Original Article

Just-in-time adaptive interventions in mobile physical activity interventions – A synthesis of frameworks and future directions

Kathrin Wunsch
Karlsruhe Institute of Technology, Karlsruhe, Germany
Tobias Eckert
Karlsruhe Institute of Technology, Karlsruhe, Germany
Janis Fiedler
Karlsruhe Institute of Technology, Karlsruhe, Germany
Alexander Woll
Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract

Mobile health (mHealth) solutions seem to be a promising approach to tackle sedentary lifestyle in modern society. They have the potential to identify situations when people are likely to engage in an unhealthy behaviour or when they face opportunities to perform healthy behaviours. These situations can serve as triggers to manipulate current behaviour, defined as just-in-time adaptive interventions (JITAIs) by using real-time behavioural data. The current position paper aims to provide a "think piece" by synthesizing evidence into a short conceptual overview of JITAI research by creating a framework and discussing future directions of JITAI research with a focus on PA interventions.

In conclusion, JITAIs are a promising feature in mHealth applications, however showing a lack of theoretical underpinning until today. To summarize evidence on JITAI implementation research and to provide some guidance, the following key features were identified: a JITAI should 1) correspond to real-time needs; 2) adapt to input data; 3) be system-triggered; 4) be goal-oriented; and 5) be customized to user preferences. These features aim to provide first insights into how to guide researchers and practitioners when developing and reporting JITAI features implemented in mHealth interventions. Concluding from the existing knowledge, the potential of machine learning and deep learning principles for JITAIs regarding mHealth should be further explored and established.

Introduction

Physical activity (PA) plays an important role in the prevention of noncommunicable diseases like cardiovascular diseases, diabetes and obesity (Penedo & Dahn, 2005). Levels of PA, however, are frequently found to be insufficient in modern society (Blair, 2009; Woll et al., 2011). Here, mobile Health (mHealth) interventions might be a promising approach to change PA behaviour and to reduce sedentary behaviour patterns (SBP) operationalized through minimal PA (i.e. PA of less than 1,5 MET) (Fiedler et al., 2020). Several key aspects have been shown to increase intervention efficacy when included in mHealth app development. One of these key components refers to the provision of behaviour change support in real time that is matched to when users are most capable of or in need of this support (Schembre et al., 2018). Various publications have used different terms to describe interventions that adapt the provision of support to an individual's changing internal and contextual state. Analogous to Hardeman and colleagues (2019) as well as Nahum-Shani and colleagues (2018), the term just-in-time adaptive intervention (JITAI) is used throughout this position paper, referring to the potential to immediately intervene in situations when people are either likely to engage in an unhealthy behaviour or when they face opportunities to perform healthy behaviours and adapt these interventions to tailoring variables (e.g. user preferences or sensor input).

The current position paper aims to a) summarize existing conceptualizations of JITAIs, to b) provide a comprehensive overview of JITAI features and mechanisms and to c) provide future directions concerning the implementation of JITAIs in mHealth research.

Theoretical foundations of JITAIs

In recent years, many widely used theories were adapted to explain within-person behavioural variability in order to support new technology-driven interventions that can adapt over time to a person's real-time behaviour and needs (e.g. the Dynamical System Model of Social Cognitive Theory; Martín et al., 2014). Since feedback as a self-regulating strategy is an important component of successful behaviour change, tailored just-in-time feedback depicts a key facet of JITAIs besides timeliness, goal-orientation, personalization and action-orientation (Schembre et al., 2018). In sum, theories indicate that feedback should be personalized, goal-oriented and that it should be presented when attention could be refocused to enhance the likelihood of goal attainment. Here, N-of-1 methodology can be insightful in order to evaluate individual trajectories and antecedents of behaviour change alongside JITAIs (Kwasnicka & Naughton, 2020; McDonald et al., 2017). Additionally, studies using ecological momentary assessments (EMAs), which are implemented to assess a desired outcome in a specific situation and the natural setting (Stone & Shiffman, 1994), grew rapidly during the past years (Reichert et al., 2020). The results of these studies can provide the foundation for more sophisticated JITAIs (Dunton, 2017; Spruijt-Metz & Nilsen, 2014) and for the application of advanced methods like machine learning algorithms (Kim et al., 2019; Maher et al., 2021; Rozet et al., 2019). By applying such algorithms, researchers aim to automatically detect meaningful patterns in behavioural data which is not feasible with pre-defined specifications due to the complexity and adaptivity of these patterns (Shalev-Shwartz & Ben-David, 2014).

Integration of JITAIs into mHealth interventions

With the continuously growing field of mHealth research and a high variety of different sensors and communication devices, the opportunities for the development and implementation of JITAIs are manifold (Reichert et al., 2020). JITAIs are especially useful for behavioural interventions to enhance PA and reduce SBP since they offer new types of timely and adaptive support in the users' natural environment. Therefore, bias due to retrospective measurement methods can be diminished and data of continuously measurements can be obtained. This is especially important as changing contexts (e.g. environmental factors) are highly associated with intervention effectiveness (Hardeman et al., 2019; Miller, 2019). Although a recent review points to the potential benefit of JITAIs as a key facet within mHealth intervention development (Fiedler et al., 2020), the current evidence on the effectiveness of JITAIs on PA and SBP is limited (Hardeman et al., 2019; Miller, 2019). Most existing JITAI studies show considerable methodological constraints regarding effectiveness measures, i.e. regarding sample size, study design and reporting of JITAI features. Due to the novelty of this research topic, most studies focus on feasibility rather than on the examination of effectiveness in order to aggregate basic knowledge about JITAIs. As an example for a study investigating effectiveness, the MyBehaviour study is interleaving machine learning mechanisms with multi-modal contextualised JITAI components (Rabbi et al., 2015). Here, automatically adapting PA and dietary behaviour advice was integrated into a smartphone application. In addition, PA energy expenditure was calculated and combined with caloric advice. Moreover, environmental information (location) was included for PA advice (Rabbi et al., 2015). Another example study is the SMARTFAMILY study which includes a JITAI (e.g. provide prompts) along with several other Behaviour Change Techniques (BCTs, e.g. provide information, goal setting, social support). Here, participants received a behavioural support message (i.e. push notification) if they were not sufficiently active (i.e. 100 steps or 2 minutes above 2 MET) during the past hour in order to reduce SBP and enhance PA (Wunsch et al., 2020). Thoroughly, existing studies point to a high acceptance of JITAIs by participants (Hardeman et al., 2019) and to an improvement of user engagement and adherence (Schembre et al., 2018). This, in turn, led to increased awareness of PA opportunities, increased PA and reduced time spent engaging in SBP (Hardeman et al., 2019) in participants using JITAI interventions as compared to no-JITAI users or no-intervention controls.

Theoretical conceptualization of JITAIs

In this position paper, three recent frameworks of JITAIs are presented and synthesized. Hardeman and colleagues (2019) defined three key features that define JITAIs: 1) the provision of behavioural support that directly corresponds to a need in real-time; 2) the adaptation of content or timing of support according to data collected by the corresponding input system since support was initiated; and 3) the system-triggered support. Nahum-Shani and colleagues (2018) distinguish between proximal outcomes (short term goals which can act as mediators to the distal outcome, e.g. daily step count or daily SBP periods), and distal outcomes (behavioural outcome of choice, e.g. increased PA level or decreased SBP level). These authors defined four key facets of JITAIs: 1) decision points (frequency of opportune moments to change the target behaviour and therefore the time at which an intervention decision is made); 2) intervention options (actions to be performed at a decision point); 3) tailoring variables (as obtained via active or passive assessments of individual information, determining intervention delivery); and 4) decision rules (link between the intervention options and the tailoring variables to provide the intervention at each decision point). Based on this conceptual framework, Gonul and colleagues (2019) additionally introduced machine learning strategies to individualize decision rules for intervention implementation (i.e. selecting BCTs) based on goal achievement.

Synthesis of theoretical foundations – A holistic and comprehensive conceptual framework for the implementation of JITAIs

As these above-mentioned conceptualizations (i.e. Gonul et al., 2019; Hardeman et al., 2019; Nahum-Shani et al., 2015) build upon different approaches (content, methodology), these conceptual frameworks are synthesized in the following paragraphs in order to provide a holistic and comprehensive overview of JITAI features and mechanisms.

Based on these frameworks, JITAI features were combined and synthesized, attaining a total of five factors which should be taken into account when constituting JITAIs for mHealth research: JITAIs should 1) correspond to real-time needs; 2) adapt to input data; 3) be system-triggered; 4) be goal-oriented; and 5) be customized to user preferences (see Figure 1). The former three factors are needed in order for an intervention to be defined as a JITAI intervention (Hardeman et al., 2019), whereas number 4) and 5) are additional factors which should be included whenever possible to enhance the likelihood of effectiveness and the quality of future interventions in terms of individual user-tailoring (i.e. personalized prevention / medicine). Subsequently, *Tailoring Variables* (e.g. GPS, sensor input data etc.) and *Decision Points and Rules* were added to the framework.

Hereafter, italic terms refer to Figure 1. *Theoretical implications* comprising of different *Antecedents of Behaviour* (e.g. mood, sleep, weather, location, opportunity for walking in green areas) and *Society / Policy Needs* determine the content of mHealth interventions. A special feature of such interventions are *JITAIs*, which use different information (i.e. *Tailoring Variables*) to compile a JITAI, e.g. data derived from a sensor, or user input data. Then, *Decision Points* are set in order to determine the points in time when a specific JITAI is triggered. The *Decision Rules* include the designation of principles like Timing (e.g. no JITAI at night), Frequency (e.g. no JITAI if another JITAI appeared just a couple of minutes ago), Duration (e.g. if a JITAI is ignored for a defined amount of time, it won't occur again for a given period of time), and BCT-related decision rules (e.g. if the BCT "comparison with others" is completed by the user, a JITAI appears). *User Input* (i.e. no Trigger during the next two hours) then lead to the decision if the JITAI is triggered and which *Trigger* will be executed. Beyond these detailed determinations, *Tailoring Variables and Decision Points and Rules* should finally be defined

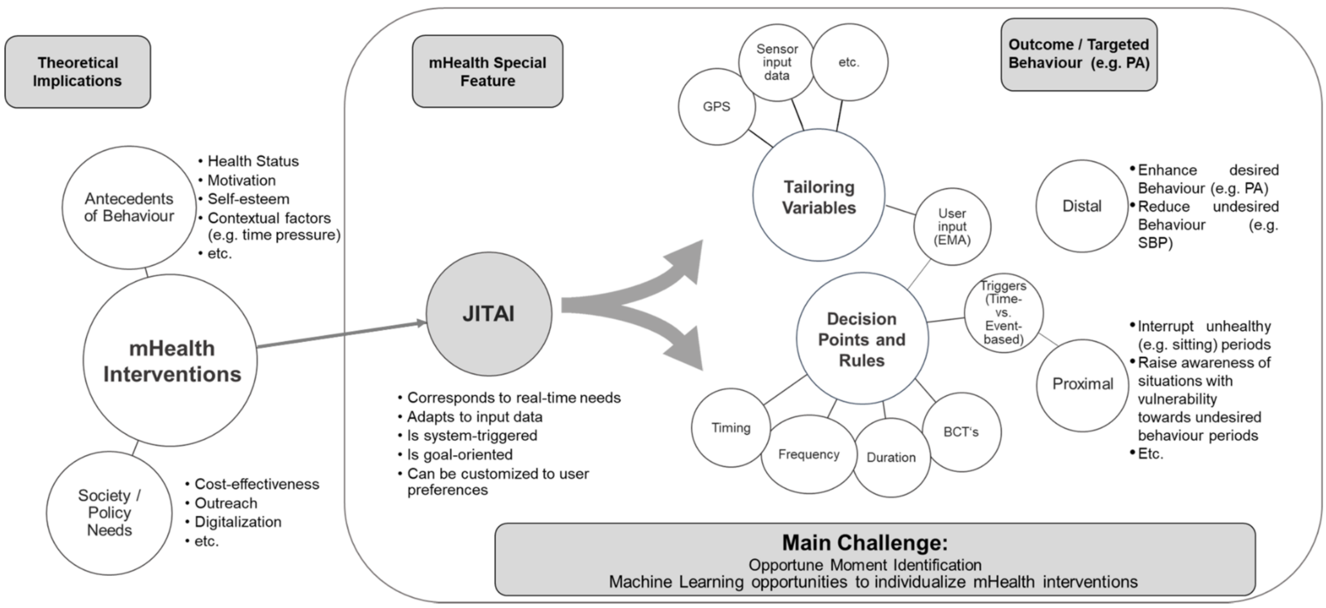

Figure 1. Conceptual framework of JITAIs.
On the left, this figure indicates the Theoretical Implications of mHealth for certain Outcome variables (on the right). Here, just-in-time adaptive interventions (JITAIs) as an mHealth Special Feature are described thoroughly concerning their key facets Tailoring Variables and Decision Points and Rules for Targeted Behaviour attainment. Note. PA: physical activity; SBP: sedentary behaviour pattern, BCTs: Behaviour Change Techniques, GPS: Global Positioning System; EMA: Ecological Momentary Assessments

in order to evaluate whether a *Proximal* goal (e.g. interruption of sitting time) is reached or not and to decide when an additional trigger is necessary and promising in order to reach a more *Distal* goal (i.e. long-term behaviour change).

In the following, an example for a mHealth application using a JITAI for the distal outcome to reduce SBP (which could be based on findings of a recent EMA study (Giurgiu et al., 2020)) by targeting the proximal outcome to interrupt inactive periods will be provided for a more comprehensive understanding of the interconnection of all facets. In a basic version, this JITAI is triggered if a) a connected sensor (e.g. an accelerometer) registers a prolonged period of a SBP (sensor input leading to a Decision Point) and if b) the user is not sleeping (e.g. it is not night-time), didn't receive a JITAI during the past 30 minutes, has not been sufficiently active on that day already (i.e. has already reached his or her step goal), and has no meeting or important appointment based on calendar entries (Decision Rules based on User Input and Tailoring Variables). If all Decision Rules are met at that certain Decision Point, the JITAI trigger will be sent in a moment where the user is likely to engage in an unhealthy behaviour and the intervention is promising for him / her to change this behaviour. This basic version could then be adapted according to user preferences and other variables (weather etc.) using machine learning principles.

Taken together, JITAIs aim to positively affect a *Targeted Behaviour*, i.e. PA or SBP based on well-aligned and user-specific adaptability. Setting up *Proximal* targets (i.e. short-term goals which can act as mediators to the *Distal* outcome) can help to achieve a long-term, i.e. Distal goal of enhancing PA and / or reducing SBP. Preliminary study results suggest that aiming at short-term goals, receiving feedback, targeting daily life activities as well as the explanation of the reason for reminders and triggers leads to a high acceptance of JITAIs by participants (Hardeman et al., 2019). Hence, implementing these features may improve user engagement and adherence and therefore enhance behaviour change (Schembre et al., 2018). Pilot and feasibility studies also revealed increased awareness of opportunities (e.g. to use active transportation opportunities), a reduction of SBP (e.g. to interrupt screen time periods) and enhanced PA levels, which underlines the potential of JITAIs to change health behaviours (Hardeman et al., 2019).

Opportunities and Challenges of implementing JITAIs in mHealth research

The implementation of JITAIs into mHealth interventions hold promising prospects for health behaviour change. Especially the ongoing development of more advanced and smaller devices to continuously and objectively assess PA and SBP (as well as other health-related variables) and the synthesis of gathered activity-data with additional sensory information (e.g. GPS, ECG, blood-sugar, etc.) further indicate the potential to adapt interventions individually to the user (Reichert et al., 2020).

However, the identification of *Decision Points and Rules* (i.e. *Opportune Moment Identification*) for behavioural support depicts the *Main Challenge* of implementing JITAIs (Gonul et al., 2019). Until today, the identification of the optimal number and timing of treatments generated by the JITAI, which are accepted by and effective for users, still remains unknown and most likely depends on the *Proximal* goal and the population of choice. Too frequently sent JITAIs within a specific context, such as the working environment or within school times, may lead to disengagement and/or low adherence and may increase the risk of intervention fatigue. With respect to the implementation of evaluation studies, researchers are advised to use conceptual foundations of JITAI research to determine the critical parameters and choices for participants which are most promising in various settings (e.g. concerning population, duration and aim of the study, and the *Targeted Behaviour*).

Additionally, there is still a need to construct personalized JITAIs comprising the inclusion of behaviour-related (e.g. inactivity) and context-related information (e.g. weather). Here, computational science and machine learning principles offer a new perspective to personalized mHealth interventions (Gonul et al., 2019). Machine learning strategies can include a variety of *Decision Points* into intervention development allowing for context-sensitive and therefore individually tailored and timely flexible support in contrast to fixed algorithms ("if then functions"). Automated system identification modelling can help to identify person-specific *Decision Points and Rules* referring to intrapersonal states and environmental conditions (Conroy et al., 2020). This allows for individually tailored feedback increasing the likelihood of high adherence, user acceptance and higher levels of PA compared to fixed conventional behavioural support. However, a precise forecast of individual behaviour based on system identification modelling requires an extensive data collection prior to intervention onset to gather training data sets derived from different sources and populations. This may impact cost-effectiveness and feasibility of study implementation within a given timeframe for researchers. Some technological aspects also need to be considered when implementing JITAIs into mHealth research, including a short durability of electronic devices due to battery requiring demands (e.g. geolocation features). Furthermore, the necessity of continuous wireless connection between sensors and mHealth devices have to be kept in mind for the development of JITAIs and mHealth interventions in general (Hardeman et al., 2019), as they potentially mitigate user satisfaction and are a source of missing data. Additionally, feasibility studies are warranted in target groups including persons without experience in using digital media, such as older adults. These individuals potentially need additional personal assistance or monitoring to assure safety during PA (Miller et al., 2014).

Conclusion and Future Directions of JITAI research

The current position paper summarized the knowledge from existing frameworks about JITAIs and synthesized and visualized knowledge into a comprehensive and holistic framework to inform mHealth practitioners about how to implement and report on JITAIs in upcoming mHealth applications. The complexity of designing personalized interventions requires the transdisciplinary collaboration between engineers, computer scientists and behavioural scientists. One of the most important issues is a clear and uniform reporting, which can be informed by the key components of our framework (see Figure 1). Furthermore, reporting should include a clear depiction of the study design (e.g. outcomes, population and duration), methodological approach of the study (e.g. theory used, BCTs and intervention setting) and *Decision Points and Rules* (e.g. precise reporting on algorithms or deep learning mechanisms used) in order to compare different studies and to evaluate best-practice approaches for highest effectiveness.

In conclusion, the framework of the current position paper not only provides a basis for the development of JITAIs but also indicates variables which should be reported by JITAI studies. Future studies should focus on forming consensus on the different parts of the framework to be able to provide a thorough checklist informing researchers and practioners about gold-standards to deploy when initializing JITAI-based mHealth interventions.

The authors KW, JF, & TE contributed equally to this position paper and therefore share first authorship.

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Kathrin Wunsch
Institute of Sports and Sports Science, Center for the Assessment of Physical Activity (CAPA), Karlsruhe Institute of Technology, Karlsruhe, Germany
kathrin.wunsch@kit.edu

Tobias Eckert
Institute of Sports and Sports Science, Center for the Assessment of Physical Activity (CAPA), Karlsruhe Institute of Technology, Karlsruhe, Germany
tobias.eckert@uni-heidelberg.de

Janis Fiedler
Institute of Sports and Sports Science, Center for the Assessment of Physical Activity (CAPA), Karlsruhe Institute of Technology, Karlsruhe, Germany
janis.fiedler@kit.edu

Alexander Woll
Institute of Sports and Sports Science, Center for the Assessment of Physical Activity (CAPA), Karlsruhe Institute of Technology, Karlsruhe, Germany
alexander.woll@kit.edu