Zeitschrift für Arbeitswissenschaft
https://doi.org/10.1007/s41449-025-00492-3

WISSENSCHAFTLICHE BEITRÄGE

Understanding teleoperation: A human-centered framework for workplace designx

Alexandra Nick[1] · Nicole Damm[2] · Julian Elias Reiser[3] · Martin Baumann[2] · Barbara Deml[1]

Accepted: 16 October 2025

Abstract

This article introduces a psychologically grounded framework to describe cognitive demands in the teleoperation of highly automated agents. It builds on established models of information processing, situation awareness, and occupational stress to explain how remote operators perceive, process, and act upon task demands in dynamic environments. Three scenarios from ground-based transportation illustrate varying operational contexts and support the identification of objective task demands. The framework highlights key human factors such as attention, working memory, and situation understanding, while also accounting for individual differences in cognitive resources. It provides a theoretical foundation for future empirical studies and supports the human-centered design of adaptive teleoperation workplaces.

Practical Relevance: The framework supports the design and evaluation of teleoperation workplaces by identifying cognitive demands across diverse scenarios. It provides guidance for designing adaptive interfaces and task allocation strategies in event-driven, safety-critical environments that feature frequent context switches and uncertain sensor-based information. It helps practitioners and system designers to address the specific challenges of teleoperation as a complex socio-technical system.

Keywords Teleoperation · Information processing · Situation awareness · Cognitive workload · Conceptual framework

✉ Alexandra Nick
alexandra.nick@kit.edu

Nicole Damm
nicole.damm@uni-ulm.de

Dr. Julian Elias Reiser
reiser@ifado.de

Prof. Dr. Martin Baumann
martin.baumann@uni-ulm.de

Prof. Dr. Barbara Deml
barabara.deml@kit.edu

[1] Institut für Arbeitswissenschaft und Betriebsorganisation, KIT, Engler-Bunte-Ring 4, 76131 Karlsruhe, Germany

[2] Institut für Psychologie und Pädagogik, Universität Ulm, Albert-Einstein-Allee 45, 89081 Ulm, Germany

[3] Leibniz Institut für Arbeitsforschung, TU Dortmund, Ardeystr. 67, 44139 Dortmund, Germany

Published online: 06 November 2025

Teleoperation verstehen: Ein menschenzentriertes Rahmenwerk für die Gestaltung von Arbeitsplätzen

Zusammenfassung

Dieser Artikel stellt ein psychologisch fundiertes Rahmenwerk vor, um die kognitiven Anforderungen bei der Teleoperation von hochautomatisierten Agenten zu beschreiben. Er baut auf etablierten Modellen der Informationsverarbeitung, des Situationsbewusstseins und des beruflichen Stresses auf, um zu erklären, wie Teleoperatoren die Aufgabenanforderungen in dynamischen Umgebungen wahrnehmen, verarbeiten und danach handeln. Drei Szenarien aus dem bodengebundenen Verkehr veranschaulichen unterschiedliche Einsatzkontexte und unterstützen die Identifizierung objektiver Aufgabenanforderungen. Das Rahmenwerk hebt menschliche Schlüsselfaktoren wie Aufmerksamkeit, Arbeitsgedächtnis und Situationsverständnis hervor und berücksichtigt dabei auch individuelle Unterschiede bezüglich der kognitiven Ressourcen. Es bietet eine theoretische Grundlage für zukünftige empirische Studien und unterstützt die menschengerechte Gestaltung von adaptiven Telearbeitsplätzen.

Praktische Relevanz: Das Rahmenwerk unterstützt die Gestaltung und Evaluierung von Telearbeitsplätzen durch die Identifizierung kognitiver Anforderungen in unterschiedlichen Szenarien. Es bietet eine Anleitung zur Gestaltung adaptiver Schnittstellen und Strategien zur Aufgabenzuweisung in ereignisgesteuerten, sicherheitskritischen Umgebungen, die häufige Kontextwechsel und unsichere sensorgestützte Informationen aufweisen. Es hilft Praktikern und Systemdesignern, die spezifischen Herausforderungen der Teleoperation als komplexes sozio-technisches System zu bewältigen.

Schlüsselwörter Teleoperation · Informationsverarbeitung · Situationsbewusstsein · Kognitive Arbeitsbelastung · Konzeptioneller Rahmen

1 Introduction

More and more systems are becoming increasingly automated. While this automaticity relieves humans of the need to take active control in a given situation, it may add complexity when overseeing one or many systems in situations the automation cannot handle itself. This is most evident when the systems are not implemented in a closed-loop system (e.g., London Underground). These situations may represent edge cases of the automation, outside its operational design domain (ODD), or problems in sensor-based detection. Academia and the industry agree that fully autonomous systems in human interaction situations can be solved with teleoperation (Kettwich et al. 2022; Majstorovic et al. 2022). Teleoperation is thereby an umbrella term for remote monitoring, remote assistance, and remote driving, where remote operators are located outside the situation and do not have direct sight of the systems environments (Working group "Research Needs in Teleoperation" 2025).

Due to the requirement for remote locations of operators, there are many challenges, especially those known from drone control research (Saffre et al. 2021; Kangunde et al. 2021; Tsung et al. 2022) and conceptual investigations into teleoperating road vehicles (Tener and Lanir 2022). These can be categorized into a lack of physical sensing (estimation of acceleration, speed, road inclination, force feedback), human cognition and perception problems (more detailed in human factors constructs situation awareness (SA), cognitive load (CL), Spatial awareness, depth perception, proper development of mental models), video and communication quality (latency, low frame rate, cameras, resolution), remote interaction with humans, impaired visibility, and lack of sounds (Tener and Lanir 2022). These challenges are primarily related to unfamiliar situations, system perception problems, ambiguity, or contradictory information, which lead to problems in decision-making, as well as sensory problems associated with poor weather or lightning conditions (Kang et al. 2018; Tener and Lanir 2023a).

Based on these challenges, it becomes clear that there are many possibilities for designing the evolving professional field of teleoperation (Lee et al. 2022). It is particularly important to think about influencing factors in advance. Teleoperation of highly automated agents, especially in the domain of transportation, is here to stay. It cannot be assumed that we will be working in closed-loop systems in the medium term. Mixed traffic and the interaction with humans can always lead to problems. It is therefore a persistent solution that is relevant to the field of human engineering (Kettwich and Dreßler 2020; Majstorovic et al. 2022; Schrank et al. 2024b). Compared to other situations, there are almost endless design possibilities that need to be utilized in the sense of prospective ergonomics. Therefore, effective workplace design is crucial for a safe and efficient work environment (Schrank et al. 2024a).

Our conceptual approach aligns with the stages of human-centered workplace design. First, we will look at the objective task demands and analyze possible effects in terms of human information processing. For this purpose, conceivable application scenarios for ground-based teleoperation are described in the following sub-section, which will be analyzed later with regard to objective task demands. The practical applicability of the established model must then be tested for empirical validity and applicability in future work. We use the term remote operators, event-based teleoperation in regards to remote assistance and remote driving, grounded in the SAE Standards (On-Road Automated Driving (ORAD) committee 2021). Continuous remote driving was excluded from our examples and framework.

This work focuses on human-centered workplace design and human engineering for ground-based transport. By this framework, we try to answer two questions: 1) Which influencing factors should be considered in the human-centered workplace design for teleoperation, and 2) how can remote operator performance and mental demands be explained by human factors in various teleoperation domains.

1.1 Application scenarios

To illustrate the various possible manifestations of ground-based traffic, we created three application scenarios for teleoperation. These examples are intended to illustrate different domains including their special requirements and characteristics, as well as their different levels of complexity and varying information needs. They are described below as examples to emphasize the relevance and influence of the framework's constructs and requirements.

Scenario 1: Teleoperation by infrastructure manipulation of an intercity train journey to transport goods

A fully automated freight train operates along a predefined intercity rail corridor. The onboard system has detected an inconsistency between the planned route and the current infrastructure configuration, which it cannot resolve autonomously. This results in a clear and well-defined transfer of control to a remote operator. The remote operator is informed of the situation by a system alert and is able to access fixed infrastructure-based cameras to inspect the physical switch status. Instead of directly controlling the train's motion, the remote operator intervenes at the infrastructure level by remotely adjusting a track switch.

The described task is primarily based in longitudinal control or the influence on infrastructure without lateral control. Since the vehicle carries no passengers, there is no requirement for user communication. The environment is clearly structured with predefined tracks and no mixed traffic. This simplifies the situation assessment for the remote operator, so that the transfer of control is highly predictable based on the identifiable system boundary.

Scenario 2: Event-based remote driving of a shuttle bus

An automated shuttle operates in an urban environment, providing last-mile transportation for multiple passengers. As it approaches a visually complex intersection with obscured sightlines and ambiguous right-of-way markings, the shuttle comes to a stop. The cause of the stop is no clear system failure but based on uncertainty in sensor-based scene interpretation, which triggers an event-based and instantaneous control transfer request to the remote operator. Upon receiving the alert, the remote operator accesses the shuttle's onboard camera views to assess the traffic situation. The operator takes over direct control of the vehicle and tele-drives the shuttle through the intersection safely, considering all other road users (VURs, other motorized vehicles). These control transfers are especially challenging, for example, when poor weather conditions or darkness impair vision. Simultaneously, passengers are informed via onboard displays or voice announcements, meeting the demand for transparency and communication with passengers. This scenario is characterized by temporary lateral and longitudinal control, necessitated by complex, unstructured environments with mixed traffic. The time to decision is moderate but constrained, requiring rapid context switching and high situational accessibility under uncertainty and sensory ambiguity. The interface provides high-fidelity information with low latency, ideally through an immersive and multimodal information display.

Scenario 3: Event-based remote assistance of a networked robot fleet

A hospital relies on a fleet of autonomous mobile robots to transport medication and lab samples between departments. The system operates under routine conditions, with intra-fleet vehicle-to-vehicle (V2V) communication managing most interactions autonomously. During one shift, a robot reports that an unexpected obstacle blocks its path in a hallway. This report triggers an alert without requiring immediate remote control. A remote operator reviews the status and determines that a rerouting strategy is required. The operator uses maneuver-based remote assistance, which relies on sensor data and fleet coordination protocols to resolve the issue. The robot's front-view camera image is visible to the operator to offer additional visual information about the obstacle. The tasks in this scenario include assisting multiple systems, event-based fleet-level coordination and control through high-level planning rather than vehicle-specific motion commands. The robot's environment is semi-structured without formal traffic rules. The interaction partners are relatively predictable.

2 Objective task demands

As illustrated in the application scenarios described above, the teleoperation of highly automated agents can place varying demands on the remote operator, depending on the application context, the type of agent, and the respective environmental conditions. Based on these different demands, the authors have identified overarching objective task demands, which, in their respective manifestations, play a crucial role in understanding and designing teleoperation.

One identified objective task demand is the *cause of the control transfer*. It can, for example, be triggered by system limitations, such as exiting the ODD, or it can be event-based, for example, caused by uncertainties in environmental perception (Bundesministerium für Digitales und Verkehr 2021, 2024; Gadmer et al. 2022; Cogan and Milius 2023). Closely related to this is the *predictability of the control transfer*, which can vary greatly, from planned handovers due to infrastructural inconsistencies to spontaneous handovers in dynamic traffic situations. Furthermore, the *type of problem*, which can be immediately apparent or initially unclear to the remote operator, was identified as another objective task demand.

Additionally, *decision-making time* can differ significantly between situations. While structured scenarios allow for longer analysis times, highly dynamic situations involving mixed traffic and potentially vulnerable agents in the vicinity of the highly automated agent require faster decisions. Depending on the scenario, the *number of agents to be monitored* is also relevant: When monitoring only one highly automated agent, full attention can be directed to it, whereas in other contexts, multiple agents may need to be monitored simultaneously.

The *degrees of freedom* in teleoperation are another central objective task demand for remote operators. Depending on the situation and the agent's automation, remote operators must either assume longitudinal control, lateral control, or both simultaneously.

Moreover, *communication with other system members* was identified as another objective task demand: in public applications communication involves passenger interaction and transparent information exchange, whereas it may not be required in purely warehouse logistics. This is closely related to *operational transparency* or *situational accessibility*, which is determined by the quality and availability of sensory and visual data. Finally, the *complexity of the environment* plays a central role: highly structured, predictable environments place lower demands on perception and interpretation than urban or semi-structured scenarios with high potential for disruption and variability.

In addition to the objective task demands derived from the application scenarios described above, the authors have identified further objective task demands, which are provided in an online repository (https://osf.io/npcyx/?view_only=f3383a397f9c44dab9b95eb9c6a315f4). However, it should be noted that the described objective task demands are merely examples and do not claim to be exhaustive. Nevertheless, the objective task demands described highlight the diversity and complexity of situations that remote operators may encounter in teleoperation. These demands not only represent situational challenges but also directly affect the cognitive information processing of the remote operator. To systematically capture these interrelations, a conceptual framework was developed based on established scientific models and expert discussions, which is described in the following section.

3 Conceptual framework

Based on the existing literature on teleoperation (especially on means of transportation) and joint expert discussions of the authors, the following framework was developed (Fig. 1). It aims to relate relevant human factors concepts to one another and to serve as the basis for planned empirical studies. It incorporates the information processing model by Wickens and Carswell (2021) and Endsley's (1995) SA idea, extended by the concept of situation understanding.

While other models concerning teleoperation have focused on the overall interaction between remote operator, environment, and assisted agents (Working group "Research Needs in Teleoperation" 2025; Yelchuri et al. 2025), we set out to highlight the human-centered view using this framework. By utilizing constructs from various psychology-related human factors disciplines (neuroscience, occupational psychology, and engineering psychology), we present a holistic, remote operator-centered approach to understand workplace and job characteristics. For in-depth explanations of each of the framework's segments, please refer to Chap. 4.

Our conceptual framework consists of three major constituents: the environment, the socio-technical system, and the remote operator. The environment imposes (objective) task demands on the remote operator, who processes these demands through multiple cognitive stages before executing motor actions, creating a feedback loop between environment and operator (Sheridan 2016). The remote operator is also part of a socio-technical system or work organization (Grabbe et al. 2024), which provides contextual constraints and characteristics to the task. To develop an appropriate response, the remote operator must process information from the environment through a series of stages as described by Wickens' and Carswell's information processing model (2021; with extensions by the authors): sensory processing, perception, working memory operations including situation understanding, comparing working memory input with long term memory representations, response selection, and finally response execution.

The relationship between the above-mentioned objective task demands and remote operator performance can also be understood through the lens of the German occupational science framework of the stress-strain concept, as defined in DIN EN ISO 10075-1. The objective task demands represent the external stress and load, which describe the to-

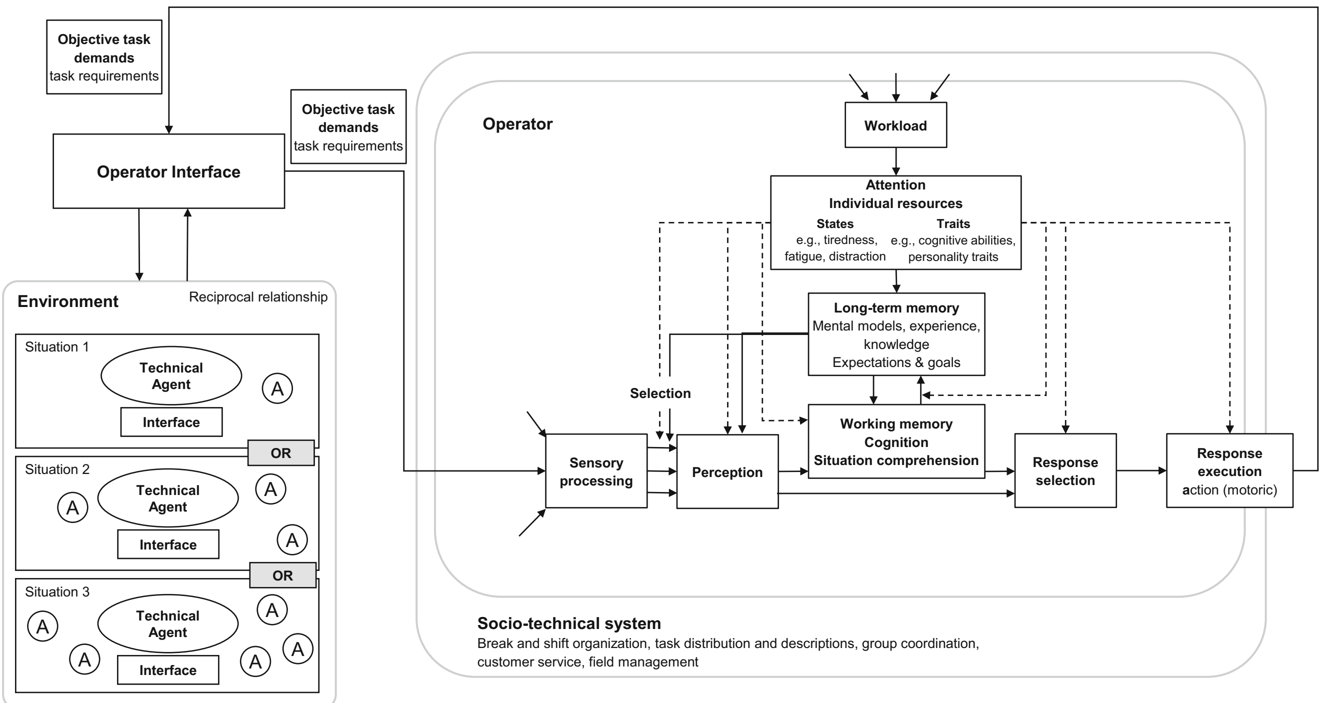

Fig. 1 Conceptual human-centered framework of remote operator task processing in teleoperation, integrating task demands, cognitive resources, and interaction via a suitable interface for dynamic environments

Abb. 1 Konzeptionelles, menschenzentriertes Rahmenmodell für die Aufgabenbearbeitung durch Remote-Operatoren in der Teleoperation. Integriert sind objektive Aufgabenanforderungen, kognitive Ressourcen und die Interaktion mit dem System über eine geeignete Schnittstelle für dynamische Umgebungen.

tality of all detectable influences from the environment affecting the person psychologically. As these demands flow through the information processing stages, they are modulated by the remote operator's individual resources, which comprise both current states (e.g., fatigue, alertness) and underlying traits (e.g., cognitive abilities, personality traits). Attention serves as a limited resource that must be selectively allocated across these information processing stages and plays a central role in forming and maintaining situation understanding. Long-term memory supports this process by providing mental models, experience, knowledge, and expectations, which together shape how information is interpreted, integrated into the situation model, and ultimately influence the response selection (Endsley 2000). The resulting strain, defined as the immediate effect of psychological stress on the individual, depends on how effectively the operator can allocate these resources to meet task demands. Importantly, identical external loads can lead to different individual strain responses among different operators or even within the same operator under varying conditions (Rohmert and Raab 1995), as the efficiency of information processing varies with available cognitive resources and individual differences in processing capacity.

This operator-centered model provides a comprehensive framework for understanding teleoperation performance by integrating information processing theory with the concept of situation understanding and occupational stress-strain concepts. By mapping the cognitive pipeline from environmental input to motor output, the framework identifies where individual differences could manifest as performance variability and reveals critical intervention points for system design. Most importantly, it demonstrates that effective teleoperation depends not merely on interface features or task characteristics in isolation, but on the dynamic interplay between environmental demands, cognitive processing capabilities, and socio-technical context. This integrated perspective is essential for developing adaptive systems that can accommodate operator variability and maintain performance under diverse operational conditions. To deepen this perspective, the following section takes a closer look at the sub-constructs of the presented framework, outlining their relevance to teleoperation.

4 Relevant constructs

As can be seen in Fig. 1, the presented framework comprises several important constituents, each representing a distinct yet interconnected element of the teleoperation process.

This chapter provides a detailed explanation of these elements and relates them to the remote operator job.

4.1 Interface and environment

The term human-machine system (HMS) refers to systems in which objectives are achieved through the integrated functions of a human operator and a machine. The role of humans is shifting from simple machine operators to supervisors of autonomous, intelligent systems (D'Aniello and Gaeta 2023). In HMS contexts, models of situation understanding are extended to include controls, input information (e.g., video, audio, tactile signals), and the machine itself as part of the system. Specific cognitive mechanisms and information-processing components are also included. It is crucial to highlight that situation understanding is essential, particularly for accurate comprehension of given situations (D'Aniello and Gaeta 2023). Human-machine interface (HMI) design involves structuring interactive systems to align with users' cognitive, perceptual, and motor capabilities. It is a central concern in human factors research, as interface design directly influences situational understanding, decision-making, and overall performance (Helle et al. 2022).

In teleoperation, interface design determines how remote operators perceive the remote environment, issue control commands, and integrate system feedback into their mental models. Key interface factors include the reliability, viewpoint, depth cues, and field of view of video feeds, as well as the clarity and relevance of contextual information (Tener and Lanir 2022). Research suggests that interface transparency, in terms of the extent to which system states and actions are observable and understandable, plays a critical role in enabling safe and efficient teleoperation (Almeida et al. 2020). Psychological and motor processes are shaped not only by the task itself but also by how information is structured, selected, and presented through the interface (Wickens and Carswell 2021). Frequent task and context switches can be assumed to elevate mental demand, reduce attentional stability, and increase the risk of information overload (Monsell 2003). In teleoperation, where time-critical and safety-relevant decisions must often be made under uncertainty, these dynamics make interface design a critical factor. How information is selected and presented influences the remote operator's ability to maintain focus and make effective decisions.

From a human-centered design perspective, this includes identifying how visual and contextual information can be prioritized and presented in a way that aligns with human cognitive capacities. While such considerations are well established in other domains (e.g., aviation, process control), their specific application to teleoperation of highly automated agents remains largely uninvestigated and is part of the exploratory focus of this work. Operating highly automated agents remotely entails interacting with complex and potentially fast-changing task environments. Remote operators may face rapid context switches. These dynamics may increase mental demand, particularly when the cause of a problem is not immediately apparent and must be identified first. The complexity of the task, the amount and clarity of required information, and the way this information is presented all influence the remote operator's ability to maintain situational understanding and decision-making performance. Frequent task and context switches require interface designs that explicitly support human attention and problem-solving under dynamic conditions (Fan et al. 2022).

While numerous guidelines exist for interaction and behavior-oriented interface design (Gnatzig et al. 2012; Gafert et al. 2022), their application to teleoperated autonomous agents is still limited. This indicates a gap between established knowledge in related domains and the current state of practice in teleoperation, especially for highly automated and complex agents. There is a need to better understand how existing design principles should be adapted or extended to support teleoperation contexts. The interface functions as a dynamic gateway to the environment of the highly automated agent. It not only transmits environmental information to the remote operator but also shapes how this information is perceived, interpreted, and acted upon. Conversely, the characteristics of the remote environment influence which interface features are most effective or necessary. For example, in highly dynamic or unstructured environments (Scenario 2), richer visual feedback or adaptive information presentation may be required. This reciprocal relationship highlights the importance of considering interface-environment coupling as a key factor in teleoperation system design. However, it is not sufficient to examine only the design of the interface itself, as even a perfect interface does not necessarily lead to a successful teleoperation. This is because the remote operator's ability to effectively extract relevant information from the presented environment, interpret it and translate it into decisions is one of the key factors for the success of teleoperation. It is therefore essential to consider the cognitive requirements and information processing of remote operators in the following.

4.2 The operator

Information processing during remote operation fundamentally differs from direct operation due to the mediated nature of sensory input. Operators must construct mental representations of remote environments through displays and interfaces, creating unique cognitive demands (Woods et al. 2004). This process follows *the stages* outlined in Wickens' and Carswell's (2021) information processing model, from perception through attention to higher-level cognitive functions, with attention serving as the critical bottleneck that determines which information reaches conscious processing. The operator receives environmental information primarily through visual displays supplemented by auditory alerts and occasionally haptic feedback.

4.3 Signal detection and perceptual organization

Following signal detection theory (Gongvatana 2011; Wickens et al. 2013), operators must distinguish meaningful signals from noise under conditions of uncertainty. In teleoperation, this challenge is amplified by factors such as sensor limitations, transmission delays, and display resolution constraints. The operator's response criterion—the threshold for declaring a signal present—must adapt to these degraded conditions while balancing the costs of misses against false alarms. Once sensory signals are detected, they are organized into meaningful patterns in the perception stage. Teleoperation interfaces typically present information across multiple displays, requiring operators to mentally integrate spatially distributed elements. This integration process can be facilitated through adherence to ergonomic design principles, e.g. the proximity compatibility principle (Wickens and Carswell 1995), which suggests that information elements requiring mental integration should be displayed in close physical proximity.

The relevance of signal detection in teleoperation is exemplified by scenarios such as intersection assistance (Scenario 2) where the remote operator must integrate information from multiple cameras, sensor displays, and status indicators to form a coherent understanding of the shuttle's position relative to traffic flow. This perceptual integration task becomes particularly demanding when sensor ambiguity requires rapid switching between information sources to resolve uncertainties, especially under conditions of poor weather or darkness that further impair vision.

4.4 Attention as the information gateway

Attention serves as the critical gateway controlling which presented information enters further processing stages. In our context, attention can be categorized into four distinct types, each serving different functions in the information processing pipeline (Kahnemann 1973; Matthews 2000).

Selective attention must be strategically deployed across multiple information sources according to their expected value—a function of information importance and change probability (Wickens 2015). The SEEV model (Salience, Effort, Expectancy, Value) predicts which information operators will selectively attend to based on bottom-up salience and top-down factors of effort, expectancy, and value. However, teleoperation introduces unique challenges as the physical separation eliminates natural attention-capturing cues like peripheral motion or subtle auditory changes (Endsley and Kiris 1995). *Sustained attention* or vigilance—maintaining alertness for rare critical events during prolonged monitoring—presents the second critical attentional challenge. This is especially challenging in highly automated systems where operators primarily supervise and monitor rather than actively control. The vigilance decrement—declining detection performance over time—poses significant risks in safety-critical teleoperation contexts (Warm et al. 2008). Environmental monotony, limited sensory feedback, and periods of passive monitoring exacerbate this decrement.

Divided attention represents the third attentional demand in teleoperation, which frequently requires attending to multiple tasks, e.g. maintaining correct mental models, monitoring system status, and communicating with agents. This multitasking is particularly evident in Scenario 3, where operators must monitor multiple robots while coordinating fleet-level decisions and managing external disruptions. The limited capacity of divided attention (Kahnemann 1973) creates performance trade-offs, as allocating attention to one robot necessarily reduces monitoring quality for others. *Focused attention* enables operators to process critical information, concentrating on a single stimulus while filtering out distractors (Kahnemann 1973). This is crucial in Scenario 1 when the operator must precisely assess track switch status through infrastructure cameras, requiring focused analysis of specific visual elements while ignoring irrelevant background information.

4.5 Working memory and situation understanding

Working memory serves as the cognitive workspace where perceived information is actively maintained and manipulated (Baddeley 2003). In teleoperation, working memory may face high objective task demands due to the need to maintain dynamic mental models of remote environments that cannot be directly perceived. These models must track spatial relationships, predict entity movements, and anticipate system behaviors based on limited and potentially delayed sensory input. The three teleoperation scenarios illustrate varying working memory demands. Scenario 1 benefits from environmental predictability and structured rail corridors, allowing operators to rely on well-established mental models. Scenario 2 imposes a high working memory load through rapidly changing spatial configurations and multiple dynamic entities, requiring constant model updating. Scenario 3 requires maintaining parallel mental models for multiple agents, taxing working memory capacity through the need to track individual robot states while maintaining awareness of fleet-level patterns.

Working memory operations are inherently supported by long-term memory, which provides schemas, procedures, and experiential knowledge (Tulving 1985). Expert teleoperators may develop specialized mental models that efficiently organize remote environment information, reducing working memory load through chunking and pattern recognition (Song and Cohen 2014; Pan et al. 2022). These models include expectations about system behavior, common failures, and effective intervention strategies.

However, long-term memory can also introduce challenges when stored mental models conflict with current remote reality. Operators may incorrectly predict system behavior based on previous experiences, leading to mode errors or incorrect situation assessments (Norman 1981). This is particularly problematic during control transitions, where operators must rapidly calibrate their mental models to match the current situation and system state.

4.6 Situation understanding

Situation understanding is a comprehension-based interpretation of SA that uses frameworks from text comprehension (e.g., Kintsch 1998) to explain the generation and maintenance of how humans create a meaningful and coherent mental representation of the current situation. This mental representation, called the situation model, is identical to Endsley's (1995) SA as a product. That is, the situation model serves to represent the results of the three levels of SA as defined by Endsley (1988): the perception of relevant information in the environment, the comprehension of this information for the current situation, and the projection of how the situation will develop in the future, but explains in more detail how it is created and maintained. Situation understanding thus means an operator's comprehensive understanding of the current, dynamically evolving situation. For the creation of situation understanding, attention is decisive for which elements of the environment are perceived. Thus, poor attention allocation or cognitive overload can create gaps in situation understanding, where critical information never reaches conscious processing (Endsley 1995).

As described in Endsley's (1995) model, the operators' situation understanding forms the basis for their decision about which action they consider appropriate in the current situation, and consequently, for the execution of actions by the operator. It is assumed that the operator's goals and expectations have a significant influence on what information the operator considers relevant in a situation to make an appropriate action decision and thus to achieve the task goal pursued (Endsley 1995). Thus, the operator's current goals and expectations strongly influence the understanding of the situation.

Achieving such a comprehensive understanding of the current situation and how it might develop is therefore essential for any operator working in a dynamic environment and controlling dynamic technical systems. This is especially challenging when the relevant situational information is only accessible remotely for the operator, as in teleoperation. The remote operator must be able to perceive relevant aspects of the teleoperated agent's environment. As the described application scenarios illustrate, one of the central challenges for the remote operator is to establish an adequate situation model despite the fact that the remote operator is not able to experience the situation directly. All information about the situation in which the to be teleoperated agent is in is mediated via the HMI that represents the remote operator's workplace. Consequently, it is of essential importance to understand how a sufficient situation understanding can be established and maintained under such circumstances and how it is influenced by environmental, task, and personal characteristics.

The three application scenarios described above can serve as examples to illustrate how diverse the environmental and task-related factors influencing the remote operator's situation model can be. One key challenge can be that the remote operator is only made aware of a situation by a system message or a specific event, and then has to gain a comprehensive understanding of the situation in a very short time. This includes, in particular, the fast identification of the problem and the assessment of whether and in what form intervention is required, for example by tele-driving, tele-assistance or indirect intervention via the infrastructure.

Another key influencing factor is the criticality of the situation (i.e., the urgency with which a decision must be made). In safety-critical contexts, the time available to make a decision can be very limited, which restricts the possibility of in-depth analysis. In this case, the remote operator must be able to quickly identify which of the many available information is relevant to the current situation. This ability is additionally influenced by the complexity of the environment at the location of the teleoperated agent. A dense urban traffic situation with unpredictable road users places completely different demands on the achievement of situation understanding than a clearly structured, predictable environment, such as an isolated rail network or a hospital corridor with restricted access. Another important factor is the time at which the remote operator is informed of the need for an intervention: if the handover to the remote operator is announced well in advance and can therefore be planned, it can be assumed that the remote operator has sufficient time to achieve adequate situation understanding before a decision and intervention by the remote operator is required. In contrast, a spontaneous handover (e.g., due to an unexpected event or sensor uncertainty) places significantly higher demands on the remote operator's ability to quickly receive and process information. Lastly, the number of highly automated agents that need to be monitored simultaneously also has an impact on the demand for the remote operator's resources to update and maintain an adequate situation model. While a single, clearly focused situation allows the operator's full attention, the parallel monitoring of several agents requires a high level of cognitive switching, prioritization and efficient resource allocation. Thus, the risk of missing or incorrectly weighting relevant information might increase as the number of highly automated agents and information density increases.

In summary, the remote operator's situation understanding appears to be characterized by a large number of environmental and task-related influencing factors, which can differ considerably depending on the context and application scenario. The influencing factors illustrated using the above-described application scenarios (e.g., the complexity of the environment, the criticality of the situation or the time at which the remote operator is notified) are merely examples and do not claim to be exhaustive. It should also be noted that personal factors also play a significant role in the remote operator's ability to create and maintain an adequate situation understanding. These can include, for example, individual experience in dealing with certain systems or situations, the remote operator's current level of attention and the goals and expectations of the remote operator.

4.7 Cognitive abilities

A question that is not sufficiently answered so far is "Who is a good remote operator?" in cases of teleoperation of highly automated agents. The individual skill set of remote operators matters and these skills can be used as cues to identify suitable persons for emerging teleoperation workplaces. Following a cognitive fit perspective, a relationship between individual and cognitive characteristics and teleoperation performance can be derived (Pan et al. 2021).

Human abilities and performance in teleoperation contexts are mainly investigated within the domain of robot teleoperation. Teleoperation performance in three-dimensional space is found to be related to control accuracy, cognitive consistency, and the challenge of perception and interaction in 3D settings (Tang et al. 2024). Research results from other domains suggest that spatial abilities (e.g., mental rotation accuracy, spatial memory), attention and sustained attention, perceptual abilities (distance perception deviation, direction perception deviation, movement anticipation), and reaction and decision time may impact performance and mental demand (Long 2011; Tang et al. 2024). These may be especially relevant in teleoperation environments where effective processing of temporal and spatial information, planning and executing control commands, as well as quick adaptation to varying task demands, is essential. In addition, in robotic arm teleoperation perception mode, individual spatial ability, and control mode were influencing performance in teleoperation (Guo et al. 2019). Remote driving and assistance in highly complex, dynamic environments (such as urban driving scenarios or Scenario 2) remain largely under-researched. The relationship between cognitive abilities and mental demands in these contexts is not yet well understood. In the context of the three application scenarios, it can be assumed that different cognitive abilities are more relevant in one domain than in the other. For example, high-level guidance in Scenario 3, giving clearance when the obstacle is no longer there or selecting one out of proposed maneuvers requires different skills than in Scenario 2. Which factors influence task-switching performance need to be investigated empirically. In addition, there is a gap in understanding how spatial awareness and situational understanding interact under varying teleoperation conditions (Yekita et al. 2024). Besides these abilities, peripheral vision, attention and working memory capacity are considered for future empirical studies.

4.8 Personality traits

In addition to cognitive abilities, several personality characteristics may influence mental demand and performance over time in different teleoperation contexts. While personality traits are not direct predictors of task-specific cognitive performance, they can moderate how remote operators experience workload and stress during prolonged or complex teleoperation tasks. For example, extraversion and conscientiousness have been associated with more effective coping strategies, greater task persistence, and more structured working styles (Pan et al. 2016; Santamaria and Nathan-Roberts 2017; Qin et al. 2022). In demanding teleoperation scenarios, higher conscientiousness may help remote operators maintain performance under a sustained workload. These influences could be empirically investigated in the three different application scenarios. It can be hypothesized that teleoperation performance in urban traffic situations with various VURs over time leads to correlations with personality traits due to the high demand. In more predictable and restricted scenarios like one and three, these effects can be overshadowed and potentially not found due to lower demands.

Another relevant characteristic is immersive tendency, particularly aspects related to the dimensions of telepresence (Witmer and Singer 1998). Operators with higher immersive tendencies may find it easier to engage with mediated environments, potentially enhancing situational understanding and reducing the cognitive costs associated with spatial dislocation. However, due to the frequent context changes, too much telepresence could also have a negative impact on performance in frequent reorientation. The differences in context changes are likely to play a central role in the impact of the immersive tendency. This could be an advantage for the robot fleet (Scenario 3) in a defined restricted space. For the teleoperation of trains (Scenario 1), there is already a larger possibility space. As in the example, it could be an overland journey in freight transport, a station entrance, or a level crossing. In urban road traffic with the last-mile shuttle (Scenario 2), the variance of possible situations is even greater. The influence of immersive tendency could vary in domains or have no relevant influence. Previous research from other domains can provide preliminary insights for the relevance of immersion (Fern and Shively 2011; Gregor et al. 2023). Whether and in which direction immersive tendencies, telepresence, and immersive interfaces have an influence on event-based teleoperation has to be investigated.

4.9 Response execution

Response execution can be described as a goal-directed output of cognitive processes as a discrete unit of behavior (Zacher 2017). In HMS, the human information processing, including situational understanding and decision-making, forms the basis for action. The remote operators' action is thereby the input to the control interface as an execution of the decision made (Endsley 1995; D'Aniello and Gaeta 2023). The range of actions available to remote operators in various systems differs substantially depending on the operational context and interface design (Rea and Seo 2022; Gholami et al. 2022). In direct remote driving, like Scenario 2, remote operators typically engage in continuous, fine-grained motor control of vehicle dynamics, requiring sustained attention and high perceptual-motor coordination. In contrast, remote assistance (Scenarios 1 and 3) and fleet management involve higher-level decision-making, supervisory control, and occasional interventions, placing different cognitive and communicative demands on the operator. The existing approaches to teleoperation of road vehicles vary greatly (Gafert et al. 2022; Tener and Lanir 2023b; Schrank et al. 2024b). The choice of input modalities ranges from physical controls (e.g., steering wheels, joysticks, gaming controllers) to graphical user interfaces or voice commands. The decision for an input affects both the remote operator's workload and the nature of the interaction (Pan et al. 2024; Wolf et al. 2024). These differences also imply that performance measurement should be adapted to the specific form of teleoperation, with distinct metrics required to validly assess remote operator effectiveness in continuous control versus supervisory or support roles.

5 Discussion and future work

The proposed framework presented in this article integrates psychological theory and domain-specific knowledge to describe cognitive requirements in the teleoperation of highly automated agents. Rather than offering an empirically validated framework, the framework serves as a theoretically grounded structure to guide future hypothesis-driven research. Its primary contribution lies in providing a generalizable structure to guide systematic investigations into the cognitive mechanisms and boundary conditions of teleoperation in complex socio-technical systems, particularly in application domains with frequent context switches.

The framework builds upon established psychological theories explaining human information processing, decision-making, and action in complex environments (Wickens and Carswell 2021) as well as Endsley's (1995) concept of SA. While rooted in these traditions, the presented framework extends them by addressing remote human operation across various teleoperation applications in ground-based transportation. Unlike other approaches tailored to specific domains or tasks, the framework provides a cross-domain explanation of teleoperation. The aim was to capture key tasks and mental demands, cognitive mechanisms, and individual resources that may apply across a broad range of teleoperated agents. This generality enables the framework to serve as a reference for both applied system design and empirical validation across diverse application domains. Beyond its theoretical contribution, the framework offers a structured perspective for approaching the design of remote operator work environments. By highlighting core mental demands and their interdependencies, it supports the identification of design requirements for adaptive interfaces, workspace ergonomics, and task allocation strategies across teleoperation scenarios.

At the same time, the framework has several limitations. It was developed conceptually and has not yet been empirically validated. In addition, the framework does not specify operational definitions or measurement strategies for constructs such as mental models, individual resources, or attentional control. This openness allows for methodological flexibility but highlights the need for future empirical studies to refine, test, and operationalize the framework in concrete settings. In particular, detailed task analyses will evaluate the validity of identified objective task demands, especially considering the variation in operational goals, assistance types, and environmental complexity across teleoperation scenarios. It is important to emphasize that existing findings from monitoring tasks in traditional control room operations cannot simply be transferred to teleoperation. Although both involve supervising technical systems, the underlying task structures, dynamics, and demands differ fundamentally. This has direct implications for the applicability of existing research and design principles.

Compared to traditional control room operations, teleoperation introduces a fundamentally different set of demands. Control room operators frequently work within stable environments, monitoring system states that require vigilance and collaborating with others to maintain and ensure safety, process stability, and correct operation (Savchenko et al. 2018; Lin et al. 2023). In contrast, teleoperation is event-driven, request-based, and reactive. A highly automated or human agent triggers teleoperation in potentially ambiguous or safety-critical edge cases that automation cannot resolve. The situations where support is required can vary a lot, as highlighted in the application scenarios. This results in high variability and low task repeatability, requiring remote operators to manage frequent context switches between different agents and operational environments, which is related to a high degree of cognitive flexibility, rapid situation understanding, and decision-making. In addition, the operational level varies from providing support in decision-making, maneuver selection, and guidance to direct control (Kettwich and Dreßler 2020; Schrank et al. 2024a). It is known that design and interaction concepts can moderate or determine operator performance (Meshkati 2003; Flegel et al. 2022), which needs to be considered in teleoperation workplace design, particularly concerning digitalization, automation, and the application of AI.

In summary, the presented framework provides a foundation for future interdisciplinary research at the intersection of cognitive psychology, human factors, and teleoperation. It encourages the integration of behavioral, physiological, and task-based approaches to understand and support remote operators in safety-critical and frequently changing environments.

Acknowledgements The authors would like to thank all researchers for their valuable feedback and insightful discussions during the development of this framework (Sofie Ehrhardt, Lina Kluy, Eileen Roesler, Natasha Merat, and Frederik Diederichs) and for the linguistic corrections by Lara Morris. We welcome further feedback from the research community.

Funding Open Access funding enabled and organized by Projekt DEAL.

References

Ahlstrom U, Friedman-Berg FJ (2006) Using eye movement activity as a correlate of cognitive workload. Int J Ind Ergon 36:623–636. https://doi.org/10.1016/j.ergon.2006.04.002

Almeida L, Menezes P, Dias J (2020) Interface Transparency Issues in Teleoperation. Appl Sci 10:6232. https://doi.org/10.3390/app10186232

Baddeley A (2003) Working memory: looking back and looking forward. Nat Rev Neurosci 4:829–839. https://doi.org/10.1038/nrn1201

Bundesministerium für Digitales und Verkehr (2021) Straßenverkehrsgesetz (StVG), § 1e – Betrieb hoch- und vollautomatisierter Fahrzeuge; Widerspruch und Anfechtungsklage (12.07.2021 (BGBl. I S. 3108), in Kraft getreten am 28.07.2021)

Bundesministerium für Digitales und Verkehr (2024) Die Zukunft fährt autonom – Strategie der Bundesregierung für autonomes Fahren im Straßenverkehr

Cogan B, Milius B (2023) Remote control concept for automated trains as a fallback system: needs and preferences of future operators. Smart Resilient Transp 5:50–69.

D'Aniello G, Gaeta M (2023) Situation awareness in human-machine systems. In: Fortino G, Kaber D, Nürnberger A, Mendonça D (eds) Handbook of human-machine systems, 1st edn. Wiley, pp 451–461

DIN EN ISO 10075-1:2018-01, Ergonomische Grundlagen bezüglich psychischer Arbeitsbelastung_-Teil_1: Allgemeine Aspekte und Konzepte und Begriffe (ISO_10075-1:2017); Deutsche Fassung EN_ISO_10075-1:2017. DIN Media GmbH

Endsley MR (1988) Situation awareness global assessment technique (SAGAT). In: Proc IEEE 1988 Natl Aerosp Electron Conf, pp 789–795 https://doi.org/10.1109/NAECON.1988.195097

Endsley MR (1995) Toward a theory of situation awareness in dynamic systems. Hum Factors J Hum Factors Ergon Soc 37:32–64. https://doi.org/10.1518/001872095779049543

Endsley MR (2000) Theoretical underpinnings of situation awareness: a critical review. In: Situation awareness analysis and measurement. Lawrence Erlbaum,

Endsley MR, Kiris EO (1995) The out-of-the-loop performance problem and level of control in automation. Hum Factors J Hum Factors Ergon Soc 37:381–394. https://doi.org/10.1518/001872095779064555

Fan J, Li X, Su X (2022) Building human visual attention map for construction equipment teleoperation. Front Neurosci 16:895126. https://doi.org/10.3389/fnins.2022.895126

Fern L, Shively J (2011) Designing airspace displays to support rapid immersion for UAS handoffs. Proc Hum Factors Ergon Soc Annu Meet 55:81–85. https://doi.org/10.1177/1071181311551017

Flegel N, Van Laerhoven K, Mentler T (2022) Scalable human computer interaction in control rooms as pervasive computing environments. In: Proceedings of the 33rd European Conference on Cognitive Ergonomics. ACM, Kaiserslautern, pp 1–5

Gadmer Q, Richard P, Popieul J-C, Sentouh C (2022) Railway automation: a framework for authority transfers in a remote environment. IFAC Pap 55:85–90. https://doi.org/10.1016/j.ifacol.2022.10.236

Gafert M, Mirnig AG, Fröhlich P, Tscheligi M (2022) TeleOperationStation: XR-Exploration of User Interfaces for Remote Automated Vehicle Operation. In: CHI Conference on Human Factors in Computing Systems Extended Abstracts. ACM, New Orleans, pp 1–4. https://doi.org/10.1145/3491101.3519882

Gholami S, Lorenzini M, De Momi E, Ajoudani A (2022) Quantitative physical ergonomics assessment of teleoperation interfaces. IEEE Trans Hum-mach Syst 52:169–180. https://doi.org/10.1109/THMS.2022.3149167

Gnatzig S, Schuller F, Lienkamp M (2012) Human-machine interaction as key technology for driverless driving—A trajectory-based shared autonomy control approach. In: 2012 IEEE RO-MAN: The 21st IEEE International Symposium on Robot and Human Interactive Communication. IEEE, Paris, pp 913–918

Gongvatana A (2011) Signal detection theory. In: Encyclopedia of clinical neuropsychology. Springer, New York, pp 2297–2299. https://doi.org/10.1007/978-0-387-79948-3_1330

Grabbe N, Brettschneider S, Bengler K (2024) The work organization in teleoperated driving—a human reliability and socio-technical systems perspective. Automatisierungstechnik 72:1169–1194. https://doi.org/10.1515/auto-2024-0089

Gregor AWH, Allison RS, Heffner K (2023) Exploring the impact of immersion on situational awareness and trust in remotely monitored maritime autonomous surface ships. In: OCEANS 2023—Limerick. IEEE, Limerick, pp 1–10

Guo J, Liu Y, Kong X et al (2019) Analysis of key cognitive factors in space teleoperation task. In: Harris D (ed) Engineering psychology and cognitive ergonomics. Springer, Cham, pp 249–258. https://doi.org/10.1007/978-3-030-22507-0_20

Helle DE, Frølich M, Langen T, Muller G (2022) Situational awareness and human factors when designing complex systems. Incose Int Symp 32:167–178. https://doi.org/10.1002/iis2.12906

Kahnemann (1973) Attention and effort. Prentice-Hall, Englewood Cliffs

Kang L, Zhao W, Qi B, Banerjee S (2018) Augmenting self-driving with remote control: challenges and directions. In: Proceedings of the 19th International Workshop on Mobile Computing Systems & Applications. ACM, Tempe Arizona, pp 19–24

Kangunde V, Jamisola RS, Theophilus EK (2021) A review on drones controlled in real-time. Int J Dyn Control 9:1832–1846. https://doi.org/10.1007/s40435-020-00737-5

Kettwich C, Dreßler A (2020) Requirements of future control centers in public transport. In: 12th international conference on automotive user interfaces and interactive vehicular applications Virtual Event DC. ACM, pp 69–73. https://doi.org/10.1145/3409251.341172

Kettwich C, Schrank A, Avsar H, Oehl M (2022) A helping human hand: relevant scenarios for the remote operation of highly automated vehicles in public transport. Appl Sci 12:4350. https://doi.org/10.3390/app12094350

Kintsch W (1998) Comprehension: a paradigm for cognition. Cambridge University Press

Lee JS, Ham Y, Park H, Kim J (2022) Challenges, tasks, and opportunities in teleoperation of excavator toward human-in-the-loop construction automation. Autom Constr 135:104119. https://doi.org/10.1016/j.autcon.2021.104119

Lin J, Matthews G, Schreck J, Dickerson K, Hughes N (2023) Evolution of Workload Demands of the Control Room with Plant Technology. In: Julia Wright and Daniel Barber (eds) Human Factors and Simulation. AHFE (2023) International Conference. AHFE Open Access, vol 83. AHFE International, USA. https://doi.org/10.54941/ahfe1003562

Long LO (2011) Visual spatial abilities in uninhabited ground vehicle task performance during teleoperation and direct line of sight. Presence Teleoperators Virtual Environ 20:466–479. https://doi.org/10.1162/PRES_a_00066

Majstorovic D, Hoffmann S, Pfab F et al (2022) Survey on teleoperation concepts for automated vehicles. https://doi.org/10.48550/arXiv.2208.08876

Matthews G (ed) (2000) Human performance: cognition, stress, and individual differences. Psychology Press, Hove

Meshkati N (2003) Control rooms' design in industrial facilities. Hum Factors Ergon Manuf Serv Ind 13:269–277. https://doi.org/10.1002/hfm.10043

Monsell S (2003) Task switching. Trends Cogn Sci 7:134–140. https://doi.org/10.1016/S1364-6613(03)00028-7

Norman DA (1981) Categorization of action slips. Psychol Rev 88:1–15. https://doi.org/10.1037/0033-295X.88.1.1

On-Road Automated Driving (ORAD) committee (2021) Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles (SAE J 301-202104)

Pan D, Zhang Y, Li Z, Tian Z (2016) Association of individual characteristics with teleoperation performance. Aerosp Med Hum Perform 87:772–780. https://doi.org/10.3357/AMHP.4557.2016

Pan D, Zhang Y, Li Z, Tian Z (2021) Effects of cognitive characteristics and information format on teleoperation performance: a cognitive fit perspective. Int J Ind Ergon 84:103157. https://doi.org/10.1016/j.ergon.2021.103157

Pan D, Liu D, Tian Z, Zhang Y (2022) Performance influence mechanism of individuals' spatial ability in teleoperation. Aerosp Med Hum Perform 93:717–724. https://doi.org/10.3357/amhp.6060.2022

Pan J, Eden J, Oetomo D, Johal W (2024) Effects of shared control on cognitive load and trust in teleoperated trajectory tracking https://doi.org/10.48550/ARXIV.2402.02758

Qin K, Zhang Y, Zhang J (2022) A study on the influence of personality on the performance of teleoperation tasks in different situations. In: Harris D, Li W-C (eds) Engineering psychology and cognitive ergonomics. Springer, Cham, pp 212–224. https://doi.org/10.1007/978-3-031-06086-1_16

Rea DJ, Seo SH (2022) Still not solved: a call for renewed focus on user-centered teleoperation interfaces. Front Robot Ai 9:704225. https://doi.org/10.3389/frobt.2022.704225

Rohmert W, Raab S (1995) The stress-strain concept as an engineering approach serving the interdisciplinary work design. Int J Hum Factors Manuf 5:139–147. https://doi.org/10.1002/hfm.4530050203

Saffre F, Hildmann H, Karvonen H (2021) The design challenges of drone swarm control. In: Harris D, Li W-C (eds) Engineering psychology and cognitive ergonomics. Springer, Cham, pp 408–426. https://doi.org/10.1007/978-3-030-77932-0_32

Santamaria T, Nathan-Roberts D (2017) Personality measurement and design in human-robot interaction: a systematic and critical review. Proc Hum Factors Ergon Soc Annu Meet 61:853–857. https://doi.org/10.1177/1541931213601686

Savchenko K, Medema H, Boring R, Ulrich T (2018) Comparison of Mutual Awareness in Analog Vs. Digital Control Rooms. In: Boring, R. (eds) Advances in Human Error, Reliability, Resilience, and Performance. AHFE 2017. Advances in Intelligent Systems and Computing 589. Springer, Cham. https://doi.org/10.1007/978-3-319-60645-3_19

Schrank A, Kettwich C, Oehl M (2024a) Aiding automated shuttles with their driving tasks as an on-board operator: a case study on different automated driving systems in three living labs. Appl Sci 14:3336. https://doi.org/10.3390/app14083336

Schrank A, Walocha F, Brandenburg S, Oehl M (2024b) Human-centered design and evaluation of a workplace for the remote assistance of highly automated vehicles. Cogn Technol Work 26:183–206. https://doi.org/10.1007/s10111-024-00753-x

Sheridan TB (2016) Human–robot interaction: status and challenges. Hum Factors J Hum Factors Ergon Soc 58:525–532. https://doi.org/10.1177/0018720816644364

Song S, Cohen L (2014) Impact of conscious intent on chunking during motor learning. Learn Mem 21:449–451. https://doi.org/10.1101/lm.035824.114

Tang W, Tian Y, Tan L et al (2024) Human factors design and evaluation of China's space manipulator teleoperation system. Int J Human Comput Interact 40:1943–1959. https://doi.org/10.1080/10447318.2023.2250055

Tener F, Lanir J (2022) Driving from a distance: challenges and guidelines for autonomous vehicle teleoperation interfaces. In: CHI conference on human factors in computing systems. ACM, New Orleans, pp 1–13

Tener F, Lanir J (2023a) Investigating intervention road scenarios for teleoperation of autonomous vehicles. Multimed Tools Appl 83:61103–61119. https://doi.org/10.1007/s11042-023-17851-z

Tener F, Lanir J (2023b) Design of a high-level guidance user interface for teleoperation of autonomous vehicles. In: Adjunct proceedings of the 15th international conference on automotive user interfaces and interactive vehicular applications. ACM, Ingolstadt, pp 287–290. https://doi.org/10.1145/3581961.3609845

Tsung C-K, Chang F-S, Liu X-Y (2022) On the construction of an edge-based remote sensing framework: the applications on automated guided vehicles and drones. Electronics 11:1034. https://doi.org/10.3390/electronics11071034

Tulving E (1985) How many memory systems are there? Am Psychol 40:385–398. https://doi.org/10.1037/0003-066X.40.4.385

Warm JS, Parasuraman R, Matthews G (2008) Vigilance requires hard mental work and is stressful. Hum Factors J Hum Factors Ergon Soc 50:433–441. https://doi.org/10.1518/001872008X312152

Wickens CD (2015) Noticing events in the visual workplace: the SEEV and NSEEV models. In: Hoffman RR, Hancock PA, Scerbo MW, al (eds) The Cambridge handbook of applied perception research, 1st edn. Cambridge University Press, pp 749–768

Wickens CD, Carswell CM (1995) The proximity compatibility principle: its psychological foundation and relevance to display design. Hum Factors J Hum Factors Ergon Soc 37:473–494. https://doi.org/10.1518/001872095779049408

Wickens CD, Carswell CM (2021) Information processing. In: Salvendy G, Karwowski W (eds) Handbook of human factors and ergonomics, 1st edn. Wiley, pp 114–158

Wickens CD, Hollands JG, Banbury S, Parasuraman R (2013) Engineering psychology and human performance, 4th edn. Pearson, Boston

Wilson GF, Russell CA (2003) Real-time assessment of mental workload using psychophysiological measures and artificial neural networks. Hum Factors J Hum Factors Ergon Soc 45:635–644. https://doi.org/10.1518/hfes.45.4.635.27088

Witmer BG, Singer MJ (1998) Measuring presence in virtual environments: a presence questionnaire. Presence Teleoperators Virtual Environ 7:225–240. https://doi.org/10.1162/105474698565686

Wolf M-M, Taupitz R, Diermeyer F (2024) Should teleoperation be like driving in a car? Comparison of teleoperation HMIs. https://doi.org/10.48550/arXiv.2404.13697

Woods DD, Tittle J, Feil M, Roesler A (2004) Envisioning human–robot coordination in future operations. IEEE Trans Syst Man Cybern Part C Appl Rev 34:210–218. https://doi.org/10.1109/TSMCC.2004.826272

Working group “Research Needs in Teleoperation” (2025) Technical report of the working group “Research Needs in Teleoperation.”. Federal Highway and Transport Research Institute

Yekita H, Pati D, Hamilton DK (2024) Could spatial awareness affect situation awareness: a conceptual examination. Herd Health Environ Res Des J 17:270–286. https://doi.org/10.1177/19375867231192116

Yelchuri H, Singh DK, Gnani NK et al (2025) RoboTwin: a robotic teleoperation framework using digital twins

Zacher H (2017) Action regulation theory. In: Oxford research encyclopedia of psychology. University Press, Oxford