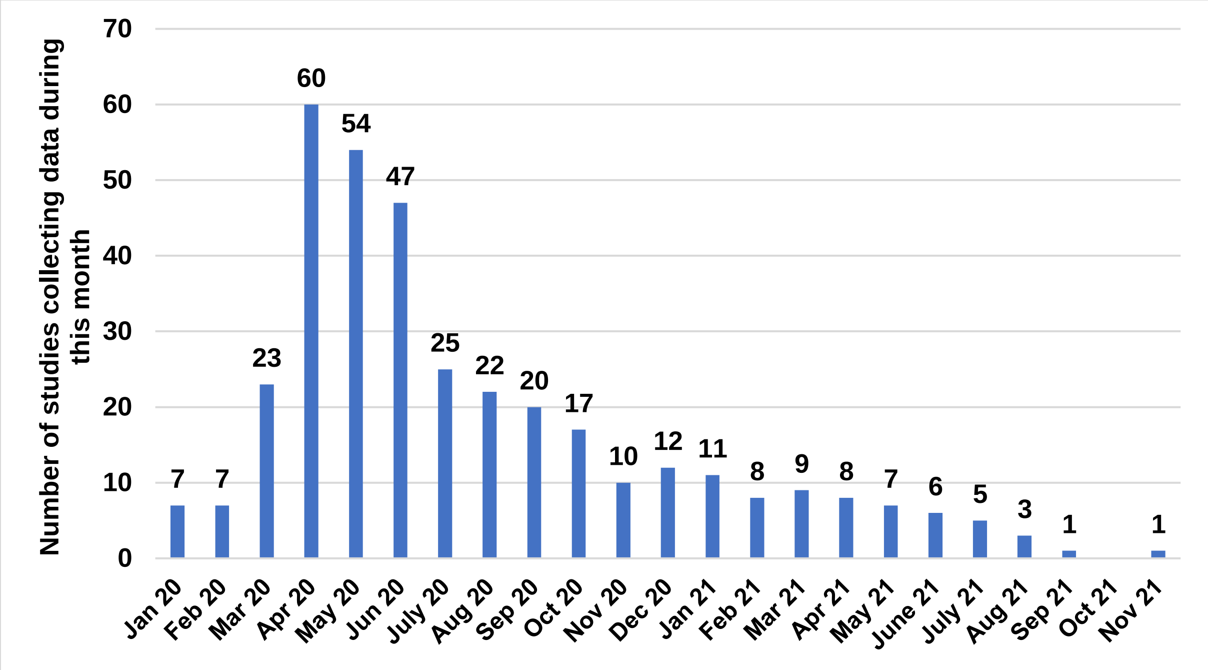
Select a field (optional) and restriction to 2020 and 2021 (Year of Publication)
(Covid 19 OR COVID-19 OR Corona OR Covid19 OR pandemic OR Sars-Cov-2 OR lockdown) AND (outdoor OR green space OR green area OR vegetation OR blue space OR blue area OR river OR lake OR ocean OR sea OR nature-based OR natural space OR natural environment OR open space OR green

infrastructure OR park OR woodland OR forest OR mountain OR beach OR wetland OR horticulture OR therapeutic landscape OR ecosystem service OR friluftsliv OR wilderness OR garden OR digital nature OR planetary health)

Greenfile
Select a field (optional)
(Covid 19 OR COVID-19 OR Corona OR Covid19 OR pandemic OR Sars-Cov-2 OR lockdown) AND (outdoor OR green space OR green area OR vegetation OR blue space OR blue area OR river OR lake OR ocean OR sea OR nature-based OR natural space OR natural environment OR open space OR green infrastructure OR park OR woodland OR forest OR mountain OR beach OR wetland OR horticulture OR therapeutic landscape OR ecosystem service OR friluftsliv OR wildernesss OR garden OR digital nature OR planetary health)

APA PsychINFO
1 Covid: Title OR Abstract OR keyword
2 Green: Title OR Abstract OR keyword
3 Year of Publication: 2020 Or 2021
1 and 2 and 3
(Covid 19 OR COVID-19 OR Corona OR Covid19 OR pandemic OR Sars-Cov-2 OR lockdown) AND (outdoor OR green space OR green area OR vegetation OR blue space OR blue area OR river OR lake OR ocean OR sea OR nature-based OR natural space OR natural environment OR open space OR green infrastructure OR park OR woodland OR forest OR mountain OR beach OR wetland OR horticulture OR therapeutic landscape OR ecosystem service OR friluftsliv OR wilderness OR garden OR digital nature OR planetary health)

Figure A1. Months during which data collection of the studies included in the review took place



Please note: We recorded each month during COVID-19 when a study collected data. For example, if a study reported data collection from April 2020 to July 2020, this study would be included in the figure for the months April, May, June, and July 2020. There were n = 20 studies that are not included in this figure as the time frame was not specifically given (e.g., spring 2020). Data collection conducted prior to the pandemic for longitudinal studies is not included.

Table A1. Countries in which studies were conducted

Country	Number of studies conducted in this country
Argentina	2
Australia	10
Austria	1
Belgium	4
Benin	1
Brazil	4
Bulgaria	1
Cambodia	1
Canada	13
Chile	4
China	16
Colombia	1
Croatia	1
Ecuador	1
Finland	3
France	5
Germany	11
Greece	1
India	3
Indonesia	5
Iran	3
Ireland	3
Israel	2
Italy	15
Japan	6
Lithuania	1
Malawi	1
Malaysia	2
Malta	1
Mexico	4
Myanmar	1
Nepal	1
Netherlands	1
New Zealand	9
Norway	3
Philippines	1
Poland	5
Portugal	3
Romania	1
Russia	2
Rwanda	1
Saudi Arabia	2
Singapore	3
Slovenia	1
South Africa	2
South Korea	5
Spain	16
Sweden	6
Switzerland	1

Taiwan	1
Tanzania	1
UK	18
USA	36
Zambia	1

Multi-country studies

Study	*Countries included*
Beukes et al. (2021)	Canada, USA
Boudreau et al. (2022)	Canada, New Zealand, France, Australia, UK, USA, Romania, Belgium
Dushkova et al. (2021)	Russia, Australia
Egerer et al. (2022)	Australia, Germany
Garrido-Cumbrera et al. (2021)	Ireland, Spain
Herman and Drozda (2021)	New Zealand, Poland
Koch et al. (2022)	Spain, Austria, Sweden
Lee, Cheng, et al. (2022)	Cambodia, Indonesia, Japan, South Korea, Myanmar
Lee, Mkandawire, et al. (2022)	Malawi, Rwanda, South Africa, Tanzania, Zambia
Passavanti et al. (2021)	Australia, Chile, Ecuador, Iran, Italy, Norway, USA
Perez-Urrestarazu et al. (2021)	Brazil, Greece, Spain, Italy, Colombia, Chile, UK
Pouso et al. (2021)	Spain, UK, Germany, France, USA, Portugal, Italy, New Zealand, Mexico
Ribeiro et al. (2021)	Portugal, Spain
Robinson et al. (2021)	USA, Canada, Australia, India, China, Brazil, Argentina, Portugal, Germany, Nepal, New Zealand, South Africa
Samus et al. (2022)	Germany, New Zealand
Ugolini et al. (2020)	Spain, Croatia, Israel, Italy, Lithuania, Slovenia

Table A2. Detailed study characteristics of the studies included in the scoping review.

Author (year), country	Study population (N, age, % female, ethnicity)	Data collection time	Study design, methodological approach, data collection methodology	Objective	Nature operationalization	Nature measurement	Health outcome/ behavior	Health outcome/behavior measurement	Main finding
Addas and Maghrabi (2022), Saudi-Arabia	Adults urban park visitors (215, largest age group 30-40 years (35.5%), 40%, 96.5% Saudi-Arabian)	June-August 2021	Observational, cross-sectional, quantitative, online and -on-site-survey	Investigate reasons for visiting urban parks during pandemic and non-pandemic periods and related socio-demographic factors	Urban parks	Questions about reasons for urban park use	Affective attachment Social attachment Reasons for visiting urban parks	Eight items to assess affective and emotional attachment rated on a 5-point Likert scale Ten questions asking about perceptions of urban parks	During the pandemic, park visits were mostly for mental refreshment (47%), escaping loneliness (22%), and physical activity (14%). 79% agreed that parks assist in eliminating psychological stress, 86% agreed that they are important for enhancing mental health and, 81% agreed that they are sufficient to meet participants' needs during the crisis period. Also, participants largely agreed or strongly agreed that they felt affectively attached to urban parks and that the urban parks are important social places regarding friends, family, and neighbors.
Akbari et al. (2021), Iran	Adults (421, 32.73 ± 9.01 years, 70.3%, n.a.)	April 2020	Observational, cross-sectional, quantitative, online survey	Evaluate mental health of residents during COVID-19 quarantine considering housing type and environmental factors	Green space	Question about satisfaction with green space	Mental health	General health questionnaire (GHQ-12)	Higher satisfaction with green space was associated with better mental health (β = -0.23). Those with the highest satisfaction level hat the lowest mental health problems (mean = 9.98), those with the lowest satisfaction the greatest mental health problems (mean = 14.85).
Amerio et al. (2020), Italy	University students (8177, 22.02 ± 2.88 years, 49.9%, n.a.)	April-May 2020	Observational, cross-sectional, quantitative, online-survey	Investigate associations between apartment architectural parameters and mental health	Green view	Question about window view on greenery or buildings	Depressive symptoms	Patient Health Questionnaire (PHQ-9)	A higher proportion of students with moderate-to-severe depressive symptoms lived in apartments with building view (34.9%) than in apartments with green view (41.2%). Logistic regression revealed no association between green view and moderate-to-severe depression (OR = 0.94, 95%CI = 0.82-1.09).
Anderson et al. (2022), USA	Perinatal women with antenatal depression (60, 32 ± 3.8 years, 100%, 28.3% minorities)	April 2020-April 2021	Observational, cross-sectional, quantitative/qualitative, online survey	Investigate clinical symptoms, stressors, and coping strategies in a sample of perinatal women with elevated depression prior to the pandemic	General nature	Question about spending time in nature as a coping strategy	Mental health	Question about spending time in nature as a coping strategy Edinburgh Postnatal Depression Scale (EPDS), including the anxiety subscale	Spending time in nature was the third most frequently endorsed coping strategy (51.7%) during the COVID-19 pandemic (out of 23 potential strategies). However, women with elevated depression symptoms during COVID-19 were less likely to report spending time in nature as a coping strategy compared to women with elevated depression levels (OR=0.30, CI=0.09–0.94). Being in nature was also reported as one of the most helpful coping behaviors in the qualitative part of the questionnaire.

Arafat et al. (2021), Indonesia	Doctors and nurses that worked in a COVID-19 ward Questionnaire: (65, n.a., n.a., n.a.) Semi-structured interviews (11, n.a, n.a., n.a.)	NR	Observational, cross-sectional, quantitative/ qualitative, online survey	Explore preferences and patterns towards open space during COVID-19	Open spaces	Questions about use and preferences of open space	Activities	Questions about use and preferences of open space	Beaches were important places for playing with the family, whereas mountain areas and sports grounds were more important for active recreation, such as biking and doing sports. Those activities were not different during compared to before the pandemic.
Astell-Burt and Feng (2021), Australia	Adults and older adults (2697, largest age group 55-64 years (20.3%), 45%, n.a.)	October 2020	Observational, cross-sectional, quantitative, online-survey	Investigate associations between health-related green and blue space benefits and sociodemographic characteristics	Green space and blue space	Three items to indicate how far green/blue space helped to stay connected with neighbors, how they brough solace and respite, and how walking/exercise frequency in green/blue space changed	Health-related benefits of nature visits	Three items to indicate how far green/blue space helped to stay connected with neighbors, how they brough solace and respite, and how walking/exercise frequency in green/blue space changed	25.7% (95%CI = 23.7-27.9) of the participants reported that they were able to reconnect with neighbors due to visiting nature during COVID-19. Social reconnection feelings were more likely for males (OR = 1.47, 95%CI 1.21-1.76), adults between 35 and 44 years and adults ≥65 years (OR = 2.25-3.10, 95%CI 1.08-6.32), having a university degree (OR = 1.53-1.54, 95%CI = 1.04-2.16), and for people with higher nature relatedness scores (OR = 1.65-2.27, 95%CI = 1.32-2.81). 53.7% (95%CI = 51.3-56.1) reported feelings of solace and respite due to visits in nature. Feelings of solace and respite were more likely for males (OR = 1.74, 95%CI 1.45-2.06), those working always or often from home and those being retired (OR = 1.47-1.57, 95%CI 1.05-2.20), having a university degree (OR = 1.77-1.84, 95%CI = 1.31-2.54), and for people with higher nature relatedness scores (OR = 2.94-3.73, 95%CI = 2.40-4.59). 28.2% (95%CI = 26.0-30.5%) reported walking or exercising more often in green or blue space since before the COVID-19 pandemic, which was less likely for people between 45 and 74 years (OR = 0.39-0.56, 95%CI = 0.22 – 0.95), more likely for people mostly working from home (OR = 1.61-1.66, 95%CI = 1.10-2.27), and more likely for people with higher nature relatedness scores (OR = 1.33-1.40, 95%CI = 1.05-1.73).
Baroqah et al. (2021), Indonesia	Adults (10, n.a, n.a., n.a.)	April-May 2021	Experimental, longitudinal, quantitative, oxygen, blood pressure, and heart rate measurement	Investigate effects of healing forest program on stress relieve	Forest	Healing forest program, including emotional freedom technique, art therapy, mindfulness yoga, and wrapping emotion	Stress relief	Oxygen levels Blood pressure Heart rate	Stress levels decreased after the healing program, shown by a 6.1% decrease in blood pressure, a 13.2% increase in heart rate, and a 3.1% increase in oxygen levels.

Barron and Emmett (2020), Ireland	Children and adolescents (1467, 4-18 years, n.a., n.a.)	May 2020	Observational, cross-sectional, quantitative/qualitative, online survey	Identify the impact of COVID-19 on children's and adolescent's play and friendship groups	Garden	Self-reported back-garden access	Play	Two items asking for the best idea for playing outside and the most difficult thing about playing outside as children used to (predominantly proxy-reported via the parents)	Back gardens were turned into multifunctional spaces serving, amongst others, as playground, socializing space, as well as sports pitch and exercise space. Children without a back garden were seriously distracted to play and socialize outdoors, which especially affected children living in appartements.
Basu et al. (2021), India	Urban adult and older adult residents (408, largest age group 25-34 years (35.5%), 53.7%, n.a.,)	May 2020	Observational, cross-sectional, quantitative, online-survey	Investigate if home gardens moderate effects on mental distress from home confinement	Home gardens	Time spent working the home garden Diversity composition of home garden	Mental health	Depression, Anxiety, and Stress scale (DASS-21)	Compared to non-garden owners, having a garden buffered the effects of number of days spent at home due to home confinement on stress and depression (both β = -0.19, p < 0.001) as well as total mental distress (β = -0.43, p < 0.001), but not on anxiety (β = -0.06, p = 0.23). Spending more time in the garden was related to a decrease in stress (β = -0.05, p = 0.02), anxiety (β = -0.04, p = 0.02), and total mental distress (β = -0.10, p = 0.01), but not in depression. There was no significant effect of the composition of the home garden mental distress. However, higher home garden composition decreased total mental distress for those spending low time in their garden, but not for those spending a lot of time in their garden.
Baumann et al. (2021), France	University students (4018, 21.7 ± 4.0 years, 70.7%, n.a.)	May 2020	Observational, cross-sectional, quantitative, online-survey	Investigate associated factors with mental health during the lockdown	Private garden	Access to private garden	Mental health	Medical outcome study short form questionnaire (SF-12) – mental component summary	Compared to having a domestic garden, having no outside access was related to an increased risk of mental impairment (OR = 1.8, 95%CI 1.4-2.2), but there was no benefit compared to a courtyard/garden for collective use or a private balcony, courtyard, or terrace.
Beckmann-Wübbelt et al. (2021), Germany	Adults and older adults in Karlsruhe and Rheinstetten (501, 43 years, 55.5%, n.a.)	August-September 2020	Observational, cross-sectional, quantitative, online-survey	Investigate perceptions of cultural ecosystem services or urban and peri-urban forests	Urban and peri-urban forests	Questions about perceptions/values of ecosystem services of forests and trees	Well-being	Questions about perceptions/values of ecosystem services of forests and trees	About 90% of the respondents indicated a high importance of urban forests for well-being. This was especially important for those without garden access (OR = 2.2). Compared to retired people, the odds of agreeing that urban forests are important for well-being were higher for those working in part time (OR = 10) and for university students (OR = 6). Walking and relaxing were the most often indicated types of use of the forests. More specifically, exercising and meeting friends were frequent reasons to use forests. Socio-demographic differences were observed, with increasing age being associated with higher values of cultural ecosystem services; however, social relation values of forests were perceived more important by younger participants.

Behe et al. (2022), USA	Adults and older adults (1211, 38.6 ± 17.95 years, 61.4%, n.a.)	July- August 2020	Observational, cross-sectional, quantitative, online-survey	Investigate motivations for plant purchases	Plants	Questions about perceived benefits of plants	Well-being Social benefits Food security	Questions about perceived benefits of plants	Well-being benefits of plant buyers differed by generation, with millennials deriving the greatest social benefits, followed by physiological (e.g., physical activity) and psychological benefits. Compared to non-plant-buyers, people buying edible plants or a mixture of edible and flower plants perceived greater food security.
Berdejo-Espinola et al. (2021), Australia	Adults and older adults in Brisbane (1002, largest age group 26-35 years (23.4%), 50.2%, n.a.)	June 2020	Observational, cross-sectional, quantitative, online survey	Investigate associations between changes people's perception of green space benefits and frequency in time spent in urban green space	Urban green and blue space	Frequency of urban green and blue space visit Rating of reasons for using urban green and blue space on a 5-point Likert scale	Reasons for visiting urban green and blue space Psychological well-being benefits	Rating of reasons for using urban green and blue space on a 5-point Likert scale Sum of three perceptions of benefits: stress, anxiety, and depression reduction	77.4% of the participants rated psychological well-being benefits as the top reasons for visiting urban green and blue space; 59%, 55%, and 48% reported more or much more importance of the benefits stress, anxiety, and depression reduction through visiting urban green and blue space, while 51% and 37% reported more or much more importance of the benefits family togetherness and sense of community during the restriction period. The psychological well-being benefits were especially important for people who used green spaces prior to COVID-19, whereas former non-green space rated physical benefits as the main reason for visiting green space.
Berdejo-Espinola et al. (2022), Australia	Adults and older adults in Brisbane (372, 43 ± 17.7 years, 48.3%, n.a.)	June 2020	Observational, cross-sectional, quantitative, online survey	Investigate changes in perceived benefits of urban green space during the lockdown and associations with socio-demographic characteristics	Urban green space	Change in self-perceived benefits of urban green space	Psychological benefits Physical activity Family and social interactions	Change in self-perceived benefits of urban green space	Being male ($b = -0.001$, $p < 0.01$) and being older than 43 years ($b = 0.001$, $p < 0.001$) were associated with reporting an increase in the importance of urban green space for psychological benefits during the lockdown. Also, younger people were more likely than older people to report increases in the importance of green space for physical activity ($RRR = 0.98$, $p < 0.01$). The odds of reporting an increase in the importance of green spaces for social interactions pandemic was significantly higher for younger individuals ($RRR = 0.98$, $p < 0.01$), and higher income earners ($RRR = 1.07$, $p < 0.01$). The odds of reporting an increase in the importance of green spaces for family interactions was significantly higher for younger individuals ($RRR = 0.98$, $p < 0.01$), and higher income earners ($RRR = 1.06$, $p < 0.05$), and those using green spaces with more complex shapes compared to those who visited more compact green spaces ($RRR = 1.27$, $p < 0.05$).
Beukes et al. (2021), Canada and USA	Adults and older adults with tinnitus (1522,ø = 64.1 ± 11.6 years, age range 18-95 years, 43%, n.a.)	May 2020	Observational, cross-sectional, quantitative/qualitative, online survey	Investigate which resources individuals utilized to cope during the pandemic	Nature	Any nature type or nature-based activity mentioned by the participants	Coping resources	Item asking about coping resources and open-ended questions	Gardening was reported as support activity for coping.

Bhalla et al. (2021), India	Employees (9, 24-36 years, n.a., n.a.)	NR	Observational, cross-sectional, qualitative, telephone interviews	Investigate if spiritual tourism provides psychotherapeutic healing during COVID-19	Nature-based tourism	Any nature reported by the participants	Mental health	Open-ended questions in interviews	Participants were looking forward to visiting nature-based places, including places such as mountains, beaches, greenery, and sun rays. Themes that emerged in relation to visiting nature-based places were recovery from the miseries and setbacks of COVID-19, facilitate transformation from a negative to a positive state of life, healing, calmness, and peace, thus allowing people to center their locus and improve mental health and well-being.
Blair et al. (2021), USA	Cancer survivors (30, 50-83 years, 70%, 27% Hispanic White or Other)	February-November 2020	Experimental, longitudinal, quantitative, telephone/paper or online surveys	Investigate preliminary efficacy of a gardening program	Gardening program	Gardening program with participant / Master Gardener dyads	Fruit and vegetable consumption Physical activity, Quality of life	EATs screener Accelerometer (activPAL3) Godin's Leisure Time Physical Activity Questionnaire PROMIS questionnaire	There was a median change of 1.2 additional vegetable servings per day (p = 0.03). No statistically significant changes in quality of life or physical activity were observed.
Boudreau et al. (2022), Canada, New Zealand, France, Australia, UK, USA, Romania, Belgium	Adventure sports participants (20, 35.7 ± 10.7 years, 20%, n.a.)	April-May 2020	Observational, cross-sectional, qualitative, semi-structured interview	Investigate lived experiences and psychological well-being of adventure recreations participants	Nature-based physical activity	Nature experienced during adventure sports such as mountaineering, rock-climbing, white water rafting etc.	Psychological well-being	Interview	Due to restricted access to their nature-based physical activity, participants reported a lack of physical and mental challenge, and emotion regulation. At the same time, they received the chance to recover from their adventure activities, while the mindset and the resilience that they developed during their usual activities helped them to cope with pandemic-related challenges and government restrictions.
Bourion-Bedes et al. (2021a), France	University students (3936, ø = 21.7 ± 4.0 years, 71%, n.a.)	May 2020	Observational, cross-sectional, quantitative, online survey	Investigate factors associated with anxiety during COVID-19	Garden	Self-reported access to private domestic garden	Anxiety	7-item Generalized Anxiety Disorder Scale (GAD-7)	Compared to students with a private garden, students without access to outside space had a higher probability of moderate to severe anxiety (OR = 1.6, 95%-CI = 1.3-2.0). No differences compared to a private balcony, courtyard or terrace or a courtyard or garden for collective use was observed (OR = 1.2-1.3, 95%CI = 0.9 – 1.8).
Bourion-Bedes et al. (2021b), France	University students (3764, 21.7 ± 4.0 years, 71%, n.a.)	May 2020	Observational, cross-sectional, quantitative, online survey	Investigate perceived stress levels of students and associated factors during COVID-19	Garden	Self-reported access to private domestic garden	Perceived stress	Perceived stress scale (PSS)	Compared to students with a private garden, students with a private balcony, courtyard or terrace and students without access to outside space had a higher probability of high perceived stress levels (OR = 1.4, 95%-CI = 1.1-1.8; OR = 1.6, 95%CI = 1.3-2.1). No difference compared to students with a courtyard or garden for collective use was observed (OR = 1.1, 95%CI = 0.8 – 1.7).

Briguglio et al. (2021), Malta	Adults and older adults (1821, n.a., n.a., n.a.)	March 2020	Observational, cross-sectional, quantitative, online survey	Investigate factors related to subjective well-being during COVID-19	Nature	Frequency of going by the sea or nature	Happinness Life satisfaction	One item question, respectively	Frequency of nature visits was related to happiness prior (B = 0.23, p < 0.001), but not during the COVID-19 pandemic. The same pattern was observed for life satisfaction (prior COVID-19: B = 0.15, p = 0.016).
Browning et al. (2021), USA	University students (2534, largest age group 18-24 years (76.8%), age range 18-74 years, 61%, 79% non-Hispanic White, 12.8% non-Hispanic Asian, 8.5% Other)	March-May 2020	Observational, cross-sectional, quantitative, online survey	Investigate psychological impact of COVID-19 and associated factors	The outdoors	Self-reported time spent outdoors at a park, greenway/trail, neighborhood/yard etc.	Psychological impact	9 items assessing negative emotion states, preoccupation with COVID-19, feeling stressed, worry, and time demands	Students spending two or more hours in the outdoors were less likely to be at risk or higher than average levels of emotional distress and worry time (RES = -3.17, p = 0.014).
Bu et al. (2021), UK	Adults and older adults (55204, largest age group ≥60 years (29.9%), 50%, 12.5% Black, Asian & Minority Ethnic)	March-May 2020	Observational, intensive longitudinal, quantitative, online survey	Investigate associations between specific activities or time use and mental health and well-being during COVID-19	Garden	Weekly self-report about time spent in gardening activity	Depression Anxiety Life satisfaction	Patient Health Questionnaire (PHQ-9) Generalized Anxiety Disorder Assessment (GAD-7) One item asking about life satisfaction in the last week	Compared to no gardening activity, <30 minutes and ≥ 30 minutes gardening activity were associated with less depressive symptoms (B = -0.15 and B = -0.30), less anxiety symptoms (B = -0.15 and B = -0.24), and more life satisfaction (B = 0.06 and B = 0.16; all p's < 0.001).
Burnett et al. (2021), UK	Adults and older adults (2252, weighted to represent adult UK population)	April-May 2020	Observational, cross-sectional, quantitative, online survey	Investigated changed experience of green space and associations with socio-demographic characteristics.	Green space	Statements regarding increased mental health benefits of green space, increased physical activity in green space, and missing social interactions during the COVID-19 lockdown	Mental health Physical activity Social interactions	Statements regarding increased mental health benefits of green space, increased physical activity in green space, and missing social interactions during the COVID-19 lockdown	65% of the respondents agreed that green spaces benefited their mental health more after movement restrictions were introduced, Agreement for mental health benefits was more likely reported by females compared to males (predicted probability (PP) = 0.70 vs. 0.59, p = 0.004), respondents from higher compared to lower social grade (PP = 0.68 vs. 0.59, p = 0.048), and people between 25 and 64 years compared to older and younger ones (PP = 0.68 vs. 0.55, p < 0.001). 29% of the respondents agreed that they had increased physical activity in green space since movement restrictions were imposed. Agreement for more physical activity in green space was more likely for younger people between 18-24 years (PP = 0.44 vs. 0.18-0.29, p = 0.002), and more likely for people who did not own a dog (PP = 0.31 vs. 0.17, p < 0.001).

									54% of the respondents agreed that they missed social interactions in green space more during the movement restrictions. Agreement for missing social interactions in green space was more likely for females (PP = 0.58 vs. 0.45, p < 0.001).
Bustamante et al. (2022), USA	Adults > 55 years Quantitative (6661, largest age group 55-64 years (41.4%), 63.8%, 15.5%) Qualitative (767, largest age group 65-74 years (47.5%), 78.5%, 6.6% Non-Hispanic Black, Hispanic, or Other)	April-May 2020	Observational, cross-sectional, quantitative/qualitative, online survey + geospatial analysis	Investigate the role of parks during the COVID-19 pandemic	Park	Number of neighborhood parks within zip-code area	Depression Anxiety Loneliness	8-item Center for Epidemiological Studies-Depression (CES-D) scale 5- item Beck Anxiety Inventory (BAI) 3-item UCLA loneliness scale Open-end responses about outdoor experience	Overall, there was no association between the number of neighborhood parks and depression, anxiety, or loneliness. However, when stratified by urban/rural status, more parks were related to less depression among urban residents: Urban residents who had 1-5 parks in their neighborhood were 26% less likely to report depressive symptoms (6-10 parks: 29% less likely, >10 parks: 32% less likely). Qualitative results revealed the importance of parks for physical activity, mental well-being such as alleviating stress and anxiety, as well as promoting positive emotions and feelings of restoration, and social well-being through bonding with others.
Butler et al. (2022), Australia	Adults and older adults (32, 34.5% 18-29 years, 34.5% 30-54 years, 66%, n.a.)	October 2020 - February 2021	Observational, cross-sectional, qualitative, focus group interviews	Explore regional nature-based tourism experiences during COVID-19	Nature	Any nature mentioned by participants	Mental health Physical activity	Coding from transcripts	Nature-based tourism supported participants' mental health and wellbeing during the pandemic via escaping from home, coming to terms with disruptions and insecurities, and managing anxieties. In addition, natural places were important destinations for physical activity.
Camerini et al. (2022), Switzerland	Children and adolescents (844, 5-19 years, 12.78 ± 4.00 years, 47.6%, n.a.)	Autumn 2020 – spring 2021	Observational, longitudinal, quantitative, online survey	Investigate within- and between-person associations between green time and mental health during COVID-19	Green time	Time spent in nature on weekdays and weekend days Self-reported availability of nearby green space	Mental health Screen time	Seven DSM-5 cross-cutting symptom measures for children and adolescents 4 items asking about time spent in screen-based activities	On a between-person level, green time was related to less mental health problems (B = -0.42, p = 0.033), but not on the within-person level. Green time and screen time were unrelated over time.
Cerda et al. (2022), Chile	Adults and older adults (305, largest age group 26-35 years (30.2%), 79.2%, n.a.)	March – April 2021	Observational, cross-sectional, quantitative/qualitative, online survey	Investigate perceived benefits of home food gardening for health and well-being	Gardening	Rating of agreement of 5 potentially perceived benefits of home food gardening Open-ended questions	Health and well-being	Rating of agreement of 5 potentially perceived benefits of home food gardening Open-ended questions	The most significant perceived benefits were feeling less stressed through practicing home food gardening (84.9% agreement), having therapeutic potential and bringing happiness. Furthermore, 68.5% agree that it improved their diet in quality or quantity, in this way contributing to food security. Also, 65.9% agreed that gardening fostered socializing and to feel part of a community.

Chen and Liu (2021), China	Adults and older adults (937, large age group 25-34 years (40.7%), 35%, n.a.)	January-February 2020	Observational, cross-sectional, quantitative, online survey + geospatial analysis	Investigate the importance of risk factors with regards to psychological distress during COVID-19	Park	Objectively measured direct distance from participant's residence to nearest park	Psychological distress	Kessler Psychological Distress Scale (K6)	Out of 18 sociodemographic, environmental, health, and individual's perception predictors, distance to the nearest park was ranked as the fourth most important predictor (relative importance: 9.38%) and the most important predictor from objective environmental measures.
Cheng et al. (2021), China	Social media users (through geotagged posts on Sina Weibo [Chinese Twitter]; 560,000 posts)	July 2019 – June 2020	Observational, longitudinal, qualitative/quantitative, social media analysis and geospatial analysis	Investigate association between urban parks, their characteristics, and happiness before and during COVID-19	Urban parks	Objectively assessed radial service buffer zones of 300-2000 meters around the parks and Normalized Difference Vegetation Index (NDVI)	Happiness	Emotional classification of posts via automated sentiment analysis	Residents living within the service buffer zone of the park showed higher happiness (0.713) than residents outside the service buffer zone (0.706). Pre-pandemic, there was no association between NDVI-values and happiness (B = -0.08, p > 0.1), whereas an association was observed during the pandemic (B = 0.37, p < 0.01). Compared to very low NDVI values, higher NDVI-values, representing higher green quality, were associated with higher happiness (low NDVI: B = 0.04, p = 0.01; medium NDVI: B = 0.05, p < 0.001; high NDVI: B = 0.06, p = 0.001, very high NDVI: B = 0.09, p < 0.001). The strength of the association varied by the type of urban park (community-scale park: B = 0.32, p < 0.01; subdistrict-scale park: B = 0.37, p < 0.01; regional-scale urban park: B = 0.35, p < 0.01, city-scale park: B = 0.33, p < 0.01).
Collins et al. (2022), Germany	International university students (10, n.a., n.a., n.a.)	October-December 2020	Observational, cross-sectional, qualitative, semi-structured interviews	Explore mental health and well-being with reference to urban green space exposure	Urban green space	Semi-structured interviews	Mental health Well-being	Semi-structured interviews	Urban green space was a resource to support wellbeing during a stressful and isolating time in various ways: It provided a safe arena to maintain social contact with friends outdoors and to disconnect and to be alone, to escape the home environment, It also facilitated positive emotions and mitigated negative emotions and thoughts, and allowed to experience respite and relaxation.
Constant et al. (2020), Scotland	Adults and older adults (4005, largest age group 18-59 years (74.3%), 55%, n.a.)	April 2020	Observational, cross-sectional, quantitative, online survey	Investigate factors associated with healthy and unhealthy lifestyle changes during COVID-19	Garden	Self-reported garden at home	Changes in health behaviors	Frequency of screen watching, snacking, eating fruits and vegetables, exercising, and walking during the lockdown compared to prior to the lockdown	Having a garden was related to a higher number of changes in unhealthy changes (RR = 1.16, 95%-CI = 1.07-1.36) and unrelated to changes in healthy behaviors (RR = 1.01, 95%CI = 0.90-1.14).
Corley et al. (2021), Scotland	Older adults (171, ø = 84 ± 0.5 years, 48%, n.a.)	May-June 2020	Observational, cross-sectional, quantitative, online survey	Investigate associations between home garden usage and mental health during COVID-19	Garden	Self-reported access to a home garden, garden usage and activities	Emotional and mental health Anxiety about COVID-19 Sleep quality	One-item question for each outcome of interest, respectively	More garden usage during compared to prior to the lockdown was associated with better emotional and mental health (B = 0.58, 95%CI = 0.02-1.13), sleep quality (B = 0.58, 95%CI = 0.70-1.09), and composite health (B = 0.79, 95%CI = 0.32-1.25), while it was unrelated to anxiety about COVID-19 (B = 0.19, 95%CI = -0.37 to 0.75). Gardening and

									relaxing in the garden were unrelated to all health outcomes (p = 0.13-0.93).
Cuerdo-Vilches et al. (2020), Spain	Adults and older adults (242, largest age group 45-54 years (31.8%), n.a.)	April-June 2020	Observational, cross-sectional, qualitative, photos with open questions	Investigate aspects of space of personal home that participants like least and that are most comfortable	Nature	Any nature places and spaces mentioned, or a picture taken by the participants	Comfort	Photos and written narratives about spaces at home during the lockdown that provide comfort	Spaces open to the outside, including gardens, were, amongst others, most valued during the lockdown for comfort, and provided a meeting place at the social level.
Czyz and Starosciak (2022), Poland	Adults and older adults (320, 18-76 years, 60.4%, n.a.)	March-April 2020	Observational, cross-sectional, quantitative, online survey	Investigate how the COVID-19 pandemic affected physical activity and sedentary behavior	Garden	Accessibility to own garden	Physical activity Sedentary behavior	International Physical Activity Questionnaire (IPAQ)	There were no differences between garden and non-garden-owners regarding moderate or vigorous physical activity, walking, and sitting time.
Daiz et al. (2022), Philippines	Adults and older adults (400, largest age group 21-40 years (63%), 56%, n.a.)	NR	Observational, cross-sectional, quantitative, online survey	Assess health and well-being in gardener and non-gardeners during COVID-19	Garden	Owning a garden for more than 6 months (control group: not owning a garden)	Health Fear of COVID-19 Perceived stress Resilience Bereavement and loss coping	Fear of COVID-19 scale Health orientation scale Perceived stress scale Brief resilience scale Coping assessment for bereavement and loss	Gardener reported better health (M=3.40, SD=0.48), higher resilience (M=3.82, SD=0.51), and better coping (M=3.82, SD=0.56) than non-gardeners. Non-gardeners were more fearful of COVID-19 than gardeners (M=3.26, SD=0.63). No differences were observed for perceived stress.
Dobson et al. (2021), UK	Interviews: Adults and green space professionals (42, n.a., n.a., n.a.) Survey: Members of voluntary community organization concerned with green space (29, n.a., n.a., n.a.)	May-July 2020	Observational, cross-sectional, qualitative, semi-structured interviews + survey	Explore the five pathways to nature in the context of the COVID-19 pandemic	Green and public space	Semi-structured interviews	Emotions	Semi-structured interviews	Experiencing the beauty of nature was closely related to positive emotions, such as enhanced mood through seeing animals, feeling relief through being outside, de-stress through having nice aesthetics while going for a walk, and being invigorated.
Doughty et al. (2022), Netherlands	Long-term residents and international university students (30, 23-67 years, 53%, n.a.)	May-June 2020 October-November 2020	Observational, cross-sectional, qualitative, semi-structured interviews + annotated photographs and videos	Investigate the role of nature in the maintenance of well-being through everyday interactions during the pandemic	Any nature mentioned by participants, including indoors and outdoors	Semi-structured interviews	Well-being	Semi-structured interviews	Natural environments served as therapeutic landscapes for well-being, enabling social interactions in person and via sharing nature experiences in social media, while also being places for solace. Green spaces were a place to deal with difficult experiences, allowing to disconnect from everyday life, making it easier to deal with stress, and bringing ease, relaxation, and rejuvenation. They allowed for multi-sensory experiences, including auditive and tactical experiences as well as embodiment experiences via physical activity in nature.

Dushkova et al. (2021), Russia and Australia	Adults and older adults in Moscow and Perth (326, largest age group 40-65 years (Perth), largest age group 20-40 years (Moscow), 67%, n.a.)	May-July 2020	Observational, cross-sectional, quantitative, online survey	Investigate perceptions, values, and use of urban green and blue space during COVID-19	Urban blue and green infrastructure	One item asking participant to rate the importance of accessing nature for personal well-being Multiple choice question with predefined answer options of nature benefits	Personal well-being and perceived benefits of urban nature	One item asking participant to rate the importance of accessing nature for personal well-being Multiple choice question with predefined answer options of nature benefits	In Moscow and Perth, 76% and >97% rated contact with nature important or very important for mental health. Among perceived personal benefits, mental health benefits (Perth: 83.8%; Moscow: 71.2%) and having a place to relax and unwind (Perth: 81.9; Moscow: 68.4%) were amongst the most frequently selected benefits as well as meeting other people (Perth: ~ 35%; Moscow: ~25%) and spending time with family (Perth: ~60%; Moscow: ~20%).
Dushkova et al. (2022), Russia	Adults and older adults in Moscow (216, largest age group 21-30 years (31.9%), 73%, n.a.)	May-July 2020	Observational, cross-sectional, quantitative, online survey	Investigate use and value of urban green space during the COVID-19 pandemic	Urban green space	Rating of the importance of urban green space for mental well-being	Mental well-being	Rating of the importance of urban green space for mental well-being	Urban green space was highly valued for mental well-being (70% agreement). The importance of contact with nature was not dependent on age group, but there was a tendency for more appreciation by older adults, while answers in the younger age group were more varied. The most frequent rated benefits were mental health benefits (12.2–12.8%) and "a place to relax and unwind" (11.1–14.4%). The value of green space for social interactions was more pronounced in younger people (<20 years: 9.6% agreement) compared to older adults (>60 years: 2% agreement), while spending time with family and visiting playgrounds was mostly valued by people with children in the age group 41-50 years (7.2% agreement).
Dzhambov et al. (2020), Bulgaria	University students (323, ø 21.99 ± 3.10, age range 18-35 years, 69%, 87% Bulgarian)	May-June 2020	Observational, cross-sectional, quantitative, online survey	Investigate associations between greenery and mental health	Greenery indoors and outdoors	Self-reported number of houseplants, exterior greenery visible from inside, presence of a domestic garden, and neighborhood greenery	Depression Anxiety	Patient-Health-Questionnaire (PHQ-9) Generalized Anxiety Disorder scale (GAD-7)	Houseplants were associated with less depressive symptoms (B = -0.02, 95%CI = -0.04 to -0.01) and a lower risk for clinically meaningful levels of depression (OR = 0.97, 95%CI = 0.94-0.99), but not with anxiety. Exterior green view was related to lower levels of depressive and anxiety symptoms (B = -0.05 to -0.06, 95%CI = -0.11 to -0.003) and a lower risk for clinically meaningful levels of depression and anxiety (OR = 0.83-0.88, 95%CI = 0.74-0.98). Having a garden was unrelated to all outcomes except for anxiety symptoms (B = -0.47, 95%CI = -0.89 to -0.06). Neighborhood greenery was related to less depressive and anxiety symptoms (B = -0.10 to -0.11, 95%CI = -0.16 to -0.05) and a lower risk for clinically meaningful depression and anxiety levels (OR = 0.79-0.80, 95%CI = 0.70-0.91).

Egerer et al. (2022), USA, Australia, Germany	Adult and older adult gardeners (3743, largest age group 51-70 years (46.7%), 83%, n.a.)	May-August 2020	Observational, cross-sectional, quantitative, online survey	Explore the perceived benefits of gardening during the COVID-19 pandemic	Gardening	Self-reported perceived benefits of gardening based on default options	Perceived benefits	Self-reported perceived benefits of gardening based on default options	Relaxation and stress release was the second most important benefit of gardening (87% agreement), followed by outdoor physical activity (78% agreement) and food production or quality (54% agreement). The number of reported COVID-19-related difficulties was associated with the importance of gardening for food provision.
Fagerholm et al. (2021), Finland	Adolescents, adults, older adults in Turku (730, largest age group 15-64 years (90%), 71%, n.a.)	May-June 2020	Observational, cross-sectional, quantitative, online survey	Explore how nature contributed to subjective well-being during the early phases of the COVID-19	Perceived benefits of nature	Nine statements about nature benefits for well-being with default answer options	Well-being	Nine statements about nature benefits for well-being with default answer options	Looking at or recreating in nature positively affected mood and social interactions (49.2–96.6 % agreement with the statements). Agreement with the statements was lower for those who spent less time in nature.
Ferguson et al. (2021), Canada	Adolescents (851, 15.6 ± 1.7 years, 71%, n.a.)	June-September 2020	Observational, cross-sectional, qualitative, online survey	Explore coping strategies for feeling and emotions during the COVID-19 pandemic	Any nature mentioned by participants	One open-ended question asking about coping strategies	Coping	One open-ended question asking about coping strategies	Leisure and health-promoting activities were one way to cope with the pandemic, including spending time outside in natural environments, such as forests, beaches, and gardens, which helped to relax. Also, being outdoors in the garden allowed social connections with the neighbors.
Fithriyah et al. (2021), Indonesia	Adults and older adults in Bogor city (192, largest age group 20-29 years (49.5%), 55%, n.a.)	June-July 2020	Observational, cross-sectional, qualitative, online survey	Explore perceptions of urban park during the pandemic	Urban park	Default answer options for reasons for park visitation	Reasons for park use	Default answer options for reasons for park visitation	During the pandemic, the park was mostly visited for physical exercise (M = 3.69 SD = 1.04), which was also the main reason prior to the pandemic (M = 4.12 SD = 0.82).
Folk et al. (2021), USA	Young adults (720, 24.7 ± 2 years, 62%, 18.2% Black/African-American, 16.5% Hispanic/Latino, 23.9% Asian American, 3.5% Native Hawaiian/American or Pacific Islander, 8.3% Other)	April-October 2020	Observational, cross-sectional, qualitative, online survey	Explore changes in physical activity during COVID-19	Any nature mentioned by participants	Open-ended questions how COVID-19 has influenced physical activity	Physical activity	Open-ended questions how COVID-19 has influenced physical activity	A dichotomy emerged in whether participants used outdoor areas, such as parks, trails, beaches, and lakes for physical activity: While some indicated that those areas were important for physical activity, others reported less use of these areas due to closures or feeling unsafe.
Garrido-Cumbrera et al. (2021), UK,	Adults and older adults (3109, 39.7 ± 14.1 years, 73%, n.a.)	April-July 2020	Observational, cross-sectional, quantitative, online survey	Explore associations between perceptions of improvement in the natural environment and self-perceived	Nature improvements due to the lockdown	Agreement with improvements in number of birds, animal life, and nature sounds	Well-being	WHO-5 Well-Being Index Rating of self-perceived health status	People with a better self-perceived health were more likely to appreciate the improvement in animal life (83.7 %), and nature sounds (92.3 %) compared to those with very poor self-perceived health (45.5 % and 81.8 %, respectively). Respondents with higher

Ireland, Spain				health and well-being during COVID-19					well-being appreciated the improvement in nature sounds to a higher extent.
Giraud et al. (2021), USA	Study 1: Farmers and gardeners (13, n.a., n.a., 23% Non-White) Study 2: Gardeners (96, largest age group >45 years (79%), n.a., 9% Afro-American, 3% Hispanic, 4%)	Study 1: 2020-2021 Study 2: NR	Observational, cross-sectional, qualitative/quantitative, semi-structured interviews + online survey	Explore associations between gardening and food well-being	Sustainable gardening	Semi-structured interview about motivation and enjoyable experiences with gardening	Eudemonic well-being Food well-being	Questionnaire	In Study 1, eleven interviewees highlighted gardening for eudemonic well-being derived from a sense of purpose and pleasure that food growing brought. Most frequently raised were physical (e.g., physical activity), social (e.g., sense of community), and emotional benefits (e.g., empathy and caring) of food growing. In Study 2, sustainable gardening was associated with better eudemonic well-being ($\beta = 0.32$, $p < 0.001$).
Gola et al. (2021), Italy	Health care workers (77, n.a., 61%, n.a.)	April-May 2020	Experimental, longitudinal, quantitative, online survey	Investigate well-being benefits of nature for hospital staff based on one self-selected nature experience	Nature	Participants reported the space they used for their nature experience, which was then categorized into garden of a health care facility, public nature space, and private nature space	Well-being	Profile of Mood States (34 items)	Hospital staff working both Covid- and non-Covid-areas decreased anxiety, depression, anger, fatigue, and confusion after the nature experience, and increased strength. Percentage change of the subscales from prior to after the nature experience ranged from 25% to 67%. The greatest benefits were obtained if the nature experience took place during or after the work shift. For strength, the hospital garden yielded the most benefits, while there were no remarkable differences for the other subscales between the different nature typologies.
Greenwood-Hickman et al. (2021), USA	Older adults with obesity (25, ø = 68 years, age range 60-77 years, 64%, 88% White, 12% Black and Indigenous people of color)	June-August 2020	Observational, cross-sectional, qualitative, telephone interviews	Investigate the impact of COVID-19 on older adult's well-being and identify coping strategies	Nature	Any nature mentioned by participants	Coping strategies	Semi-structured interviews	Many participants reported more gardening, tending to plants, or doing major yard improvement projects as coping strategies. Simultaneously, yard work had the additional benefit of physical activity and allowing contact with neighbors.
Grima et al. (2020), USA	Visitors of parks and natural areas (346, n.a., n.a., n.a.)	March-June 2020	Observational, cross-sectional, quantitative/ qualitative, online survey	Investigate how natural areas provide basic non-material basic needs of urban communities	Urban and peri-urban natural areas consisting of various green and blue space types	Question asking respondents to indicate what motivates them to visit natural areas with pre-defined and open answer options	Motives for visiting natural areas	Question asking respondents to indicate what motivates them to visit natural areas with pre-defined and open answer options	18.6% reported exercise, 13.8% finding peace and quiet, and 2.7% socializing as key reasons for visiting nature.
Halliday et al. (2022), UK	Public advisors of a research collaboration	April-June 2020	Observational, cross-sectional, qualitative, semi-	Explore how mental health was affected during the first COVID-19 lockdown	Nature	Any nature mentioned by participants	Coping	Semi-structured online diaries	Spending time in gardens, parks or other green spaces improved well-being and facilitated unwinding from daily pressures.

	(15, 30-70 years, 67%, 40% Non-White)		structured online diaries						
Hansen et al. (2022), Sweden	Survey 1 + interviews: Adults (530 – 22 being interviewed, n.a., n.a., n.a.) Survey 2: Adults (1506, n.a., n.a., n.a.) Survey 3: Adults (1023, n.a., n.a., n.a.)	Survey 1: April-June 2020 August-October 2020 Survey 2: July-October 2020 Survey 3: September 2020	Observational, cross-sectional, quantitative/qualitative, online survey + semi-structured + Public Participation Geographic Information System	Explore changes in the use of outdoor areas during COVID-19	Nature	Any nature mentioned or mapped by participants	Motives for visiting green space	Open-ended questions and mapping	About half of all survey respondents (49%) of Survey 2 reported having experienced changes in recreational habits, which was motivated due to perceiving the outdoors as a calm and safe place, as a place to escape the city, and as a place to socialize. In all three studies, nature was a place to experience relief from stress and anxiety, as well as to recover, and re-energize. Managing mental and physical health were frequent reasons for spending time in the outdoors.
Harding et al. (2022), Indonesia	Urban gardeners (67, largest age group 51-60 years (58%), n.a., n.a.)	NR	Observational, cross-sectional, quantitative/ qualitative, online survey	Investigate well-being of urban gardeners during COVID-19	Gardening	Gardens	Subjective well-being	Satisfaction with life scale (SWLS) Scale of positive and negative experiences (SPANE) Reasons for gardening	52% reported high and 40% reported medium life satisfaction, while 16% reported never experiencing negative emotions, while 83% reported mixed positive and negative emotions. Most frequently reported motives for gardening where hobby (34%), relating to stress relief and reduction of boredom, and happiness (18%). Health, exercise, and people were the least mentioned reasons.
Hazlehurst et al. (2022), USA	Child-parent and adolescent-parent dyads (Child and adolescents characteristics: 1000, 10.8 ± 3.5 years, 47%, 11% African-American/Black, 16% Other, 5% Asian-(American), American-Indian, or Alaska Native) Parent characteristics: 1000, n.a., 55%, 11% African-American/Black,	October-November 2020	Observational, cross-sectional, quantitative, online survey	Investigate associations between parks access and child and parent physical activity and mental health	Park access	Self-reported park access within 10 minute walking distance from home	Mental health problems Physical activity	Patient Health Questionnaire (PHQ-4) Strength and Difficulties questionnaire (SDQ) International Physical Activity Questionnaire (IPAQ)	Park access was associated with a lower SDQ total score among children (β: -1.26, 95% CI: -2.25, -0.27) and a lower PHQ-4 total score among parents (β: -0.89, 95% CI: -1.39, -0.40). In models stratified by child age, these associations were observed for SDQ scores among adolescents ages 11–17 and for PHQ-4 scores among parents of children ages 6–10 years. Park access was also associated with higher levels of parent physical activity (β: 1009 MET-min/week, 95% CI: 301, 1717), but not child physical activity (β: 0.31 days/week, 95% CI: -0.03, 0.66).

	13% Other, 5% Asian-(American), American-Indian, or Alaska Native)								
Heidarzadeh et al. (2021), Iran	Adult and older adult walking path users (100, 40.4 ± 16.5 years, 45%, n.a.)	January 2021	Experimental, longitudinal, quantitative, paper-pencil survey	Investigate impact of walking on mood	Green walking path	Walk along a 3km green walking path	Mood	Mood and Feelings Questionnaire Self-Repot Profile of Mood States (POMS)	Walking enhanced mood during the pandemic; with more frequent walks resulting in better mod enhancement. The change in mood was also influenced by baseline mood and age.
Heo et al. (2021), South Korea	Adults and older adults (322, largest age group 30-49 years (35.7%), 76%, n.a.)	September-December 2020	Observational, cross-sectional, quantitative, online survey	Investigate associations between patterns of greenspace use and psychological symptoms	Green space Vegetation	Self-reported type, frequency, duration, and social aspects of green space visits One item asking about changes in frequency of green space visits during compared to pre-pandemic One item about health-related reasons for visiting green space with predefined response options Objectively measured enhanced Vegetation Index (EVI) for each ZIP code	Depression Anxiety Motives for visiting green space	Patient Health Questionnaire (PHQ-9) Generalized Anxiety Disorder (GAD-2) One item about health-related reasons for visiting green space with predefined response options	There was no statistically significant association between decreased visits to green space and major depressive disorder (OR = 2.06, 95%CI = 0.91-4.67) and generalized anxiety disorder (OR = 1.45, 95%CI = 0.63-3.34). In addition, neither were association observed for the frequency of visits pre-pandemic and risk for major depression (OR = 1.08-3.08, 95%CI = 0.22-12.72) and anxiety disorder (OR = 0.56-1.29, 95%CI = 0.23-7.97), nor between the EVI and major depression and anxiety disorder (OR = 0.62-0.63, 95%CI = 0.28-1.41). Regarding reasons for visiting green space, during the pandemic, respondents were more likely to visit green space for stress relief compared to pre-pandemic (52.2% vs. 50.3%), whereas less people reported visiting green space for relaxation, social reasons, or exercise compared to pre-pandemic.
Herbec et al. (2022), UK	Adults and older adults (2657, 50 ± 16 years, 53%, 9.5% Non-White ethnicity)	April-June 2020	Observational, cross-sectional, quantitative, online survey	Explore changes in COVID-19 related physical activity changes	Access to park/green space	Self-reported access to public park or green space that is open during COVID-19	Physical activity	Questions on engagement in moderate-to-vigorous and muscle-strengthening activity prior and during COVID-19	The odds for meeting the WHO recommendations for moderate-to-vigorous physical activity were higher for those with access to green space within walking distance (aOR = 1.31, 95%CI 1.03-1.66), but was unrelated to meeting the guidelines for muscle-strengthening-activity. Access to green space was unrelated to increases or decreases in moderate-to-vigorous physical activity and muscle-strengthening activity for both active and non-active participants.

Herman and Drozda (2021), New Zealand and Poland	Parks users (12, 11-70 years, 50%, n.a.) For social media: 144 posts of 113 users	May, August, and December 2020	Observational, case study qualitative, pandemic urban ethnography	Investigate the functioning of green infrastructure during COVID-19	Two parks in Wellington and Warsaw	Parks and social media posts related to the parks	General health and well-being, including health behaviors	Autoethnography, interviews, non-participant observations, digital ethnography based on social media (Instagram)	Green space played a crucial role for health and well-being, physical activity, sports, and play, and social life during the pandemic.
Hino and Asami (2021), Japan	Adults and older adults in Yokohama (18817, largest age group ≥ 65 years, 52%, n.a.)	First half of 2019 First half of 2020	Observational, longitudinal, quantitative, step counter and geospatial analysis	Investigate associations between changes in step counts and the neighborhood environment	Park	Average distance to the nearest park calculated via geographic information systems	Step counts	Pedometer (Omron HJ-326F)	In 2019, the distance to the park was not associated with step counts. During the COVID-19 state of emergency, shorter distance to the nearest park mitigated the decline in step counts in older women (year-on-year ratio short distance = 0.70, year-on-year ratio long distance: 0.67). The associations remained after the state of emergency was lifted. In some weeks, the association between distance to the park and step count change was also present for younger women, while there were no associations for younger or older males.
Houessou et al. (2021), Benin	Adults and older adults (240, 38.9 ± 11.5, 45%, n.a.)	September-October 2020	Observational, cross-sectional, quantitative, online survey	Investigate the role of allotment gardens in food security	Gardens	Access to a garden	Food security	Rapid Food Security Appraisal (RFSA)	Access to allotment gardens effectively supported households in mitigating the effects of the COVID-19 pandemic on the food crisis.
Howarth et al. (2021), Canada	Recreational fishers (789, 51 years, age range 12-81 years, 8.5%, 90% Canadians)	August 2020	Observational, cross-sectional, quantitative, online survey	Investigate how the pandemic impacted recreational fishers	Fisheries	Self-reported recreational fishing	Motivation for fishing during the pandemic	Opinion statements about fishing motivation during the pandemic	Recreational fishing may enhance well-being: 86% of participants agreed or strongly agreed that fishing improves their mental or physical well-being, while 62% agreed or strongly agreed to go fishing to spend time with family/kids.
Hsieh et al. (2022), Taiwan	Older adults with mild-to-moderate cognitive impairment in nursing homes (14, n.a., n.a. n.a.)	NR	Experimental, longitudinal, quantitative, biofeedback instruments	Investigate impact of immersive garden experience during COVID-19	Virtual gardens	Six-minute exposure to virtual vegetable garden	Heartrate Heartrate variability Standard deviation of NN interval (SNN) Low and high frequency	Electrocardiography (ECG)	Within 6 min of completing the experiment, heart rates of participants dropped slightly, while SDNN and HF values continued to rise. SDNN values before and after the experiment demonstrated a statistically significant improvement, indicating less anxiety. Also, participants reported that this program allowed them to feel as if they were actually experiencing nature and brought up past social memories.
Hu et al. (2022), China	Medical doctors, nurses, and police officers (71, 36.15 ± 8.66 years, 35%, n.a.)	March-April 2020	Experimental, longitudinal, quantitative, online survey	Investigate impact of nature-based intervention on well-being during COVID-19	Virtual nature	Two-minute video clips of natural scences for five days (control group: urban scenes)	Subjective well-being	Satisfaction with Life Scale (SWLS) Positive and Negative Affect Schedule (PANAS)	Interaction analysis revealed a significant condition x time on positive affect, $F(1, 61) = 6.14$, $p = .016$, $n_p^2 = 0.091$, revealing that the nature group maintained positive affect, whereas the control group decreased. Similar patterns were observed for negative affect, $F(1, 61) = 2.82$, $p = .098$, $n_p^2 = 0.091$, indicating that negative affect increased among the city group at a marginal-significant level, $p = .058$, while a reduction of negative affects was found among nature group, p

									< .001. Also, life satisfaction showed greater improvement in the intervention group, but decreased in the control group, $F(1, 64) = 12.92$, $p = .001$, $n_p^2 = 0.17$. Looking at instant effects on a daily basis, compared to the urban stimuli, the natural stimuli had significantly higher restorative effects of positive affects (B = 0.41, t = 3.41, CI95%, 0.19–0.66, p = .001) and lower restorative effects of negative affect (B = −0.30, t = −4.82, CI95%, −0.41 to −0.18, p < .001).
Hubbard et al. (2021), Scotland	Older adolescents and adults (502, median age = 53 years, interquartile range = 38-65 years, 59%, n.a.)	June-July 2020	Observational, cross-sectional, quantitative, telephone interviews	Investigate if frequency and duration of green space visits are related to mental health during COVID-19 and moderate relationships between individual demographics, illness beliefs, and mental health	Public green and open space	Self-reported frequency and duration spent in public green and open space	Psychological distress	Patient Health Questionnaire (PHQ-4)	More frequent visits of green/open space were associated with more psychological distress (B = 0.18, p < 0.001), whereas duration was not (B = 0.11, p < 0.06). Frequency and duration of green space visits moderated the association between being in a high-risk group for COVID-19 and psychological distress, with more frequent visits and shorter visits in green space relating to higher psychological distress (both p's < 0.01). For less frequent visits and longer visits in green space, people in the high-risk group for COVID-19 did not differ from those who were not at risk for COVID-19 with regards to psychological distress.
Huerta and Cafagna (2021), Mexico	Adults in Mexico City (16, 22-58 years, 69%, n.a.)	September-October 2020	Observational, cross-sectional, qualitative, solicited audio, photo diary, interviews	Investigate the association between participants' urban green space use and well-being	Urban green space	Perception of the neighborhood quality, quality-related interview questions including size and amenities	Well-being	Semi-structured interviews based on photo-diaries	Urban green space use appears to serve as a coping mechanism to decrease the effects of stress and isolation caused by the pandemic and increase overall well-being, however, disparities of well-being benefits emerged with regards accessibility barriers for urban green space and women fearing violence. Almost all participants expressed that nature contact brought them positive emotions that increased their mental well-being. The seven participants who used urban green space regularly reported experiencing positive feelings such as comfort, happiness, and tranquility during their use. Individuals in the group who did not use urban green space described as consequence of the deficiency more frequent sensations of anxiety and stress as well as reduced physical activity. Disparities were revealed, including barriers to accessing green space for people with a low socio-economic status and violence fears of women across all socio-economic levels, thus hindering positive effects of urban green space. In addition, most participants reported that green space quality, characterized by greenery and vegetation, were important for satisfaction.

Huerta and Utomo (2021), Mexico	Adults and older adults in Mexico City (1945, largest age group 18-24 years (27%), 59%, n.a.)	June 2020	Observational, cross-sectional, quantitative, online survey	Investigate associations between the frequency of urban green space use and subjective well-being pre- and during COVID-19	Urban green space	Frequency of urban green space use Time to closest urban green space Urban green space quality based on infrastructure, maintenance, size, and events (all self-reported)	Subjective well-being	Warwick-Edinburgh mental well-being scale	Using green space frequently was related to higher subjective well-being, with the relationship being stronger during COVID-19 (B = 1.65, p < 0.01) compared to pre-COVID-19 (B = 0.87, p < 0.01). Urban green space quality was associated with better subjective well-being both prior and during COVID-19 with a similar strength (B = 2.22-5.81, all p's < 0.01). Longer time to the closest urban green space (21+ minutes) was related to lower subjective well-being prior to COVID-19 (B = -1.32, p < 0.01), but not during COVID-19 (B = -0.33, p > 0.10). Compared to those who stopped using urban green space during COVID-19, those who kept or started using urban green space had higher odds for maintained or increased well-being (OR = 1.46, 95%CI = 1.21-1.76), while there was no association or urban green space quality or time to the closest urban green space observed (all p's > 0.10).
Humberstone (2021), New Zealand	Older adults (1, n.a., 100%, n.a.)	March-June 2020	Observational, case study, qualitative, autoethnography	Investigate nature-based recreation and its contribution to health and well-being	Green and blue space	Any green and blue space experienced by the autoethnographic researcher	Health and well-being	Realist tales of first kayaking and hiking experiences after the lockdown	Being in the outdoors affords enormous emotional and spiritual benefits for older people.
Idoiaga Mondragon et al. (2021), Spain	Children and adolescents (250, ø = 7.24 ± 2.57 years, age range 3-12 years, 52%, n.a.)	March-April 2020	Observational, cross-sectional, qualitative, online survey	Investigate the impact of the COVID-19 lockdown on children's emotional response	Nature	Any self-reported nature places and spaces mentioned by the children (e.g., parks, mountains; transcribed by the parents)	Emotional response	Open question "How are you feeling these days"?	Children missed the outdoors and contact with natural elements during the lockdown, which was reflected in a negative emotional response.
Jackson et al. (2021), USA	Adolescents (624, 10-18 years, 50%, 59.8% White, 11.4% Black, 12.5% Hispanic, 14.9% Other)	April-June 2020	Observational, cross-sectional, quantitative, online survey	Investigate associations between different types of outdoor activities and subjective well-being during COVID-19	Nature	Self-reported nature-based activities (e.g., hiking) Single item asking if time spent in nature helped to deal with the stress caused by physical distancing	Subjective well-being Mental health	Modified 5-item Subjective Health and Well-being scale One-item question to report mental health prior and during COVID-19 Single item asking if time spent in nature helped to deal with the stress caused by physical distancing	Continued participation in nature-based activities during COVID-19 was related to a weaker decline in subjective well-being (B = 0.21, β = 0.14, p = 0.016). Children who increased participation in nature-based activities displayed levels of subjective well-being similar to the ones prior COVID-19. Engagement in nature-based activities prior to COVID-19 were unrelated to changes in subjective well-being scores (B = -0.08, β = -0.01, p = 0.271). 76.4% of children and adolescents reported that spending time outside in nature helped them to deal with stress caused by physical distancing, which translated to mitigated declines in subjective well-being (M = −0.39, SD = 0.73) and self-reported mental health (M = −0.35, SD = 0.89), compared to the ones not reporting those benefits (M = −0.70, SD = 0.87; M = −0.54, SD = 0.90).

Janus et al. (2022), Poland	Allotment garden owners (203, largest age group 41-50 years (28.6%), 49%)	NR	Observational, cross-sectional, quantitative/qualitative, online survey	Investigate value and reasons for purchasing allotment gardens during COVID-19	Gardens	Questions about perceived value and reasons for gardening	Perceived value	Questions about perceived value and reasons for gardening	Relaxation was the most frequently reported benefit of a home garden across age groups (33-70% agreement) except in the <20 year-olds and 61-70 year-olds. For <20 year-olds and 61-70 year-olds, growing fruit and vegetables was most frequently reported (38% and 35% agreement, respectively). Spending time with family was most frequently reported by 31-40 year-olds (21%). Physical activity was barely mentioned. Reasons for purchasing an allotment garden also varied across age groups, with a place to meet family and friends being the most important for <20 year-olds (38% agreement), while physical activity was the most important reasons for 41-50 year-olds (21% agreement). For most of the <20 year-olds and 41-50-year-olds, the gardens were a place to escape from everyday problems (83% and 50% strong agreement, respectively).
Jarratt (2021), mostly UK	Webcam travelers (227, n.a., 69%, n.a.)	NR	Observational, cross-sectional, quantitative, online survey	Investigate connections to places and nature via webcam travels	Digital nature	Self-reported webcam travel	Well-being	Scale items asking participants to indicate how viewing webcams made them feel, including scales on feeling more positive, more connected, and relaxed Description in one word chosen by the participant how viewing webcams made them feel.	68% of webcam viewers looked at nature, with most of them viewing wildlife cams. Overall, the results suggests that webcam viewers experienced an uplift in mood: 83% felt more positive, 90% more relaxed, and 90% more connected after webcam traveling. Of those who had visited the place in real-life before, 83% indicated that this brought back happy memories. The most commonly words used to describe the experience were terms around happy, relaxed, fascinated, and connected.
Jato-Espino et al. (2022), Spain	Adults and older adults (9883, >50% 16-49 years, >53% women, n.a.)	April-May 2020 March 2020 - June 2021	Observational, cross-sectional, quantitative, online survey	Investigate associations between living close to green infrastructure and mental health during the COVID-19 lockdown	Green infrastructure	Geospatial analysis of green space 150, 300m, and 500m circular buffers	Stress Anger Enjoyment Alcohol Consumption Medication use Doctor visits	Secondary data obtained from another study	Stress (r = -0.66 to r = -0.72), anger (r = -0.40 to r = -0.57), medication use (r = -0.53 to r = -0.67), alcohol consumption (r = -0.82 to r = -0.84), or visits to the doctor (r = -0.79 to r = -0.84) significantly decreased if citizens lived close by green infrastructure. Results for enjoyment were less consistent.
Jenkins et al. (2021), New Zealand	Adults and older adults (759, ø = 43.04 ± 13.71 years, age range = 18-81 years, 79%, 82.9% New Zealand	April 2020	Observational, cross-sectional, quantitative/qualitative, online survey	Investigate if physical activity context (nature-based vs. non-nature based) moderates the association between physical activity and psychological well-	Nature during physical activity	Two items asking participants if they have the option to be active in or around natural environments and if they participated in nature-based physical activity	Psychological well-being Motivational quality	WHO-5 Well-Being Index Behavioral Regulation in Exercise questionnaire	Both nature- and non-nature based physical activity were positively related to psychological well-being, with no moderation of the context.

	European, 15.4% Other)			being during the COVID-19 lockdown					
Jo et al. (2022), Japan	Adults and older adults in megacities (5756, largest age group >70s (22%), 51.3%, n.a.)	November 2020	Observational, cross-sectional, quantitative, online survey	Investigate the role of blue space for well-being during the COVID-19 pandemic	Blue space	Questions about purpose and motivation of visitation of blue space	Well-being	Questions about purpose and motivation of visitation of blue space	People primarily visited sea and river areas to feel at ease (sea: 53.2% agreement; river: 33.5% agreement) and for walking (sea: 56.4% agreement; river: 63.0% agreement).
Johnson and Sachdeva (2022), USA	Social media users (through Twitter posts in metropolitan US regions; 971,968 tweets)	March-July 2019 March-July 2020	Observational, longitudinal, quantitative, social media analysis (Twitter)	Investigate associations between nature and well-being during COVID-19	Nature	Tweets with nature- and green space-based keywords	Well-being	PERMA lexicon	Socializing outdoors was associated with increased well-being during the pandemic ($\beta = 1.06$, $p < 0.001$), as well as gardening ($\beta = 0.50$, $p < 0.001$), with the associations of the latter one with well-being being stronger during the prior to during the pandemic. Hiking/camping/beach was unrelated to well-being.
Joshi and Wende (2022), Canada	Gardeners and garden coordinators in Edmonton (215, n.a., n.a., n.a.)	May-October 2020	Observational, longitudinal, qualitative, ethnographic + interviews + survey	Investigate opportunities and challenges of community gardening	Community gardens	Gardening	Opportunities and challenges of com	Ethnographic observations and open-ended questions	A majority of the community gardeners experienced positive social association with community gardening activities during the pandemic, including getting a break from the lockdown, having a space for safe outdoor gathering, meeting other gardeners, as well as stress relief and happiness through gardening. Negative experiences were also mentioned by some participants, such as feeling isolated and lonely in the garden.
Kang et al. (2022), China	Adult and older adult urban residents (1364, largest age group 18-30 years (42%), 65%, n.a.)	January-April 2020	Observational, cross-sectional, quantitative, online survey	Investigate if community parks helped to reduce stress levels during the lockdown	Community park	Frequency and duration of community park use during lockdown Reasons for park use	Stress	Visual analogue scale Reasons for park use	There was no significant relationship between stress level and community park use. Participants agreed to use the park to relax (21.74%), ease stress (14.12%), and to exercise (10.61%), whereas only 1.24% reported to use the park for social needs.
Karpinski and Skrzypczak (2022), n.a.	Recreational anglers (564, largest age group 25-65 years (79.3%), n.a., n.a.)	July-August 2021	Observational, cross-sectional, quantitative, online survey	Investigate perceptions and behavior of recreational anglers during the COVID-19 pandemic	Angling	Reasons for angling	Stress	Reasons for angling	Perceptions of pandemic stress reduction were confirmed by 63.8% of anglers. Feelings of stress reduction were most strongly related to a preference for fishing with friends and family. Escaping the pandemic media hype was a reason for more angling during the pandemic.
Khalilnezhad et al. (2021), Iran	Adults and older adults (394, largest age group 30-39 years (33%), 61%, n.a.)	January-February 2021	Observational, cross-sectional, quantitative, online survey	Investigate use and motivation to visit green space during COVID-19 and the effect on user's feelings	Public and private green space	Frequency and type of green space visitation; motivation to visit green space	Feelings Reasons to visit green space	Feelings in green space during and prior to the pandemic	Walking was the most reported reason to visit public green space (27%), whereas private green space was more important for relaxing (15% agreement). Being in a green space resulted in enhanced positive feelings, such as happiness, pleasure and physical energy, without difference between public or private

									green spaces. The majority of respondents indicated that green spaces contribute to reducing a series of negative feelings, including anxiety, tension, sadness, depression. Private green spaces contributed more to the reduction of anxiety and fear than the public green spaces.
Kim et al. (2022), Korea	Medical workers (13, 42.23 ± 10.99 years, 85%, n.a.)	November 2021	Experimental, longitudinal, quantitative, survey + physiological parameter assessment	Investigate effects of a forest healing program on health during COVID-19	Forest healing therapy	Two-day forest treatment program with various components, e.g., a walk in the forest, woodworking, and relaxation program	Stress Sleep quality	Perceived stress scale (PSS) Epworth sleepiness scale (ESS) Stanford sleepiness scale (SSS) Pittsburgh Sleep Questionnaire Index (PSQI) Hospital Anxiety and Depression scale (HADS) Somatization symptoms (KSCL95) Salivary cortisol Dehydroepiandrosterone sulfate (DHEA-S) Melatonin	There was an improvement in sleep duration from prior to post-treatment (+41.54 ± 46.70 minutes, $p < 0.05$) as well as in perceived stress (-2.69 ± 3.73, $p < 0.05$) and in dehydroepiandrosterone sulfate (-1.42 ± 2.07, $p < 0.05$), indicating that some sleep and stress parameters improved.
King and Dickinson (2022), UK	Urban adults and older adults (12, late 20s – 70s, n.a., n.a.)	March 2020	Observational, longitudinal, qualitative, mobile instant messaging diaries	Investigate value of urban green space during COVID-19	Urban green space	Any green space presented by the participants	Value of urban green space	Any benefits brought up by the participants	Contact with nature contributed to the participant's physical, psychological, and social well-being. Green space became a meaningful place that allowed activities to alleviate boredom from the lockdown. At the same time, the large number of people using green space seemed to be perceived in a negative way, with the green spaces being very busy.
Koch et al. (2022), Spain, Austria, Sweden	Adult population of three cities	March-April 2020 (acute period) May-June 2020(deconfinement period)	Observational, longitudinal, quantitative, health impact assessment	Investigate impact of changes in green space visits on depression and anxiety during COVID-19 acute lockdown period and deconfinement period	Green space	Secondary data on green space visits from other surveys (Baseline) Variable "Parks" from the COVID-19 Community Mobility Reports (Google)	Mental health and vitality	Secondary data from other surveys	If the decrease in green space visits lastet for a longer duration, the risk of worse mental health and vitality would increase by 82% in adult residents in Barcelona during the lockdown, while there was no significant association between green space visit changes and mental health in Vienna and Stockholm. No associations in the post-confinement period were observed. These observations were impacted by seasonal variability.
Kolbe et al. (2021), USA	Patients and hospital staff in the COVID-19 recovery unit	Spring 2020	Experimental, cross-sectional, qualitative /quantitative, survey	Investigate satisfaction and perceived benefit of a virtual reality tool during COVID-19	Digital nature	Virtual reality sessions with three different categories, max 30 minutes, free choice of the	Satisfaction Perceived benefits	Four-item survey after the first virtual reality session	On a scale of 1-10, patients reported a mean of satisfaction of 8.42 of the virtual experience with regards to helping to manage their pain and anxiety. Hospital staff reported a mean satisfaction of 9.45 of the virtual reality experience with regards to helping

	(13 patients, 11 staff, n.a., n.a., n.a.)					participants what to do: 1) guided meditation in highly realistic immersive nature scenes, 2) guided active or passive nature experience, 3) cognitive stimulation games. In appearance, all modules three-dimensional soothing natural settings.			to manage stress. Open-ended responses revealed several benefits such as feelings of escape from problems, relaxation, enhanced alertness, and feeling connected to others on the patient side, as well as feelings of escape, relaxation, coping, and self-care on the hospital staff side.
Kondo et al. (2022), USA	Adults and older adults in New Orleans (244, 52 years, age range 22-94 years, 70%, 82% Black)	January 2019-March 2020 (pre-pandemic) March 2020 – April 2021 (during pandemic)	Observational, longitudinal, quantitative, online survey + census tract data	Investigate associations between neighborhood characteristics and psychological distress during the COVID-19 pandemic	Parks	Objectively assessed park score with different parameters, such as park quality, accessibility, facilities, and investment	Psychological distress	Kessler 6 Psychological Distress Scale (K6)	A higher park score, representing park systems with higher quality, was associated with reduced distress related to the pandemic (β = −0.03; 95% CI: −0.05, −0.01).
Kontsevaya et al. (2021), Russia	Adults and older adults (2432, ø = 37.6 ± 13.4 years, 83%, n.a.)	April-June 2020	Observational, cross-sectional, quantitative, online survey	Investigate factors associated with physical activity and sleep changes during COVID-19	Green space	Self-reported access to private or public green zone	Physical activity Sleep habits and quality	Self-reported physical activity frequency, intensity, time, and type Self-reported sleep items about getting enough sleep, trouble falling asleep, and waking up earlier than wanting to	Having access to green space compared to no access was associated with an increased chance to meet the physical activity (OR = 1.17, 95%CI = 1.09-1.24) and muscle-strengthening (OR = 1.14, 95%CI = 1.06-1.23) recommendations. Having access to green space was unrelated to changes in moderate (β = -0.38, 95%CI = -1.10 to 0.34) and vigorous (β = -0.33, 95%CI = -1.17 to 0.50) physical activity, walking (β = -0.60, 95%CI = -1.74 to 0.54), muscle-strengthening activity (β = 0.00, 95%CI = -0.01 to 0.02), and not getting enough sleep (β = -0.10, 95%CI = -0.29 to 0.09).
Korpilo et al. (2021), Finland	Adults and older adults in Helsinki (418, n.a., 57%, n.a.)	May 2020	Observational, cross-sectional, qualitative, public participation survey + open-ended questions	Investigate changes in urban green infrastructure use during COVID-19	Urban green infrastructure	Frequently visited places mapped by participants Open questions about outdoor recreation and perception of green space	Green space perceptions	Open questions about outdoor recreation and perceptions of green space	Urban green infrastructure, especially nearby forests, played a critical role for well-being during the pandemic. While it allowed to meet people, crowded places in nature seemed to be perceived in a negative way.

Kou et al. (2021), China	Shanghai community gardeners, citizens and people outside the community (1154, largest age group 26-40 years (50.25%), 55%, n.a.)	August 2020	Participatory action research, cross-sectional, quantitative/qualitative, questionnaire surveys and interviews	Investigate the impact of community gardening on resident's daily life during COVID-19	Gardens	„Seeding Plan", a contactless community gardening program	Mental health Social interactions Perceived benefits	Items to indicate negative, no, and positive changes in mental health, family harmony, neighborhood interaction, and relative/friend interaction, and optimism Semi-structured interviews to identify perceived benefits	Results revealed that participants of the community garden project reported the most positive changes in mental health (M = 2.29, SD = 1.78), as well as family harmony and social interactions (M = 2.28-2.45, SD = 1.67-1.80), while they reported stable optimism pre- and during the pandemic (pre-pandemic: M = 2.60, SD = 1.65, during the pandemic: M = 2.63, SD = 1.58). Those changes were significantly more positive than reported by people who live in the same community, but did not participate in the program and people living outside the community (all p's < 0.01). However, people living in the community, but not participating in the program, reported more positive changes than people not living in the community (all p's < 0.01). Semi-structured interviews revealed that the seeding activities did not only promote mental health, but also allowed reconnecting with family members, neighbors, and other seeding participants both in-person and digitally, while the seeding program also promoted participation in other online and offline community activities.
Lades et al. (2020), Ireland	Adults and older adults (604, ø = 47.2 ± 12.1 years, 68%, n.a.)	March 2020	Observational, cross-sectional, quantitative, day reconstruction method via an online survey	Investigate associations between daily activities and affective experiences	Garden	Participants described 5 'sequential' episodes of their day and what they did, with gardening being one of the reported activities	Emotional well-being	3 items asking about positive and 6 items asking about negative feelings	Gardening activity was related to higher positive affect (B = 0.29, p < 0.01), but not negative affect (B = -0.09, p > 0.05).
Lanza et al. (2021), USA	Children and adolescents (361, 1-12 years, 45%, n.a.)	Autumn 2019 Autumn 2020	Observational, longitudinal, quantitative, observation	Investigate the impact of the pandemic on park use outside school hours during COVID-19	School parks	Observation of children in parks	Physical activity	System for Observing Play and Recreation in Communities (SOPARC)	Compared to prior the COVID-19 pandemic, a 42% [95% CI: 16–59%] and 60% [95% CI: 36–75%] decrease in the number of girls and boys engaging in physical activity was observed in the parks, respectively (p < 0.01).
Larcher et al. (2021), Italy	Adults and older adults (3286, largest age group 46-60 years (33.8%), 64.5%, n.a.)	April-May 2020	Observational and case study, cross-sectional, quantitative, online survey	Investigate public green area perception during the physical distancing period	Public green-area	One item asking about thoughts related to participant's physical/psychological need to enjoy a public green area?	Psychological and physical need for green space	One item asking about thoughts related to participant's physical/psychological need to enjoy a public green area?	23.3% of the participants reported a pressing physical or psychological need for green areas, 47.5% reported a recurrent need, 21.7% an occasional need, and 7.5% no need. The need was especially relevant for people who used to frequent public green areas prior to the physical distancing period and who had no outside (green/non-green) access options, whereas it was absent for those who did not visit public green space and those who had a private garden.

Larson et al. (2022), USA	University students (1280, 80% < 25 years, 61%, 11% Asian, 4% Hispanic/Latinx and Black, respectively)	March-May 2020	Observational, cross-sectional, quantitative/qualitative, survey + geospatial analysis	Investigate associations between outdoor recreation and psychological health during COVID-19	Parks	Self-reported changes in park use due to COVID-19 Geospatial assessment of park area / 10 000 residents and NDVI at zip code level Open ended questions about reasons for changes in park use	Emotional distress	Visual analogue scale based on PANAS items Open ended questions about reasons for changes in park use	General health was unrelated to park use during COVID-19 (OR = 0.97, 95%CI = 0.86-1.08). Area of national/state parks was associated with less emotional distress (B = -1.70, 95%CI = -2.9, -0.6), whereas reducing park use during the pandemic was related to greater emotional distress (B = 3.40, 95%CI = 1.6, 5.2). Area of local parks and NDVI were unrelated to emotional distress. Qualitative data analysis revealed that for people who increased park use, improving mental health and reducing boredom were important reasons as well as parks being a replacement for former indoor exercise. Among those who reduced park use, negative emotions were mentioned as one barrier that hindered them to go out in the park.
Lee and Jeong (2021), UK	Social media users (through Twitter posts in London; 427 tweets during the lockdown, 367 tweets in 2019)	March-May 2019 March-May 2020	Observational, longitudinal, quantitative, social media analysis (Twitter)	Investigate changes in noise sources of annoyance during COVID-19	Nature sounds	Outdoor noise in the category nature and animal	Noise complaints	Analysis of Twitter posts regarding noise complaints and annoyances of nature and animal soundscapes	Prior to the lockdown in 2019, there were 2 posts reporting annoyances through nature and animal soundscape, which increased to 15 posts during the same time of the year in 2020 during the lockdown period. Most complaints were about bird noise (N = 12).
Lee et al. (2021), South Korea	Park visitors (1196, largest age group 50-59 years (31.8%), 48.7%, n.a.)	May-July 2020	Observational, cross-sectional, quantitative, survey	Investigate associations between forest types and well-being during COVID-19	Forests in different parks: national park, natural recreational forest, urban forest	Frequency and duration of forest visits Multiple choice questions with predefined answer options with visiting reasons	Perceived restorativeness Social-psychological stress Reasons for visiting forests during COVID-19	Perceived Restorativeness Scale (PRS) Psychological Well-Being Index Short Form (PWB-SF) Multiple choice questions with predefined answer options with visiting reasons	Perceived restorativeness of forests was negatively related to social-psychological distress (r = -0.40, p < 0.001). Perceived restorativeness was higher in the national park (M = 5.36, SD = 0.79) and natural recreation forest (M = 5.57, SD = 0.91) compared to urban forests (M = 5.17, SD = 0.77; p < 0.001), while there was no difference in social-psychological stress observed (p = 0.060). There were significant differences in the time spent in the forest depending on health status, with healthy people tending to spend more time in the forest (>5 hours: 12.6%) compared to the potential stress group (5.2%) and the high-risk stress group (4.4%). The most common reason (67%) for visiting forests during COVID-19 was for physical activity (exercise, walking, mountain climbing).
Lee, Bae, et al. (2022), Korea	University students (175, ~ 20 – 23 years, 0%, n.a.)	March 2021	Experimental, longitudinal, quantitative, survey + cognitive test	Investigate effects of nature-based physical activity during COVID-19	Nature-based physical activity	Exposure to real natural environment during outdoor exercise and exposure to virtual natural environment during indoor exercise (control group: indoor	Concentration Psychological capital	Cognitive function test (Trail Making Test Part 2) Positive psychological capital test	The scores for positive psychological capital sub-factors (self-efficacy, optimism, and hope) in the groups with the natural environmental exposure with outdoor exercise and visual stimulation with indoor exercise conditions experienced more positive change than the indoor exercise group (p < 0.05). Concentration improved through the trial, with no differences between the groups.

					exercise without real-world/virtual exposure to natural environment); 30 minute exercise session with 5 minute breaks after every 10 minutes				
Lee, Cheng, et al. (2022), Cambodia, Indonesia, Japan, South Korea, Myanmar	Adults and older adults (542, largest age group < 29 years, 57.4%, n.a.)	June-July 2020	Observational, cross-sectional, quantitative, survey	Investigate perceived benefits of nature during COVID-19	Nature	Question about benefits of nature for psychological health	Psychological health	Question about benefits of nature for psychological health	Respondents across all countries showed high agreement for strengthened awareness regarding the benefits of nature for their psychological health.
Lee, Healy, et al. (2022), USA	Children and adolescents with autism spectrum disorder (92, 13.26 ± 2.21, 23.9%, n.a.)	October 2020 – January 2021	Observational, cross-sectional, quantitative, online survey + geospatial analysis	Investigate correlates of leisure-time physical activity during COVID-19	Parks	Walking distance to nearest park based on zip code entered in Google Maps	Leisure-time physical activity	Godin Leisure Time Questionnaire (filled in by the parents)	Local park proximity was positively associated with leisure time physical activity (r = -0.33, p = 0.006) and number of days with at least 60 minutes of physical activity (r = 0.51, p < 0.001).
Lee, Lee, et al. (2022), USA	Adults in El Paso (720, 44.56 ± 0.52 years, 67.7%, 14.4% Non-Hispanic White)	July-August 2020	Observational, cross-sectional, quantitative, survey	Investigate correlates of physical activity during COVID-19	Park and green space	Self-reported presence of parks / natural green space in the neighborhood	Moderate-to-vigorous physical activity Recreational walking	Questions adapted from the International Physical Activity Questionnaire (IPAQ)	Presence of neighborhood parks and green space was unrelated to moderate-to-vigorous physical activity and walking.
Lee, Mkandawire, et al. (2022), Malawi, Rwanda, South Africa, Tanzania, Zambia	Adults and older adults in the capitals of the respective country (430, largest age group < 29 years, 45.2%, n.a.)	April-June 2020	Observational, cross-sectional, quantitative, survey	Investigate changes in health recovery perceptions and forest outdoor activity during COVID-19	Urban forests	Question about perception of health recovery in urban forest	Mental health	Question about perception of health recovery in urban forest	Most of the respondents answered that it was newly recognized that nature experience in urban forests helped people to recover their psychological health during the pandemic.
Lehberger et al. (2021), Germany	Adults and older adults (495, largest age group 50-59 years (24.8%), age range 18-65 years, 49%, n.a.)	May 2020	Observational, cross-sectional, quantitative/ qualitative, online survey	Investigate associations between use of green space and well-being during COVID-19	Garden Public green space	Garden owners: Time spent in the garden; non-garden owners: Time spent in public green space Changes in time spent in the garden/public green space	Mental well-being Life satisfaction Meaning of green space during COVID-19	Warwick-Edinburgh Mental Wellbeing Scale (WEMWBS) One item asking participants to rate their current life satisfaction Open-ended question asking participants to	Garden owners showed higher life satisfaction and mental well-being (M = 7.40, SD = 1.80; M = 50.71, SD = 8.69) compared to non-garden owners (M = 6.31, SD = 2.26; M = 46.55, SD = 9.01; p < 0.001). However, garden ownership was neither associated with mental well-being (B = 0.26, 95%CI = -1.51 to 2.03) nor life satisfaction (B = 0.20, 95%CI = -0.22 to 0.61). Rather, variables related to garden ownership, including time spent in green space, less fear of job loss, higher income, and lower neuroticism scores

						Open-ended question asking participants to describe the meaning of green space		describe the meaning of green space	were related to better mental well-being and life satisfaction. For life satisfaction, lower neuroticism scores and higher income were Time spent in green space was related to mental well-being (B = 2.32-2.73, 95%CI = 0.13-4.52), but not life satisfaction (B = 0.18-0.22, 95%CI = -0.35 to 0.70). The vast majority of participants associated positive meanings (e.g., joy) and family time with private gardens and public green spaces during the pandemic.
Lenaerts et al. (2021), Belgium	Adolescents, adults, and older adults (11352, largest age group 41-65 years (51-65 years), age range 12-65+ years, 68%, n.a.)	April 2020	Observational, cross-sectional, quantitative, online survey	Investigate factors that influence nature visits during COVID-19	Nature	Frequency of nature visits	Mental health Well-being	One item asking about how healthy that participants is feeling in the head 11 items asking about feelings after visiting nature	Those who were mentally healthy were more likely to visit nature more frequently than the ones that were mentally unhealthy (OR = 1.31, 95%CI = 1.18-1.46). 51.6% of the people who went into nature during COVID-19 experienced it more positive than before.
Lenzi et al. (2021), Basque Country	50 audio-recordings in Getxo evaluated by experts (14, median age 40 years, age range 24-53 years, 50%, n.a.)	March-May 2020	Observational, case study, qualitative, observations, field audio recordings, photography, diary notes	Investigate feelings about natural soundscapes	Nature sounds	Any nature sound within the audio recording	Feelings about the soundscape (soundscape quality) rated by experts	Adapted version of the Swedish Soundscape Quality Protocol	Pleasantness was correlated with perceived natural sounds (ρ = 0.44, p< 0.001).
Lesser and Nienhuis (2020), Canada	Adults and older adults (1098, ø = 42 ± 15 years, 79.3%, n.a.)	April-May 2020	Observational, cross-sectional, quantitative, online survey	Investigate changes in COVID-19 related physical activity	Nature	Natural / non-natural physical activity context	Physical activity	Godin Leisure Questionnaire and classification in active (≥ 150 minutes moderate-vigorous physical activity/week) and inactive participants (< 150 minutes moderate-to-vigorous physical activity/week)	There were no statistically significant differences between the proportion of active and inactive participants conducting physical activity in natural environments (82.6% vs. 75.6%, p = 0.053).
Li, Luo, et al. (2021), China	Adults and older adults in megacities (628, largest age group 18-35 years (71.3%), 64.5%, n.a.)	December 2020-March 2021	Observational, cross-sectional, quantitative, survey	Investigate components of urban green space that relate to health benefits	Urban green space	Self-reported green space access, size, maintenance, and soundscape	Mental health benefits Social health benefits	Question asking about agreement of urban green space contributing to mental/social health	Green space access was associated with improved mental and social health (both β = 0.15, p < 0.01), as was green space maintenance (mental health: β = 0.18, p < 0.01, social health: β = 0.15, p < 0.01). Green space size and type were unrelated to mental and social health.

Li, Zhang, et al. (2021), China	Prisoners (269, 34.45 ± 8.09 years, 0%, n.a.)	March 2020	Observational, cross-sectional, quantitative, survey	Investigate effects of nature view outside the window on psychological well-being during COVID-19	Nature window view	Self-reported nature visibility through the window Frequency and duration of viewing	Depression Anxiety Loneliness Well-being	Patient Health Questionnaire (PHQ-9) Generalized Anxiety Disorder Scale (GAD-7) UCLA Loneliness Scale short form (ULS-6) Distress Tolerance Scale (DTS) Satisfaction with Life Scale (SWLS) WHO Well-Being Index (WHO-5)	Frequency of looking at nature outside the window was associated with increased well-being ($\beta = 0.10$, $p < 0.05$), while nature visibility was associated with higher distress tolerance ($\beta = 0.15$, $p < 0.05$) and greater life satisfaction ($\beta = 0.14$, $p < 0.05$). Duration was not associated with any of the outcomes. No direct relationships emerged with any of the other variables.
Lin et al. (2022), China	Questionnaire: Adults and older adults (743, largest age group (41.5%), 47%, n.a.) Interviews: River improvement participants and experts (12, n.a., n.a., n.a.)	June-September 2021	Observational, cross-sectional, quantitative/ qualitative, online survey + interviews	Investigate the impact of river improvement and greening on the urban well-being index during COVID-19	River and greenspace	Urban river improvement and greening project	Well-being	Urban happiness index	The project has the potential to help people to relieve stress and improve their mental health. However, due to poor management, visiting this area posed an infection risk, resulting in limited leisure benefits and thus not being helpful for improving mental health or having fun. Additionally, survey responses by people from different backgrounds varied.
Liu et al. (2021), China	Urban older adults (248, largest age group 70-80 years (52.4%), n.a.)	February-April 2020	Observational, cross-sectional, qualitative, interviews	Influences on elderly mobility during COVID-19	Nature	Any nature mentioned by participants	Physical activity	Interviews	Walking and other physical exercises remained enjoyable for those who lived in communities with accessible and attractive green spaces (71 out of 248).
Logan et al. (2021), Scotland	Adults and older adults living in woodlands Questionnaires (765, n.a., n.a., n.a.) Interviews (31, n.a., n.a., n.a.)	January-March 2020 September-October 2020	Observational, longitudinal, quantitative/ qualitative, online survey + semi-structured interviews	Investigate the contribution of community woodlands to well-being during COVID-19	Woodlands	Questions about physical and mental health benefits provided by woodlands	Well-being	Questions about physical and mental health benefits provided by woodlands Semi-structured interviews	Physical well-being benefits, including physical activity, were the most frequently mentioned benefits from woodlands, followed by mental well-being. Social benefits were least mentioned. The majority of respondents did not feel that their appreciation and use of woodlands had changed during COVID-19.
Lõhmus et al. (2021), Sweden	Adults (2060, largest age group < 70 years (82%), 55%, 89% from Scandinavian	June-August 2020	Observational, cross-sectional, quantitative, online survey	Investigate if people's mental health and well-being differed depending on greenness exposure during COVID-19	Greenness Nature	Objectively measured Normalized Difference Vegetation Index (NDVI) with buffers between 50-500	Alcohol consumption Sitting score Mental health Vitality Anxiety Depression Perceived stress	Self-reported frequency and amount of alcohol consumption International Physical Activity Questionnaire Short Form	Problematic alcohol consumption was more likely for participants with low NDVI values compared to high NDVI values (57% vs. 43%, $p = 0.019$). High sitting scores were also more likely for participants with low NDVI values (54% vs. 46%, $p = 0.017$). Increases in sitting behavior were observed independent of the NDVI-value.

	countries or Baltic States)					meters around participant's home address Self-reported visits to natural areas Reasons for visiting nature areas pre- and during COVID-19	Cognitive stress	Mental health and vitality subscales of RAND-36 Depression and anxiety subscales from the Hopkins Symptom Checklist 90 6-item perceived stress scale Cognitive stress scale from the Stress Profile Reasons for visiting nature areas pre- and during COVID-19	Higher NDVI values within 50 meters were related to mental health (B = 5.95, 95%CI = 0.69-11.21), anxiety (B = -0.62, 95%CI = -1.10 to -0.14), and cognitive stress (B = -6.31, 95%CI = -12.60 to -0.01). Vitality, depression, and perceived stress were unrelated for the 50 meter buffer, but showed some associations for the other buffer sizes. For those visiting nature often or very often, the reasons for visiting nature changed from prior to during COVID-19: Decreases were observed for stress recovery (36% to 33.8%, p = 0.028) and relaxation reasons (62.4% to 52.5%, p = 0.001), and increases for physical activity (69.7% to 72.1%) and health reasons (68.8% to 72.5%, p = 0.001).
Lopez et al. (2021), USA	Adults and older adults in New York (1145, largest age group 20-39 years (45%), 70%, 8% Black, 7% Asian, 1% Native American, 10% Latinx)	Spring 2020	Observational, cross-sectional, quantitative, online survey	Investigate who benefits of urban green space during COVID-19	Urban green space	Questions about changes in perceptions of urban green space benefits Frequency of urban green space visitation, changes in visitation, and important features	Mental health	Question about green space exposure impacting mental health	Over 80% reported that urban green space was either extremely or very important for mental health, with increased importance since the onset of the pandemic. Men assessed green space less important than women, people with Black ethnicity assessed green space less important than other ethnicities, and people from Queens assessed green space less important compared to people from Manhattan.
Luo et al. (2021), China	Urban adult and older adult residents (47, 35.4 ± 15.4 years, age range 21-84 years, 64%, n.a.)	March-May 2020	Observational, cross-sectional, qualitative, telephone interviews	Investigate motives of urban residents to visit green space during COVID-19	Urban green space	Interview questions about reasons for visiting green space as well as experiences and activities	Reasons for visiting green space	Interview questions about reasons for visiting green space as well as experiences and activities	Urban green space served as therapeutical place during COVID-19 via providing relaxation, a place to escape from pandemic-related stressors and a break from negative emotions, and mental health promotion via engagement in outdoor activities and physical exercise. Also, urban green space served as meeting place through simple social interactions, hence providing social support.
Mackinnon et al. (2022), New Zealand	Wellington residents (118, n.a., n.a., n.a.)	April-May 2020	Observational, cross-sectional, quantitative, survey	Investigate reasons for visiting green space during COVID-19	Urban green space	Questions about reasons for visiting green space	Reasons for visiting green space	Questions about reasons for visiting green space	The most frequently reported reason for visiting green spaces during lockdown was mental wellbeing. Park visits helped participants alleviating negative emotions and stress, while it helped to combat loneliness and allowed safe social interactions. Most respondents indicated that the benefits of nature remained constant during COVID-19 compared to prior to the pandemic.
Marconi et al. (2022), Argentina	Residents of Buenos Aires (298, n.a., n.a., n.a.)	December 2020-January 2021	Observational, cross-sectional, quantitative, online survey	Investigate perceptions of urban green space during COVID-19	Urban green space	Questions about reasons for visiting green space and services provided by green space	Reasons for visiting green space	Questions about reasons for visiting green space and services provided by green space	Green spaces were visited due to providing a space for social gatherings as well as a place for sports.

Marques et al. (2021), Brazil	Adult and older adult residents of Rio de Janeiro (173, n.a., 78%, n.a.)	November 2020-January 2021	Observational, cross-sectional, quantitative, online survey + geospatial analysis	Investigate associations between different types of urban green infrastructure and mental distress during COVID-19	Urban parks Green views Gardens	Distance to parks based on zip code Questions about frequency of visiting green space, seeing trees from home, garden at home, and taking care of plants	Mental distress	Depression, Anxiety, and Stress scale 21 (DASS-21)	Although urban parks and green views were important, home gardens were most efficient in mitigating mental distress. Home gardens were most efficient in mitigating mental distress. (LMM model coefficient = -5.2), while visits to parks, green view, and taking care of plants had a smaller relative importance in reducing mental distress (LMM model coefficients: -1.9, -0.7 and -0.5, respectively). The increased distance from parks and leaving home for non-essential activities had a minor relative importance in enhancing mental distress (LMM model coefficients: 1.1 and 0.4, respectively).
Marques et al. (2022), New Zealand	Adults and older adults (212, largest age group 18-25 years (33.8%), 76.6%, n.a.)	May 2020	Observational, cross-sectional, quantitative, online survey	Investigate links between nature exposure and well-being	Outdoors	Any natural environments brought up by participants	Physical activity	Questions about sports and physical activity	Different natural environment, such as urban parks, forest, mountains, and marine blue spaces, such as seafront, beach, or harbor were important places for physical activity during the pandemic.
Mastorci et al. (2021), Italy	Children and adolescents (1289, 12.5 ± 1.3 years, 51.7%, n.a.)	September 2019 April 2020	Observational, longitudinal, quantitative, online survey	Investigate health-related quality of life during COVID-19	Garden	Question about garden at home	Health-related quality of life	KIDSCREEN-52	The perception of physical well-being was lower for those who did not have green space (−4.4 ± 7.5 vs. −2.8 ± 7.2, $F = 11.1$, $p = 0.001$) during the COVID-19 phase compared to prior COVID-19.
Maurer et al. (2021), USA	University students (1200, n.a., 67.1%, 26.5% people of color)	Spring 2020	Observational, cross-sectional, quantitative, online survey	Investigate between going outdoors and subjective well-being during COVID-19	Public and private greenspace	Self-reported frequency and distance to green space	Subjective well-being	Rating of overall life satisfaction, momentary life satisfaction, and outdoor life satisfaction with one item, respectively	Time spent in greenspace correlated with higher levels of subjective wellbeing, while type of greenspace (public vs. private) did not have a significant effect on subjective well-being.
Maury-Mora et al. (2022), Spain	Adult and older adult residents of Madrid (132, largest age group 41-55 years (40%), 64%, n.a.)	May-June 2020	Observational, cross-sectional, quantitative, online survey	Investigate associations between urban green space and stress during COVID-19	Urban green space	Self-reported typology and use of urban green space	Stress	Questions about physical and behavioral stress symptoms and mood	Main findings showed that indoor plant interaction is not a substitute for different outdoor green experiences to manage stress. Those who interacted with green spaces in a daily manner managed stress levels better than people who didn't (but their effects might lose strength over time); and turning to green spaces for comfort during stressful times even if not done so usually helps overcoming difficult situations.
McCormack et al. (2020), Canada	Children and adolescents in Calgary (328, Children: 5–17 years; 10.8 ± 4.0 years; 55%,	April-June 2020	Observational, cross-sectional, quantitative, online survey	Examine associations between parent's COVID-19 anxiety and physical activity and sedentary	Park	Frequency in play behavior at a park proxy-reported via the parents	Child play	Frequency in play behavior at a park proxy-reported via the parents	Approximately half of parents perceived decreases in their child's play at the park (52.7%), while only 15.5% reported increases.

	parental ethnicity: 56.4% Caucasian, 11.3% Chinese, 13.7% Asian other, 18.6% Non-Asian or multiple ethnicities)			behaviors among school-aged children					
Millán-Jiménez et al. (2021), Spain	Undergraduate students (188, 20-32 years, 68%, n.a.)	June-July 2020	Observational, cross-sectional, quantitative/ qualitative, online survey	Investigate associations between home characteristics and health during COVID-19	Park/garden and river/sea	Self-reported window view from home, including park/garden or river/sea	Feelings when looking through the window	Questions about sensations when looking out of the window	Feelings of imprisonment were linked to window views of other buildings (p = 0.005, IC 0.06–0.34), while those feelings were not experienced for park/gardens and river/sea window views. Feelings of peace were related to park/garden and river/sea window views (p = 0.003, IC 0.33–0.08), but not to window views including buildings.
Mitra et al. (2020), Canada	Children and adolescents (1472, largest age group 5-11 years (53%), age range 5-17 years, parental ethnicity: 79.2% European, 13.2% Asian, 7.6% Other)	April 2020	Observational, cross-sectional, quantitative, online survey and geospatial analysis	Investigates associations between changes in patterns of physical activity, sedentary and sleep behavior patterns and the built environment during COVID-19	Objective assessment of access to parks within 1 km	Total number of parks, playgrounds, and open recreational areas based on parental-reported zip code within a 1 km radial buffer distance	Movement behavior clusters	Parental proxy-reported changes and time spent in 11 movement behaviors via parents on a 5-point-Likert scale for each behavior	For children (5-11 years), park access was unrelated to chances of increased outdoor activities cluster membership (OR = 0.83, p = 0.067), whereas access to parks increased the chances of increased outdoor activities cluster membership for adolescents (12-17 years) living in high-density neighborhoods (OR = 1.35, p < 0.001)
Mouratidis (2022), Norway	Adults and older adult residents in Oslo and Viken (1796, 49.7 ± 16.5 years, 50%, n.a.)	June-August 2020	Observational, cross-sectional, quantitative, online survey + geospatial analysis	Investigate changes in health and well-being during COVID-19 and related city characteristics	Green space	Objectively assessed green space % within 1km radius around participant's residential address	Health and well-being	Questions based on the European Social Survey and OECD	Green space was unrelated to life satisfaction, satisfaction with personal relationships, general health, happiness and during COVID-19 as well as to perceived health-related changes.
Mouratidis and Yiannakou (2022), Greece	Adults and older adults in Greek cities (1201, 41.6 years, 57.7%, n.a.)	April-May 2020	Observational, cross-sectional, quantitative, online survey + geospatial analysis	Investigate built environment characteristics in relation to changes in health and well-being during COVID-19	Green space and parks	Objective assessment of park area (m^2 within 1km radius) and tree cover (% within 1km radius)	Health and well-being	Questions based on the European Social Survey and OECD	Park proximity and tree cover were mostly unrelated to life satisfaction, satisfaction with personal relationships, and overall health during COVID-19.
Mullins et al. (2021), Canada	Adults and older adults (1023, largest age group 24-38 years (39%), 52.5%, n.a.)	September 2020	Observational, cross-sectional, quantitative, online survey	Investigates associations between home food gardening and attitudes, beliefs and motivations during COVID-19	Garden	Home food gardening	Well-being related attitudes, beliefs and motivations concerning home food production	14 questions related to attitudes, beliefs, and motivations	All home food gardeners agreed that gardening is important for mental and physical well-being; 70.6% of long-term gardeners and 61.6% of gardeners agreed that they garden for relaxation; 57.6% of long-term and 61.6% of new gardeners considered their gardening as physical exercise.

Muro et al. (2022)	Adults (16, 47.5 ± 8.3 years, 87.5%, n.a.)	May 2020	Experimental, longitudinal, quantitative, survey	Investigate psychological benefits of forest bathing during COVID-19	Forests	Three-hour session of forest bathing	Psychological well-being and overall health	State-Trait Anxiety Inventory (STAI) Positive and Negative Affect Schedule (PANAS) Profile of Mood States (POMS) State Mindfulness Scale	Results showed pre-post improvements across all measurements, specifically in positive affect, vigor, friendship and mindfulness, and decreases in negative affect, anxiety, anger, fatigue, tension, and depressive mood. Effect sizes observed for all the outcomes were significant and large, ranging from d = 1.02 to d = 2.61.
Narea et al. (2022), Chile	Mothers with children between 12-15 months (985, 29.5 years, 100%, n.a.)	2019 September-November 2020	Observational, longitudinal, quantitative, online survey + geospatial analysis	Investigate impact of COVID-19 lockdowns on maternal mental health parental practices and their relationship with urban green space	Green space	Objectively assessed green space within a 300-m radius around mother's residential address	Mental health Parental practices	Parent Stress Index Scale (PSI-SF) Center for Epidemiological Study's Depression Scale (CES-D) Parental Cognitions and Conduct toward the Infant Scale (PACOTIS)	Lockdown duration increased dysfunctional interactions with children for mothers with little access to green space, while this was not seen for mothers living close to green space.
Niles et al. (2021), USA	Adults and older adults (600, largest age group 55+ years (43.8%), 67.3%, 93.2% White, 6.7% Other)	August-September 2020	Observational, cross-sectional, quantitative, online survey	Investigate the association between home food procurement activity and dietary quality during COVID-19	Home food procurement activities	Self-reported engagement and changes in gardening, fishing, foraging, hunting, backyard livestock	Dietary quality	Fruit, vegetable, red meat, processed meat intake and changes in fruit/vegetable and red meat intake	Gardening since the beginning of COVID-19 was related to increased fruit (B = 0.39, 95%CI = 0.16-0.63) and vegetable intake (B = 0.55, 95%CI = 0.31-0.79), whereas foraging was unrelated to fruit and vegetable intake. More gardening/foraging was unrelated to current fruit and vegetable intake and changes in fruit and vegetable intake. Results showed that the increase in fruit and vegetable was only observed for food secure households (B = 0.31, 95%CI = 0.39-0.95; B = 0.67, 95%CI = 0.39-0.95), but not for food insecure households. Livestock since COVID-19 was related to increased red meat intake (B = 1.02, 95%CI = 0.40-1.64), whereas fishing and hunting were not. Fishing and hunting since COVID-19 and more livestock, fishing, and hunting since COVID-19 were unrelated to red meat and processed meat intake.
Noel and Dardenne (2022), Belgium	Adults and older adults (675, 28.63 ± 12.75, age range = 17-77 years, 76.2%, n.a.)	April 2020	Observational, cross-sectional, quantitative, online survey	Investigate relationship between green space and prosocial behavior	Public green space	Self-reported frequency of green space visit since start of the lockdown	Prosocial behavior	Social Value Orientation (SVO) slider	There was no association between green space attendance and prosocial behavior (Spearman rank r = -0.001, p = 0.971), however, interaction analysis showed that green space attendance was related to more prosocial behavior at places that were perceived as little crowded (β = 0.13, p = 0.030).
Noszczyk et al. (2022), Poland	Adults and older adults in Krakow	December 2020-February 2021	Observational, cross-sectional, quantitative, online survey	Investigate the importance of urban green space to the	Urban green space	Reasons for visiting urban green space and impact on mental health	Mental health	Reasons for visiting urban green space and impact on mental health	Over 50% of the respondents indicated visits to green spaces during the pandemic as the most important factor for the improvement of their general well-being (54.2%) and for having a walk (50.6%). Over

	(1251, largest age group 25-40 years (42%), n.a., n.a.)			public during COVID-19					75% of the participants considered visits to green spaces as having a very big (42.2%) or big (34.5%) impact on stress level reduction. Simultaneously, exercise at an outdoor gym did not matter for 35.5% of the respondents and had a very small importance to 16.5% or them. At the same time, almost half of the respondents that visiting urban green space was an opportunity to spend time with friends and family. According to the study, residents believed green spaces to be important for their mental and physical health. Over 75% of the participants considered visits to green spaces as having a very big or big impact on stress level reduction.
Olszewska-Guizzo, Fogel, et al. (2021), Singapore	Urban adults and older adults (25, 40.4 ± 17.9, age range 21-74 years, 56%, n.a.)	January 2020 April 2020	Experimental, longitudinal, quantitative, electroencephalography (EEG) and paper-pencil survey	Investigate whether contact with nature and perception of natural environments during home confinement can mitigate the impact of the stay-at-home order on mental health and well-being.	Digital nature Nature areas	Three 20-second video scenes from lush gardens and residential green, respectively (control condition: busy downtown without green) prior (T1) and right after the stay-at-home order (T2) Self-reported frequency and duration of visits to parks, gardens, or nature reserves (self-reported)	Frontal alpha symmetry (FAA) brain activity as a proxy for positive emotions Depressive symptoms Valence Energetic arousal Mood disturbances	Electroencephalography (EEG; antiCAP) Becks Depression Inventory-II (BD-II) Self-Assessment Manikin (SAM) Profile of Mood Scale (POMS)	Positive emotions assessed via brain activity decreased among those participants with high nature exposure during the stay-at-home order, while it remained stable in those with low nature exposure (p = 0.005). Valence response to the videos remained stable over time and was not moderated by nature exposure, whereas the intensity of positive emotions towards busy downtowns decreased among those with high nature exposure (p = 0.002). Changes in total mood disturbances and depressive symptoms based on Beck's Depression Inventory were not moderated by nature exposure.
Olszewska-Guizzo, Mukoyama, et al. (2021), Singapore	Urban adults and older adults (12, males: ø = 47.8 ± 17.8 years, females: ø = 17.8 ± 18.2 years, age range 21-75 years, 58%, n.a.)	Second quarter 2019-first quarter 2020 June 2020	Experimental, longitudinal, quantitative, fNIRS scans	Investigate changes in hemodynamic activation patterns of the prefrontal and occipital cortices from pre- to during COVID-19	Digital nature	Three 20-second video scenes from lush gardens and residential green, respectively (control condition: busy downtown without green) prior (T1) and right after the stay-at-home order (T2)	Cortical hemodynamic brain activation	Portable fNIRS cap set	Significant decreases were observed in average oxyhemoglobin over time for the urban park (p < 0.05, Cohen's d = -1.01), while the decreases for residential green and the city center were not significant, but yet of large effect size (Cohen's d = -0.91 to -1.00). There were no statistically significant interactions observed.
Oswald et al. (2021), Australia	Young adults in metropolitan areas (1004, 21.23 ± 1.93 years, age	November 2020-January 2021	Observational, cross-sectional, quantitative, online survey	Investigate associations between potential risk and protective factors and mental illness and	Nature	Incidental nature contact (3 items; outdoor access, living within 300-meter walking	Complete mental health state	Four categories based on scores of the Kessler Psychological Distress Scale (K-10) and the Mental Health	High perceived neighborhood nature or greenness was associated with a decreased risk for the mental health states languishing (RRR = 0.35, 95%CI = 0.14-0.85) and floundering (RRR = 0.25, 95%CI = 0.07-0.91). More than 300 meters walking distance to

	range 18-24 years, 55%, n.a.)			well-being during COVID-19		distance to a green space or blue space, perceived neighborhood greenness or nature) Purposive nature contact (4 items; changes in nature contact, going out in the neighborhood, spending time at the local park, planning activities in nature)		Continuum Short Form (MHC-SF): Flourishing, Languishing, Struggling, Floundering	the closest by green or blue space was associated with an increased risk for languishing (RRR = 1.77, 95%CI = 1.02-3.06). Those who decreased nature contact during COVID-19 were more likely to be floundering (RRR = 1.98, 95%CI = 1-09-3.58), whereas those who increased nature contact were less likely to be floundering (RRR = 0.49, 95%CI = 0.26-0.95). More detailed, those who decreased being out in the neighborhood were more likely (RRR = 1.85, 95%CI = 1.00-3.41) and those increasing time at the local park (RRR = 0.41, 95%CI = 0.20-0.81) and planned activities in nature (RRR = 0.40, 95%CI = 0.20-0.82) were less likely to be floundering. Those who increased planned activities in nature were less likely to be languishing (RRR = 0.54, 95%CI = 0.32-0.91). Those who disagreed that nature felt like getting away were more likely to be languishing, struggling, or floundering (RRR = 3.22-5.92, 95%CI = 1.18-17.03). Those who were neutral or agreed that nature felt uncomfortable were more likely to be struggling (RRR = 2.61-5.51, 95%CI = 1.46-9.94).
Ottoni et al. (2022), Canada	Older adults (31, 55% < 75 years, 87% women, 10% Jewish, 3% Chinese, 3% South Asian, 84% White)	May-June 2020	Observational, cross-sectional, quantitative, semi-structured interviews	Investigate how neighborhood factors shape social experiences during COVID-19	Nature	Any nature mentioned by participants	Social connectedness	Any social connectedness mentioned by participants	The outdoors provided a place to meet with others while socially distance to go for walks, however, while some participants perceived those spaces to promote social connectedness for one-on-one interactions, others intentionally chose walking routes and times to avoid people, and almost always walked alone.
Pasek and Szark-Eckardt (2021), Poland	Women engaging in water-based outdoor and indoor physical activity (60, ice-swimming: N = 30, 39.9 ± 11.2, 100%, n.a.; aqua fitness: N = 30, 50.6 ± 10.9 years, 100%, n.a.)	NR	Observational, cross-sectional, quantitative, online survey	Investigate differences between indoor and outdoor water-based physical activity regarding mental health outcomes during COVID-19	Ice water	Engagement in ice-water swimming	Anxiety Body esteem	State-Trait-Anxiety Inventory (STAI) Body Esteem Scale (BES)	Women engaging in ice-swimming felt, compared to women engaged in aqua fitness, more relaxed and less tense, resentful, depressed and worried. Regarding body esteem, out of 35 indicators, women engaging in ice swimming reported higher body esteem on eight indicators.
Passavanti et al. (2021), Australia, China, Ecuador,	Adults and older adults (1612, 28 ± 9.36, 60%, n.a.)	April 2020	Observational, cross-sectional, quantitative, online survey	Investigate the impact of COVID-19 on mental health and associated factors	Private garden	Garden as open space in one's home	Mindfulness Post-traumatic stress disorder Depression Anxiety Stress	Event Scale-Revised (IES-R) Depression, Anxiety and Stress Scale (DASS-21)	In the PSS10 Scale, those without access to open air space had significantly higher stress scores (M = 19.52, SE = 1.79) than those with a private garden (MD = 1.25, p = .014, 95% CI: 0.31 to 2.16). No other differences were observed.

Iran, Italy, Norway, USA								Patient Health Questionnaire (PHQ-9) Perceived stress scale (PSS10)	
Pearson, Breeze, et al. (2021), USA	Breast cancer patients (56, 63.1 ± 10.7, 98%, 7.1% Black, 3.6% Native American, a.8% Hispanic/Latino, 88% White)	July 2020	Observational, cross-sectional, quantitative, online survey	Investigate associations between changes in nature use and perceived stress	Nature	Self-reported frequency and engagement in nature-based active and passive activities prior and during COVID-19	Stress	Perceived stress scale (PSS10)	Decreased usage of parks/trails was significantly associated with higher stress (B = −2.30, p = 0.030)
Pearson, Horton, et al. (2021), USA	Low-income adults and older adults (86, 56.8 ± 14.6, 57%, 83% African-American)	August-October 2019 June-July 2020	Observational, longitudinal/cross-sectional, quantitative, online survey + geospatial analysis	Investigate associations between quality of nature views from home and mental health issues	Nature	Objectively assessed park view from home Self-reported access and use of nature	Stress Anxiety Depression	Perceived stress scale (PSS10) Patient-Reported Outcomes Measurement Information System (PROMIS)	Higher visibility of greenspace was associated with higher anxiety (β = 3.97, p = 0.025), but not depression or stress. Use and accessibility were unrelated to all constructs.
Perez-Urrestarazu et al. (2021), mostly Brazil, Greece, Spain, Italy	Adults and older adults (4205, largest age group 26-65 years (~ 20%), 56%, n.a.)	April-May 2020	Observational, cross-sectional, quantitative, online survey	Investigate the impact of indoor and outdoor vegetation on emotional well-being during COVID-19.	Indoor and outdoor vegetation Green space	Self-reported number of indoor and outdoor plants at home Two items with statements that general green space and indoor vegetation are beneficial for participant's well-being	Emotional well-being	Frequency of positive and negative emotions Two items with statements that general green space and indoor vegetation are beneficial for participant's well-being	89.5% indicated that green space was necessary for their psychological well-being, while 76.0% indicated that indoor vegetation was beneficial for their psychological well-being. People frequently visiting green areas prior to COVID-19 displayed better emotional well-being (weekly visits: mean = 12.25, SD = 2.7; less than once a month: mean = 12.62, SD = 2.8; p < 0.001) as did people with a higher number of indoor plants (1-3 plants: mean = 12.35, SD = 2.6, >10 plants: mean = 11.92, SD = 2.7), while there was no difference in emotional states for outdoor plants. For some countries, emotional states were no different for the frequency of nature visits and the number of indoor plants.
Poortinga et al. (2021), UK	Adults and older adults (5566, largest age group 61-70 years (32.5%), 68.9%, n.a.)	March-April 2020 June-July 2020	Observational, cross-sectional, quantitative, online survey	Explore potential benefits of public and private green space during and after the first peak in COVID-19 infections.	Public green space Private green space	Self-reported walking time to nearest public green space areas Self-reported access to own or communal garden	Subjective wellbeing Self-rated health	SF36 scale One item for self-rated health	During the first COVID-19 peak (lockdown) and post-peak (restrictions loosened), compared to public green space within <5 minutes walking distance, public green space within 5-10 minutes and >10 minutes walking distance was associated with lower subjective wellbeing (B = -0.12 to -0.34, 95%CI = -0.05 to -0.43) and lower self-rated health (B = -0.20 to -0.48, 95%CI = -0.13 to -0.56). During the first peak, having garden access could compensate for

								walking distance >10 minutes to public green space for subjective well-being (B = 0.31, 95%CI = 0.03-0.59) and self-rated health (B = 0.36, 95%CI = 0.09-0.63), while this was not the case post-peak. Interaction revealed that with one exception (private green space having a bigger impact on male's subjective well-being during the first peak, B = 0.23, 95%CI = 0.03-0.44), private and public green space had a similar impact independent of gender, age, working status, and marital status.
Pouso et al. (2021), Spain, UK, Germany, France, United States, Portugal, Italy, New Zealand, Mexico	Adults and older adults (5218, largest age group 36-45 years (25.6%), 65%, n.a.)	April-May 2020	Observational, cross-sectional, quantitative, online survey	Investigate whether maintained contact with outdoor nature spaces was associated with better mental health and mood during lockdown restrictions	Direct and indirect outdoor nature	General nature accessibility based on self-reported lockdown level Individual nature accessibility: self-reported window views of natural features (indirect contact) and public and private outdoor space availability One-item asking participants if indirect and direct outdoor nature helped them to deal with the lockdown	Mental health Mood	4-item Patient Health Questionnaire (PHQ-4) Choice of 1-3 emotions based on Plutchik's wheel of emotions One-item asking participants if indirect and direct outdoor nature helped them to deal with the lockdown	Moderate or severe poor mental health was more prevalent for people with severe lockdown restrictions (level 1; 23.9%) compared to less strict lockdown restrictions (level 2: 18.4%, level 3: 19.2%; $p < 0.001$). People with nature views were less likely to exhibit depressive symptoms (OR = 0.77, 95%CI = 0.67-0.89) and anxiety symptoms (OR = 0.82, 95%CI = 0.72-0.93), as were people with access to outdoor nature space (depressive symptoms: OR = 0.72, 95%CI = 0.61-0.84; anxiety symptoms: OR = 0.75, 95%CI = 0.64-0.87). For people in the strictest lockdown situation in Spain, moderate or severe poor mental health prevalence was lower for views of natural area elements (17.8%) compared to limited or urban views (27.2%, $p < 0.001$). During the lockdown, individuals with natural elements in their views mentioned more positive emotions than individuals with limited or urban views.
Pringle et al. (2022), UK	People living with and beyond cancer (PLWBC) (9, 78%, 78%, n.a.)	May-July 2021	Observational, cross-sectional, qualitative, semi-structured interviews	Investigate indoor and green space-outdoor physical activity experiences during COVID-19	Green space	Structured exercise sessions in green space	Physical activity	Physical activity experience in green space	Participants expressed different experiences regarding the exercise session in green space: While some expressed that the sessions in green space facilitated continuing with the structured exercise sessions and reported wonderful feelings, others reported the exercise sessions in green space to be a barrier due to temperatures, the lack of infrastructure, and the barrier of using public transport to get there.
Puhakka (2021), Finland	University students (47, 19-33 years, 80.8%, n.a.)	March-April 2020	Observational, cross-sectional, qualitative, thematic writings	Investigate the role of nature for university students well-being during COVID-19	Nature	Thematic writings of students how nature impacts their well-being	Well-being	Open question about effects of nature on psychological, physical, and social well-being	Nature can have an important role in students' well-being during COVID-19, providing opportunities for physical activity, emotional and cognitive renewal, strengthening social relationships and sharing experiences, reducing loneliness, and relieving the negative physiological effects of various stressors, and supporting retreating behaviors by enabling 'being away' and providing freedom from the pressures of student life.

Qiu et al. (2021), Australia	National forest park visitors (pre-pandemic: 526, ø= 38.4 ± 8.5 years, age range 20-70 years, 55%, n.a.; during the pandemic: 371 adults, ø = 36.2 ± 6.5 years, 56%, n.a.)	October 2019 October 2020	Observational, longitudinal, quantitative, paper-pencil survey	Investigate the perceived restorative characteristics of natural soundscapes before and after COVID-19 outbreak	Natural soundscapes	Continuous equivalent sound pressure level in Burleigh Heads National Park, Australia Perceived Restorativeness Soundscape Scale (PRSS) adapted to natural sound environments	Perceived restorativeness	Perceived Restorativeness Soundscape Scale (PRSS) adapted to natural sound environments	Perceived restorative characteristics of natural soundscapes were mostly higher for the during-pandemic group compared to the pre-pandemic group.
Quarta et al. (2022), Italy	University students and academic staff (University students: N = 939, largest age group 18-24 years (62.4%), 75%, n.a.; Staff: N = 238, largest age group 45-54 years (40.3%), 54.2%, n.a.)	April-May 2021	Observational, cross-sectional, quantitative, online survey	Investigate associations between time spent in nature and mental health	Nature	Self-reported frequency of spending time in nature	Anxiety Depression Quality of life Subjective well-being Energy levels	Depression Anxiety Stress Scales Short Version (DASS-21) WHOQoL-Brief questionnaire 9-item subjective well-being (SWB) questionnaire Fatigue scale	Students with low depression, anxiety, and stress spent more time in nature than students with moderate/high depression, anxiety, and stress. Simultaneously, students with low subjective well-being spent less time in nature than students with moderate/high subjective well-being (effect size: r = 0.14-0.19). These associations were not observed for staff members. Time spent in nature was positively associated with quality of life and energy levels both in students and staff members.
Rajoo et al. (2021), Malaysia	Adults with depression, anxiety, or stress symptoms (30, 26.2 ± 4.14 years, 33%, n.a.)	April-May 2020	Experimental, longitudinal, quantitative, survey	Investigate the potential nature-based exercise and nature therapy in improving mental wellbeing during COVID-19	Urban greenery	One week of unsupervised exercise (circuit training without equipment) or nature therapy activities (sensory enjoyment, stretching, mediation) conducted by each participant on their own in urban greenery (Rooftop and neighborhood parks, home gardens	Stress Anxiety Depression	Depression Anxiety Stress Scales Short Version (DASS-21)	Both the nature-based exercise and the nature therapy program resulted in stress, anxiety and depression symptom reductions. When evaluating the effectiveness of exercise and nature therapy on a case-by-case basis, nature therapy was more effective in treating mental health issues.
Reid et al. (2022), USA	Adults and older adult in Denver (911, largest age group 30-49 years (43%), 58%, 3.8% Black, 1.8% Asian/Pacific	November 2019-Janury 2021	Observational, cross-sectional, quantitative, online survey + geospatial analysis	Investigate if green space exposure buffers against stress and distress during COVID-19	Green space	Objectively measured Normalized Difference Vegetation Index (NDVI) within 300m and 500m	Stress Depression Anxiety	Perceived Stress Scale (PSS-4) Center for Epidemiological Studies Depression Scale (CES-D-10)	Spending a lot of time in green space (usage) was significantly associated with lower anxiety and depression. In both buffers, NDVI (objective abundance) was significantly associated with lower depression scores, while perceived green space abundance was associated with lower anxiety scores.

	Islander, 2.1% Native American, 3.3% Multiracial, 89% White)					circular buffers around participant's home Self-reported abundance, visibility, access, usage, and quality of green space		Minnesota Multiphasic Personality Inventory-2 Anxiety Scale (MMPI-2 Anxiety)	Results for green space quality and lower anxiety scores were inconsistent. No associations between green space and stress were observed.
Rhodes et al. (2020), Canada	Adults and older adults (1055, ø = 48.8 ± 16.7 years, 51 %; 82.8% Caucasian, 17.1% Other)	May 2020	Observational, cross-sectional, quantitative, online survey	Investigate socio-ecological correlates of current moderate to vigorous physical activity and COVID-19 related moderate-to-vigorous physical activity shifts	Nature Parks and trails	Neighborhood Environment Walkability Scale (NEWS) for self-report about attractive natural sights and proximity to parks and trails	Moderate to vigorous physical activity COVID-19 related transitions in meeting the physical activity guidelines	Modified version of Godin Leisure-Time Questionnaire Modified stage questionnaire to assess transitions	Proximity to parks and trails (β = 0.03) and nature aesthetics (β = 0.07) were unrelated to moderate-to-vigorous during lockdown (both p's > 0.01) and changes in moderate-to-vigorous physical activity (proximity to parks and trails: β = -0.01, nature aesthetics: β = 0.02, both p's > 0.01). No difference in nature aesthetics and park proximity was observed between transition groups.
Ribeiro et al. (2021), Portugal and Spain	Adults (3157, largest age group 40-64 years (46.7%), 74.6%, n.a.)	March-May 2020	Observational, cross-sectional, quantitative, online survey	Investigate associations between changes in nature contact and mental health during COVID-19	Greenery, including private indoor and outdoor green space and public green space	7 items covering nature visit frequency, views, and care of different types of natural elements	Psychological distress Somatization Perceived stress	General Health Questionnaire (GHQ-12) Adapted 4-dimensional symptom questionnaire One question asking about stress during the lockdown	In Portugal, maintaining/increasing views of nature were associated with less psychological distress (B = -0.27, 95%CI = -0.51 to -0.03), less somatization (B = -0.79, 95%CI = -1.39 to -0.20), and lower stress levels (B = -0.48, 95%CI = -0.73 to -0.23). Public natural spaces were associated with lower stress levels (B = -0.29, 95%CI = -0.49 to -0.08). None of these observations was made in Spain. In Spain, indoor plants were associated with less stress (B = -0.52, 95%CI = -0.96 to -0.07), while community private green space (B = -0.82, 95%CI = -1.61 to -0.03) and other natural spaces or elements (B = -1.06, 95%CI = -1.79 to -0.32) were associated with less somatization. None of these findings were observed in Portugal.
Robinson et al. (2021), mostly UK	Adults and older adults (1184, largest age group ≥ 55 years (53%), 72%; n.a.)	April-July 2020	Observational, cross-sectional, quantitative, geospatial analysis and online survey	Investigate nature's potential health and well-being benefits during COVID-19	Green space	Objectively measured Normalized Difference Vegetation Index (NDVI), green space presence, and green space abundance around participant's postcode with 50–500-meter buffers Self-reported duration and	Mental well-being Perceived Stress	Warwick–Edinburgh Mental Wellbeing Scale (WEMWBS) Perceived Stress Scale Items asking about perceived health benefits of nature	48% of respondents agreed that spending time in nature helped them to cope with COVID-19, with the response strength being stronger for females and those not working or being unemployed due to COVID-19. The most popular reasons for visiting nature were exercise, stress and anxiety reduction, and relaxation. There were no statistically significant associations between green space abundance or presence, the NDVI index, and mental well-being or perceived stress for any buffer distance. Further analysis of green space typology revealed that the mean number of food-growing allotments was higher for those with higher mental well-being scores within a 100-meter (p<0.01) and 250-meter buffer (p=0.03).

						frequency of green space visits Items asking about perceived health benefits of nature			
Roche et al. (2022), UK	Adults and older adults (116, 49.5 ± 20, 61.2%, 70.7% White British)	May 2020-January 2021	Observational, cross-sectional, qualitative, topic guided interviews	Investigate physical activity facilitators and barriers during COVID-19	Nature	Any nature mentioned by participants	Physical activity	Any physical activity mentioned by participants	Green space in rural areas that allowed physical distancing as well as observing seasonal changes in nature were reported as facilitators of physical activity. Also, garden access was reported as an opportunity for physical activity engagement via gardening.
Rogers et al. (2020), UK	COVID-19 risk group adults and older adults (9190, largest age group 55-69 years (46.1%), 78%; 95% Caucasian, 3.7 black and minority background)	April 2020	Observational, cross-sectional, quantitative, online survey	Investigate the impact of the COVID-19 lockdown on physical activity	Garden	Self-reported garden access	Physical activity intensity	Self-reported changes in PA intensity from pre-COVID-19 lockdown to the time of survey participation during COVID-19 lockdown	Lack of garden access was associated with increased odds of starting to do less intense physical activity during the lockdown (OR 1.74, 95%CI = 1.56–1.91, p = .001), while garden access was unrelated to starting more intense physical activity (OR = 1.21, 95%CI = 0.96-1.47).
Samuelsson et al. (2021), Sweden	Adults and older adults (684, largest age group 35-49 years (37.6%), 67.0%, n.a.)	April-June 2020	Observational, cross-sectional, quantitative, online survey + geospatial analysis	Investigate associations between changes in visiting natural areas and well-being changes during COVID-19	Nature	Landcover data on fields, forests, and water	Well-being	Question about how well-being changed in relation to visiting natural places	Abstaining from visiting places with natural features located in high densely populated areas was related to a negative influence on wellbeing. Yet, fields, forests and water were strongly associated with places people claimed wellbeing benefits from during pandemic restrictions. The further a visited place was from the respondent's home, the more likely it was to have a positive wellbeing influence.
Samus et al. (2022), Germany, New Zealand	Urban adults and older adults (Germany: 101, largest age group 35-44 (31.7%), 76.2%, n.a) New Zealand: 160, largest age group 25-34 years (28.1%), 89.4%, n.a.)	May 2020	Observational, cross-sectional, quantitative, online survey	Investigate associations between biodiversity of private gardens, and mental wellbeing during COVID-19	Private garden Nature	Habitat heterogeneity scale Ten questions about plant growth forms Self-reported time spent in nature Self-reported garden size	Mental well-being	Positive and negative affect schedule (PANAS) Center for Epidemiological Studies Depression Scale (CES-D)	Time spent in nature was positively associated with positive affect (B = 0.32, p = 0.002). Garden size was positively associated with positive affect (B = 0.26, p = 0.034) and negatively related to negative affect (B = -0.24, p = 0.044) and depression (B = -0.38, p = 0.002). These associations were only observed in Germany, but not New Zealand. Garden feature richness was related to less depressive symptoms only in New Zealand (B = -0.25, p = 0.042). No other associations emerged.
Sanusi et al. (2021), Malaysia	Adults and older adults (30, largest age group 41-50 years (40%), 83.3%, n.a.)	NR	Observational, cross-sectional, quantitative, online survey	Investigate the role of home pocket gardens for quality of life during COVID-19	Home pocket garden	Self-reported ownership of home pocket garden	Food security Quality of life	Agreement with statements regarding the contribution of home pocket garden to food security and quality of life	A large part of the respondents (strongly) agreed that home pocket gardens contributed to food security during the pandemic, enhanced interactions amongst family members and among neighbors, and contributes to enhanced quality of life for oneself and the community.

Schmidt et al. (2021), Germany	Children and adolescents (1394, 46.5% 6-10 years, 53.5% 11-17 years, 50.5%, n.a.)	August 2018-March 2020 April-May 2020	Observational, longitudinal, quantitative, online survey	Investigate the role of the housing situation in physical activity changes during COVID-19	Garden	Access to garden owned by the family	Physical activity	One item asking about the number of days with at least 60 minutes physical activity	Daily life physical activity (playing outside, walking/cycling, gardening, housework) increased for children and adolescents with garden access, but not for those without garden access.
Schweizer et al. (2021), Germany	Strava segments (30 segments in urban areas, 14 segments in rural areas)	March-June 2020	Observational, cross-sectional, quantitative, fitness app data analysis (Strava)	Investigate cycling behavior in urban and rural public green spaces during COVID-19	Nature parks (rural areas) and urban green space	Strava segments in green space	Cycling	User frequency of Strava cycling segments	During the lockdown, there was a 55% cycling increase in urban green space (95%CI = 45%-75%), but not in rural green space. After lockdown restrictions were loosened, no increased cycling frequency was observed anymore.
Sia et al. (2022), Singapore	Urban adults and older adults (Gardening group: 8786, largest age group 35-44 years (27.4%), n.a., n.a.) Community group: 1849, largest age group 25-34 years (35.1%), n.a., n.a.)	Community group: May-June 2020 Gardening group: May-July 2021	Observational, cross-sectional, quantitative, online survey	Investigate the impact of gardening on mental resilience during COVID-19	Garden	Self-reported time spent in gardening activity	Mental resilience	Singapore Youth Resilience Scale	Gardeners had higher mental resilience than people from the non-gardening community group. Within the gardening group, those with less than one hour of weekly gardening time had significantly lower scores in their mental resilience compared to those with more weekly gardening time.
Soga et al. (2021), Japan	Adults and older adults (3000, n= 500 for each age group, 50%, n.a.)	June 2020	Observational, cross-sectional, quantitative, geospatial analysis and online survey	Investigate nature's role in mitigating adverse mental health outcomes due to the pandemic.	Green space Neighborhood greenness	Self-reported frequency and duration of green space use, green view from window Objectively measured Normalized Difference Vegetation Index (NDVI) within a 250m buffer around the centroid of respondent's postcode.	Self-esteem Life satisfaction Subjective happiness Loneliness Depression & anxiety	Rosenberg Self-Esteem Scale Liang's (1984) version of the Life Satisfaction Index A Subjective Happiness Scale UCLA Loneliness Scale (Version 3) 12-item General Health Questionnaire	Green window view was associated with increased self-esteem (B = 0.13, 95%CI = 0.04-0.21), live satisfaction (B = 0.21, 95%CI = 0.14-0.32), and happiness (B = 0.16, 95%CI = 0.07-0.25), decreased loneliness (B = -0.11, 95%CI = -0.20 to -0.02) and decreased depression and anxiety (B = -0.10, 95%CI = -0.19 to -0.01). The frequency of green space use was associated with increased self-esteem (B = 0.06, 95%CI = 0.03-0.10), live satisfaction (B = 0.07, 95%CI = 0.04-0.11), and happiness (B = 0.09, 95%CI = 0.06-0.13), and decreased loneliness (B = -0.08, 95%CI = -0.20 to -0.02) and depression and anxiety (B = -0.05, 95%CI = -0.09 to -0.02). Neighborhood greenness assessed via the NDVI index was unrelated to any of the five health metrics (all p's > 0.05).
Spano et al. (2021), Italy	Adolescents, adults, and older adults (3886, 41.9 ± 15.2 years; age range: 14-93 years, 62%, n.a.)	March-April 2020	Observational, cross-sectional, quantitative, online survey	Investigate associations between home greenness and psychological health during lockdown	Greenery at home	Self-reported indoor and outdoor green features, including green view, presence of plant pots, accessibility to private green space, type of road the house was located as	Psychological state	Self-reported changes in anxiety, anger, fear, confusion, moodiness, boredom, irritability, recurrent thoughts and/or dreams, poor concentration, and sleep disturbance	Plant pots were associated with less worse changes in anger, fear, irritability, and sleep disturbance (β = -0.08 to -0.10, all p's < 0.05). Green view (β = -0.04 to -0.08, all p's < 0.05) and private green space (β = -0.04 to -0.09, all p's < 0.05) were associated with less negative changes in all psychological states. General natural environment was related to less negative changes in anxiety, fear, boredom, irritability,

						proxy for the natural environment			recurrent thoughts/dreams, and sleep disturbance (β = -0.04 to -0.06, $p < 0.05$).
Sun et al. (2021), China	University students (819, n.a., 57.3%, n.a.)	May-August 2020	Observational, cross-sectional, quantitative, paper-pencil questionnaire	Investigate psychological recovery effect of campus environment during COVID-19	Blue and green space	Questions about preferences for blue and green space	Restoration	Perceived Restorativeness Scale	Compared to grey space and sports grounds, perceived restorativeness was highest for blue and green space, with varying results across campus time or stay duration.
Szpunar et al. (2021), Canada	Parents and children (Parents: 12, 40.7 ± 7.5, 91.7%, n.a.; Children: 9, 7.3 ± 2.9, 66.7%)	December 2020-January 2021	Observational, cross-sectional, qualitative, guided interview	Investigate physical activity barriers and facilitators during COVID-19	Nature	Any nature mentioned by participants	Physical activity	Any physical activity mentioned by participants	Closure of nature-based physical activity locations, such as parks and outdoor trails, as well as lacking access to a garden, constituted barriers to physical activity during lockdown. At the same time, engagement in nature-based outdoor activities, such as hiking and exploring trails, as well as having a garden were physical activity facilitators.
Talal and Gruntman (2022), Israel	Adults and older adults in Tel-Aviv (458, 42, 56%, n.a)	March-May 2021	Observational, cross-sectional, quantitative, online survey	Investigate how urban nature site shifts relate to mental health during COVID-19	Urban nature	Changes in urban nature visitation based on self-reported distance to and time spent in urban nature sites	Mental health	WHO Well-Being Index Statement about mental health contribution of visiting urban nature site	A relative increase in urban nature visitation was positively associated with higher ratings of mental health (B = 0.15, $p < 0.05$).
Tarsitano et al. (2021), Italy	Children, adolescents, adults, and older adults participating in guided tours at an urban park (401, largest age group 40-55 years (23%), age range 5-74 years, n.a., n.a.)	September-October 2020	Experimental, case-study, qualitative, interview	Investigate the social and sensorial-perceptive impact of the guided tour experience on social relationships and well-being after the COVID-19 lockdown	Urban park, dinosaur museum, nature-based laboratory activities	4 hour guided tours at the urban park of Lama Balice, dinosaur museum, and nature-based laboratory with an interactive experiential approach of Landsense Ecology	Social relationships Well-being	Questionnaire interview about experiences at the workshop with one question asking if the experience encouraged the emergence of friendships or other social relationships and one question asking if the experience influenced well-being after the pandemic restrictions	87% rated the workshop experience as good or excellent regarding the encouragement of friendships or other social relationships. In addition, 95% rated the workshop experience as good or excellent regarding the influence on overall well-being after the pandemic restrictions.
Tavares and Marinho (2021), Brazil	Older adults (23, 68.4 ± 6.2, 69.7%, n.a.)	July-October 2020	Observational, cross-sectional, qualitative, semi-structured interviews	Investigate the influence of the COVID-19 pandemic on frequent urban nature park visitors	Urban nature	Urban nature park visitors	Physical activity	Any physical activity mentioned by participant	Park closures impacted physical activity opportunities for adults, which were the designated location for physical activity prior to the pandemic.
Theodorou et al. (2021), Italy	Adults and older adults (303, ø = 39.9 ± 13.4 years, age	March-May 2020	Observational, cross-sectional, quantitative, online survey	Investigates the relation between gardening and psychopathological distress during the	Garden	Self-reported engagement in gardening activities during COVID-19	COVID-19 related distress Psycho-pathological distress	22-item Impact of Event Scale-Revised (IES-R)	Gardening was related to lower COVID-19 related distress (r = -0.18, $p < 0.01$) and psychopathological distress (r = -0.23, $p < 0.01$). COVID-19 related distress mediated the association between gardening and psychopathological distress.

	range 18 to 74 years, 68.3%, n.a.)			lockdown of the first wave of COVID-19				9-item Symptom-Checklist-K-9 (SCL-K-9)	
Tomasso et al. (2021), USA	Adults and older adults in metropolitan areas (529, largest age group 25–34 years (29%), 75%, 82% white non-Hispanic)	April-May 2020	Observational, cross-sectional, quantitative, online survey	Investigates how nature exposure and perceived nature deprivation relate to well-being during COVID-19	Any type of nature	One-item statement asking for feelings of nature deprivation	Flourishing	Harvard Flourishing Index	Strong agreement with nature deprivation was associated with a flourishing decline (B = -4.04, 95%CI = -7.33 to -0.74, p = 0.03) relative to those who strongly disagreed with feeling nature deprived. Feelings of nature deprivation and ethnicity interacted, with Caucasians decreasing flourishing with feelings of nature deprivation (B = -6.03 to -4.08, 95%CI = -9.60 to -0.93), while non-whites increased flourishing with feelings of nature deprivation (B = 4.70-7.15, 95%CI = 2.25-19.83).
Tomikawa et al. (2021), Japan	Parents of primary school children (310, largest age group 40-45 years (35%), 56%, n.a.)	April 2020	Observational, cross-sectional, qualitative, online survey	Investigate associations between current life satisfaction and spatial characteristics during COVID-19	Parks	Total amount of park space	Life satisfaction	One open-ended question to describe aspects what participants are currently satisfied in their life	Based on text mining analysis, for people living in the Western area, satisfaction with the circumstances surroundings parks was observed, however, for the Eastern and Central City area, there was a weak or no relationship observed.
Toselli et al. (2022), Italy	Adults and older adults (328, largest age group 18-44 years (46.7%), 77.1%, n.a.)	May-September 2021	Experimental, longitudinal, quantitative, online survey	Investigate the impact of a structured park-based physical activity intervention on well-being during COVID-19	Urban parks	Three-month park-based exercise intervention	Well-being	Psychological General Well Being Index short form (PGWB-S)	For women, psychological well-being improved across all six domains (feeling nervous, full of energy, downhearted, emotionally stable, cheerful, tired), whereas for men, improvements were only observed for two domains (feeling full of energy, feeling tired).
Trevino et al. (2022), USA	University students (353, largest age group 18-24 years (77.5%), 75.3%, n.a.)	Spring-fall 2020	Observational, cross-sectional, quantitative, online survey	Investigate how nature interactions impact mental health during COVID-19	Nature	12 questions about active and passive interactions with nature	Depression Anxiety Stress Academic stress	Depression Anxiety Stress (DASS) Depression Anxiety Stress and Academic Stress (DAAS)	Outdoor plant exposure was related to better mental health, however, indoor plant exposure and plant access were mostly unrelated to mental health.
Ugolini et al. (2020), Spain, Croatia, Italy, Lithuania, Slovenia, Israel	Adults (2540, majority 30–69 years, 74-84%; n.a.)	March-May 2020	Observational, cross-sectional, quantitative/ qualitative, online survey	Investigate human behaviors, perceptions, and attitudes towards urban green space in relation to COVID-19 related restrictions	Urban green space	Self-reported type and visit frequency of urban green space, distance to urban green space Multiple choice and open-ended questions asking about motivation visit a green area and factors most missed during	Motives related to visiting urban green space use Nature deprivation	Multiple choice and open-ended questions asking about motivation visit a green area and factors most missed during isolation in relation to green areas	During the COVID-19 isolation, urban green space was important for providing places of solace and respite, and for exercise and relaxation. The main motivation to visit urban green space similar for frequent and infrequent urban green space visitors, namely exercise (2%-47%), followed by relaxation (2%-50%), with large variations across countries. In all except for one country, more than 50% indicated that they missed urban green space “rather” or “a lot”, with missed aspects, amongst others, exercising outdoors (9%-44%) and meeting others (6%-40%). Agreement for missing nature was dependent on

						isolation in relation to green areas			frequency of visiting urban green space during COVID-19 and window views of natural elements.
Ugolini et al. (2021), Italy	Adults (2081, largest age group 40-50 years (24.5%), 57%, n.a.)	March-May 2020	Observational, cross-sectional, qualitative, online survey	Investigate perceptions and behavioral patterns related to urban green space	Urban green space	Self-reported visit frequency of and distance to urban green; green view from the window Multiple choice questions with mostly predefined answer options regarding reasons for urban green space use	Motivation to visit green space Feelings of deprivation	Multiple choice questions with mostly predefined answer options regarding reasons for urban green space use	During the lockdown, 20% in red zones (areas severely affected by COVID-19) and 32% in non-red zones ($p < 0.001$) reported the main reason for visiting urban green space was exercise, while 24% in red zones and 19% in non-red zones ($p < 0.05$) reported relaxing as a main reason. Meeting people was mentioned by 1%. Physical exercise was a motivation that increased by 8% during the lockdown in the non-red zones, whereas all other motivation reasons decreased during lockdown. Engagement in physical exercise during the lockdown was related to frequency of urban green space visitation prior to the lockdown ($B = 0.02$, $p < 0.05$). In areas where people could not access urban green space, feelings of deprivation were reported by 86% of the respondents. Feelings of urban green space deprivation were more likely for frequent pre-pandemic urban green space visitors ($B = 0.27$, $p < 0.005$) and for people that had no green view from the window ($B = 0.05$, $p < 0.05$).
van Houweling en-Snippe et al. (2020), Northern Europe and North America	Adults and older adults (1203, largest age group 40-49 years (41%), 35%, n.a.)	April 2020	Experimental and observational, longitudinal and cross-sectional, quantitative/qualitative, online survey	Investigate the influence of digital nature on social and mental well-being, and the association between real nature access and loneliness	Digital nature General nature	Participants watched one of four nature landscape videos (~ 5 minutes): dense-tended, dense-wild, spacious-tended, spacious-wild nature scene Self-reported walking time towards nearby nature, number of nature interactions, and garden access	Connectedness to community Loneliness	Inclusion of in the Community Self-scale UCLA loneliness scale	Connectedness to the community scores were higher post-exposure to digital nature ($M = 3.94$, $SD = 1.27$) than pre-exposure ($M = 3.72$, $SD = 1.24$; $p < 0.001$). Peoples' comments on the video revealed that they allowed to relax and were ideal for people in a lockdown situation to stop worrying. Longer walking time towards nature was associated with higher loneliness scores ($B = 0.24$, $\beta = 0.30$, $p < 0.001$), whereas garden access ($B = 0.44$, $\beta = 0.03$, $p > 0.05$) and the number of nature interactions ($B = 0.02$, $\beta = 0.00$, $p > 0.05$) were unrelated to loneliness.
Vega-Perona et al. (2022), Spain	Teachers and parents in in the early childhood education and care setting with 2-3 year old toddlers (34, 38, 67.6%, n.a.)	October 2020-March 2021	Observational, cross-sectional, qualitative, semi-structured interviews	Investigate physical activity barriers and facilitators during COVID-19	Nature	Any nature mentioned by participants	Physical activity	Any physical activity mentioned by participants	Parents reported the poor availability, difficult accessibility, and closure of parks as a physical activity barrier for toddlers.

Veitch et al. (2022), Australia	Adult park users (9, n.a., n.a., n.a.)	Up to July 2020	Observational, cross-sectional, qualitative, semi-structured walk-along interviews	Investigate perceptions of parks and park use during COVID-19	Parks	Park users	Perceptions of park use	Any health outcome or behavior mentioned by participant	Parks were important locations during the pandemic to leave the house and go for a walk, provide a safe place for physical distancing, and to relax.
Venter et al. (2021), Norway	Strava users in Oslo (~ 53000, 13 years and older)	January 2019-August 2020	Observational, longitudinal, quantitative, fitness tracker app analysis (Strava)	Investigate the longevity of increases in recreational urban green space use during the lockdown	Green and blue space	Coastal zone, forest, agriculture, city park, protected areas (based on land use zone data)	Walking and cycling	Mobile tracking data in Oslo	During the lockdown, increases of +228% for walking activities (running, walking, hiking) and +252% for cycling were observed. The strongest increase was observed in forest areas (pre-pandemic: 9%, during the pandemic: 23%) and protected areas (pre-pandemic: 0.6%, during the pandemic: 1.5%). The increase was especially strong in adolescents (13-19 years), while a drop was observed for people between 35-64 years. While the increase was not maintained during Norway's summer holidays, while another +89% increase above baseline was observed after the summer holidays.
Vogel et al. (2021), USA	Adults and older adults (990, 50.5 ± 16.7 years, 77%; 69.4% White/Caucasian, 21.2% Asian, 9.4% Other)	March-May 2020	Observational, cross-sectional, quantitative, online survey	Investigate associations between physical activity, stress, and coping strategies in the during early and mid-COVID-19 lockdown	Gardens	One item asking participants what they do to manage their stress with predefined answer options including gardening during mid-COVID-19 lockdown	Physical activity	Stanford Leisure-Time Activity Categorical Item (L-Cat)	During mid-COVID-19 lockdown, participants meeting the physical activity guidelines were more likely to report gardening as a coping strategy (adjusted odds ratio = 1.68, 95%CI = 1.22-2.29).
Vos et al. (2022), Belgium	Mothers of young children (766, 36.6 ± 4.9, 100%, n.a.)	December 2020-May 2021	Observational, cross-sectional, quantitative, online survey + geospatial analysis	Investigate how residential proximity to green space was related to stress response buffering during COVID-19	Green space	Objectively assessed green space within 50, 100, 300, 500, and 1000m circular buffer around participant's home based on land cover data	Stress Physical activity	Two items asking about feeling more stressed compared to prior the pandemic One item asking about physical activity participation	For an inter-quartile range contrast in residential green space 300 m and 500 m around the residence, participants were respectively 24% (OR = 1.24, 95%CI: 1.03 to 1.51) and 29% (OR = 1.29, 95%CI: 1.04 to 1.60) more likely to be more resistant against stress. Associations were not observed for the 50, 100, and 1000m buffer. No associations were observed with physical activity.
Weinbrenner et al. (2021), Germany	Urban forest visitors (Questionnaire: 714, 41 years, age range 16 and 82 years, 59%, n.a., Ethnographic observation: 18 participants Instagram analysis: 5172 posts)	April-May 2020	Observational, case study, qualitative and quantitative, online survey, ethnographic observations, Instagram post analysis	Investigate the relevance of forests for city residents during the COVID-19 pandemic.	Forests around a German city	Questions regarding free time activities in the forest pre- and during the pandemic Reasons for visiting forests Behavioral participant observations (with protocol) in forests	Coping and social contacts	Reasons for visiting forests Behavioral participant observations (with protocol) in forests Instagram picture analysis	Respondents visited the forest for different purposes, including staying healthy and doing sports (98% full/partial agreement), reduced psychological stress (91% full/partial agreement), and keeping in touch with friends and family (58% full/partial agreement). Of those respondents who agreed that there is a connection between their forest visits and COVID-19 (67.2%), reasons for this were that forest visits were retreats from the pandemic and helped to cope with changed everyday life, with the latter one being the most important one. In addition, the forest became a replacement to fulfill different needs without

						Instagram picture analysis			breaking the rules, including a functioning as social meeting point, gym, and playground.
Wendtlandt and Wicker (2021), Germany	Adults and older adults (412, 27 years, age range 18-64 years age, 66.8% female, n.a.)	June-August 2020	Observational, cross-sectional, quantitative, online survey	Investigate the effects of nature-based, natural resource-using, and nature-neutral sport activities before and during the COVID-19 lockdown on subjective well-being	Nature-based physical activity	Time spent in nature-based (e.g., canoeing, skiing, hiking)	Subjective well-being	WHO-5 scale	Nature-based activities were related to individuals' subjective well-being pre- (B = 0.22, p < 0.05) and even stronger during the COVID-19 lockdown (B = 0.52, p < 0.01) period. This was also the case for nature-neutral sports, but not for resource-using sports. An increase in nature-based sports was positively associated with a change in subjective well-being (B = 0.36, p < 0.01), as was nature-neutral sports, but not resource-using sports.
Whitehead and Torossian (2021), USA	Older adults (825, largest age group 60-69 years (63.8%), 79.3%, 96.6% non-Hispanic White, 3.4% Other)	March 2020	Observational, cross-sectional, qualitative/quantitative, online survey	Investigate the impact of COVID-19 on psychological well-being assessed through stressor and coping mechanisms	General nature	Any nature elements and places mentioned by the participants	Perceived stress Negative affect Positive affect	Perceived stress scale (PSS) Positive and Negative Affect Schedule (PANAS) Two open-ended questions asked about stressors and joys/comfort (coping)	11% of the participants mentioned nature as a source of joy during the pandemic. Those who mentioned nature as a source of joy (N = 82) demonstrated enhanced positive affect compared to those who did not mention it (M = 43.0 vs. 41.8), but no differences regarding perceived stress and negative affect were observed.
Xie et al. (2020), China	Adults and older adults in Chengdu (386, largest age group 18–35 (67.9%), 58.3%, n.a.)	April 2020	Observational, cross-sectional, quantitative, online survey	Investigates the role of urban parks during the pandemic period for perceived health and social interaction needs	Urban parks	Self-reported weekly visit frequency, duration, preferred time of urban park visit and activities Items asking if participants believe that urban park visits improve mental health and allow fulfilling social interaction needs	Mental health Social interactions Perceived health benefits of park visit	Self-assessed mental health and social interaction level Items asking if participants believe that urban park visits improve mental health and allow fulfilling social interaction needs	Most residents agreed that urban park visits allowed them to meet their social interaction needs (M = 4.1, SD = 0.99) and to improve their mental health (M = 3.46, SD = 1.11). Park visit duration was positively related to improved mental health (B = 0.22, p < 0.001) and fulfilling social interaction needs (B = 0.17, p < 0.001), whereas frequency of visits was unrelated (all p's > 0.05). The lower the resident's perception of their social interaction level, the more beneficial the urban park use was for them. Regarding activities, the number one reason to visit an urban park was for a walk (N = 268).
Yamazaki et al. (2021), Japan	Adults and older adults in Tokyo (3085, n.a., 47%, n.a..)	June 2020	Observational, cross-sectional, quantitative, online survey	Investigate urban green space perceptions during COVID-19	Urban green space	Self-reported use of different urban green space locations	Reasons for visiting urban green space	Agreement with statements regarding urban green space	More than half of the participants agreed that urban green space helps to relieve stress, whereas only about a quarter agreed that it helps to connect with others and to reduce loneliness. The perceptions regarding usefulness varied across user type (e.g., telecommuters, older adults, family with children).

Yang et al. (2021), China	Children, adolescents, and adults in Hong Kong (661, largest age group 18-44 years (43.9%), 47.7%, n.a.)	January 2020 May 2020	Observational, longitudinal, quantitative, survey via face-to-face interviews	Investigates if urban greenery mitigates COVID-19 related decreases in leisure-time physical activity	Urban greenery	Objectively measured Normalized Difference Vegetation Index (NDVI) based on the tertiary planning unit	Physical activity	Three items adopted from the International Physical Activity Questionnaire (IPAQ) and asked prior (T1) and during (T2) COVID-19	People who lived in a high greenery neighborhood did not decrease their leisure time physical activity (△ =−0.23 minutes/week), while people in less green neighborhoods decreased their total physical activity (△ = 78.84 minutes/week, p = 0.003). Decreases for leisure-time physical activity conducted in the neighborhood (△ = -15.85) and for leisure physical activity at home (△ = -0.74 minutes/week) were less pronounced for people living with high greenery compared to those living in areas with low greenery (neighborhood physical activity: △ = -53.77 minutes/week, p = 0.025; home physical activity: △ = -21.78 minutes/week, p = 0.016). Additionally, people who lived in greener neighborhoods experienced increased levels of physical activity related to visits to country parks during the pandemic (△ = +16.36 minutes/week), whereas people living in neighborhoods with low greenery did not (△ = -3.29 minutes/week), however, this was not statistically significant (p = 0.101).
Yi et al. (2022), USA	Young adults (168, 23 ± 2.9, 47%, 30.4% Hispanic)	May 2020-June 2021	Observational, intensive longitudinal, quantitative, e-diary	Investigate effects of physical activity location choices on physical activity maintenance during COVID-19	Parks	Self-reported physical activity location	Physical activity	One question asking about physical activity engagement the previous week compared to prior the pandemic	Participants performing physical activity at parks/open spaces were twice as likely to maintain physical activity levels.
Yuan et al. (2022), China	Older adults at an elderly care institution (63, 82.0 ± 7.1, 33%, n.a.)	March 2021	Experimental, longitudinal, quantitative, online survey	Investigate effects of a virtual forest experience on psychological well-being during COVID-19	Virtual forest	One short break (immediate) and three short breaks over three days (sustained) in a virtual forest	Positive affect Negative affect Stress recovery	Positive and negative affect schedule (PANAS) ROS scale	Compared to the control group, results showed immediate improvements in negative affect (F (2, 60) =20.42, $p < .001$, $\eta^2 = 0.25$) and stress recovery (F (2, 60) =33.44, $p < .001$, $\eta^2 = 0.35$), whereas no significant effects for positive affect were observed. Looking at effects across the three days, improvements were observed for negative affect (F (3, 187) = 14.40, $p < .001$), stress recovery (F (5, 247) = 11.94, $p < .001$), and positive affect (F (3, 169) = 10.09, $p < .001$).
Zabini et al. (2020), Italy	Adults and older adults (75, 47.3 ± 13.1 years, 59%, n.a.)	April-May 2020	Experimental, longitudinal, quantitative, online survey	Investigates the restorative effects of forest vs. urban videos during COVID-19	Digital nature	Participants watched the same forest-based audio-video (intervention condition) or same urban space video (control condition) on five consecutive days (video length: 5 min.)	Anxiety	State-Trait Anxiety Inventory (STAI) Sheehan Patient Rated Anxiety Scale (SPRAS)	For each day of the five study days, results of the interaction analysis revealed that the group watching the forest video exhibited lower anxiety scores after watching the video compared to the pre-value (Pre: M = 3.61-5.20, SD = 3.63-5.22; Post: M = 2.37-3.17, SD = 2.73-3.76), whereas the group watching the urban videos maintained or increased their anxiety score compared to the pre-value (Pre: M = 2.82-4.47, SD = 2.96-4.32; Post: M = 3.12-4.41, SD = 3.09-4.20; p = <0.001 – 0.006). No one-week pre-post differences

									were observed for either condition (p = 0.241 – 0.915).
Zagalaz-Sánchez et al. (2021), Spain	Children (837, 6.22 ± 3.36 years, age range 0-12 years, 49.8%, n.a.)	March-May 2020	Observational, cross-sectional, quantitative, online survey	Investigate whether children's living conditions during the COVID-19 related confinement period influenced their daily activities	Garden	Self-reported house with garden access	Screen time Physical activity Free play Psychosocial aspects	Parental proxy-report: Daily time spent in screen time (game consoles, televisions, computers, tablets, and mobile phones), physical activity, and free play Items (scale 1-10) asking about parental perceptions of the child's state of fatigue, happiness, energy level, self-esteem, and creativity	Children with a garden had the lowest television time (M = 68.64; SD = 44.94, p = 0.015), and the highest physical activity (M = 45.89; SD = 42.01, p < 0.001) and free play levels (M = 118.11; SD = 85.41, p = 0.045). No differences for in any of the other screen time variables were observed (p > 0.05). Parent of children with a garden perceived them happier (M = 8.32; SD = 1.63, p = 0.028) and less tired (M = 3.37, SD = 2.29, p = 0.016). No other differences in psychosocial aspects were observed.
Zhuo and Zacharias (2020), China	Young adults (284, 19–30 years, 59.7%, n.a.)	February 2020	Observational, cross-sectional, quantitative, online survey	Investigates associations between leisure types and living environments with subjective well-being during COVID-19.	City greenness	Self-reported view from home on city greenery	Overall well-being Mental well-being Function well-being Social well-being	14 items on the four domains with 5-point Likert scale, 1 additional item with range 1-11	View from home on city greenery was unrelated to all types of well-being (p > 0.06).

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Appendix G: Publications

Research articles as author or co-author *(* these authors contributed equally to the work)*

31. **Nigg, C.,** Fiedler, J., Burchartz, A., Niessner, C., Woll, A., & Schipperijn, J. (submitted). Distinct Associations between Green Space and Youth's Physical Activity in Urban and Rural Areas - Results of the MoMo Study. *Landscape & Urban Planning.*

30. Reichert, M.*, **Nigg, C.*,** Brüßler, S., Burchartz, A., Jekauc, D., Limberger, M., Fiedler, J., Krell-Rösch., J., von Haaren-Mack, B., Ebner-Priemer, U. W., Niessner, C., Schipperijn, J., & Woll, A. (submitted). City-Living Can Level Physical Activity Up: Germany's Youth City Dwellers Engage in More Moderate to Vigorous Physical Activity than Their Rural Counterparts. *Environment & Behavior.*

29. Klos, L., Eberhardt, T., **Nigg, C.**, Niessner, C., Wäsche, H. & Woll, A. (1st revise & re-submit). The relationship between perceived physical environment and active transport in adolescents – A systematic review. *Journal of Transport and Health*.

28. Wallman-Jones, A., **Nigg, C.**, Schmidt, M., & Benzing, V. (accepted). Leave the screen: the influence of everyday behaviors on self-reported interoception. *Biological Psychology*

27. Lohmann J., **Nigg, C.**, Hertle, I., & Kugelmann, C. (accepted). Pre-service physical education teachers' beliefs about sustainable development in physical education – scale development and validation. *German Journal of Exercise and Sport Research.*

26. **Nigg, C.,** Petersen, E., & MacIntyre, T. (2023). Natural environments, psychosocial health, and health behaviors in a crisis – A scoping review in the COVID-19 context. *Journal of Environmental Psychology, 8*, 102009. https://doi.org/10.1016/j.jenvp.2023.102009

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24. Giurgiu, M., **Nigg, C.**, Fiedler, J., Timm, I., Rulf, E., Bussmann, J., Nigg, C.R., Woll, A., & Ebner-Priemer, U. W. (2022). The Assessment of 24-Hr Physical Behavior in Children and Adolescents via Wearables: A Systematic Review of Laboratory Validation Studies. *Journal for the Measurement of Physical Behaviour, 8*, e001267. https://doi.org/10.1123/jmpb.2022-0014.

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21. Finne, E., **Nigg, C.**, Weyland, S., Sauzet, O., Wienke, B., & Jekauc, D. (2022). Examining the role of affective states in relation to exercise intentions and participation in extra-curricular exercise classes at university: A repeated measurement observational study. *Frontiers in Psychology, 13*. https://doi.org/10.3389/fpsyg.2022.815466

20. **Nigg, C.,** Schipperijn, J., Hennig, O., Petzold, M. B., Rulf, E., Meyer-Lindenberg, A., Tost, H., Ebner-Priemer, U. W., & Reichert, M. (2022). Time to Go Green? Nature-Based Physical

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