Human Factors Issues in Conditional Automated Driving Takeover Processes Based on Cognitive Mechanisms

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Abstract

Autonomous driving can largely alleviate modern traffic problems and improve driving comfort. Under conditional autonomous driving, drivers can perform non-driving-related tasks but need to take over the vehicle when the system cannot handle the situation. In this critical process, drivers need to perform attentional switching and acquire situational awareness to successfully take over. Existing research has shown that takeover requests, non-driving-related tasks, driving scenarios, and driver factors are important factors affecting the takeover process. Future research could investigate the effects of various factors on the takeover process from a cognitive mechanism perspective, and explore potential interactions among these factors during the takeover process.

Full Text

Preamble

Human Factors in the Take-Over Process of Conditional Automated Driving Based on Cognitive Mechanisms

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Abstract

Automated driving can substantially alleviate modern traffic problems and enhance driving comfort. During conditional automated driving, drivers may engage in non-driving-related tasks but must take over vehicle control when the system encounters situations it cannot handle. In this critical process, drivers need to shift their attention and acquire situation awareness to successfully execute the take-over. Existing research has shown that take-over requests, non-driving-related tasks, driving scenarios, and driver-related factors are all important influences on the take-over process. Future research should investigate how these factors affect the take-over process from a cognitive mechanism perspective and explore potential interactions among them.

Keywords: automated driving; take-over process; attention; situation awareness

1. Introduction

As a hot topic in transportation research in recent years, automated driving can significantly improve driving safety and mitigate modern traffic issues such as accidents, fuel emissions, and road congestion (Kyriakidis, Happee, & De Winter, 2015; Meng & Spence, 2015; Wan & Wu, 2018), while also enhancing driving comfort and reducing environmental impacts (Petermeijer, Doubek, & De Winter, 2017). The Society of Automotive Engineers (SAE) classifies automated driving into six levels: L0 (manual driving), L1 (driver assistance), L2 (partial automation), L3 (conditional automation), L4 (high automation), and L5 (full automation) (SAE International, 2016).

Before full automation is realized, conditional automated driving is expected to be the first level introduced to public roads within the next decade, heralding a major transformation in future transportation (Bazilinskyy, Petermeijer, Petrovych, Dodou, & De Winter, 2018; Begg, 2015). Conditional Automated Driving (CAD), or L3 automation, refers to a system that controls both lateral and longitudinal vehicle operations under specific driving conditions, freeing the driver from monitoring the road ahead. However, due to technological limitations, when the automated system fails or encounters traffic situations it cannot handle, drivers must assume manual control to ensure safety—a process known as "take-over" (SAE, 2014). On one hand, the automated system relieves drivers from most driving tasks, allowing them to engage in non-driving-related activities such as using mobile phones, making calls, or reading. On the other hand, when faced with hazardous situations, distracted drivers may lack sufficient situation awareness and fail to shift their attention back to the driving task within the relatively short time available, leading to take-over failure.

Therefore, as a critical link in the safe operation of conditional automated vehicles, the take-over process represents a key focus of human factors research in automated driving. When dangerous situations arise, the take-over request system can detect them in advance and provide situation-relevant information to the driver through appropriate interfaces. The distracted driver, engaged in a non-driving-related task, must then respond rapidly. In this process, the warning system, non-driving-related tasks, driving scenarios, and driver factors collectively influence the take-over process. This article analyzes these influencing factors from the perspective of cognitive mechanisms of driver attention and situation awareness, aiming to better understand the interactions among humans, machines, and the environment during the take-over process.

2. Attention and Situation Awareness Issues in the Take-Over Process

As the primary participant in the take-over process, the driver is responsible for responding promptly to system requests and serves as an important guarantee for the safe operation of conditional automated systems. Understanding the cognitive mechanisms underlying driver behavior during take-over is essential for exploring how various factors influence the process.

During manual driving, driver activities primarily involve three stages: information perception, decision-making, and action execution (Wang, 2001). The take-over activity in automated driving follows a similar pattern, as shown in Figure 1 [Figure 1: see original paper]. Using the take-over request as a dividing point, before the request occurs, the automated system controls the vehicle while the driver focuses most of their attention on non-driving-related tasks. After the request is issued, the driver must first shift attention to the driving task, then acquire situation awareness, make decisions, and perform driving operations until full control is established (Ito, Takata, & Oosawa, 2016).

Figure 1. The Take-Over Process (Source: Ito et al., 2016)

During automated driving, the driver' s attentional and situation awareness states differ from those in manual driving. In manual driving, drivers maintain most of their attention on the road ahead. Once freed from the driving task, however, drivers in automated vehicles tend to concentrate on non-driving-related tasks. When a take-over request is issued, they must rapidly switch attention between non-driving and driving tasks. Second, in manual driving, drivers typically keep their eyes on the road, enabling real-time situation awareness. Even when performing distracting tasks, they can perceive current danger levels and adjust their behavior to avoid accidents (Zhou, 2014). In automated driving, however, drivers' visual attention often deviates from the driving scene, and they invest more time and effort in non-driving-related tasks, resulting in varying degrees of situation awareness impairment that hinders successful take-over. Therefore, attention and situation awareness are crucial cognitive mechanisms in the take-over process. Clarifying how drivers shift and allocate attention and acquire situation awareness during this critical period helps us understand how system and environmental factors affect take-over performance by influencing these cognitive mechanisms.

2.1 The Take-Over Process and Attention

Wickens' multiple resource theory model is widely applied in dual-task and distraction research. The model comprises three dimensions: "stages," "codes," and "modalities," with the modality dimension describing attentional channels including auditory and visual modalities (Wickens, Holland, Banbury, & Parasuraman, 2014; Wickens, 2008). Processing sensory information from different channels utilizes distinct cognitive resources. Due to limited cognitive resources, when different tasks compete for the same resource channel, task performance may be impaired. For example, tasks that simultaneously occupy auditory or visual channels can cause attentional resource competition, whereas allocating tasks across different modalities yields better performance.

When the automated system controls the vehicle, most of the driver's attention is focused on non-driving tasks. Upon receiving a take-over request, the driver engaged in a non-driving-related task must quickly switch attention to the driving scene (Ito et al., 2016; Zeeb, Buchner, & Schrauf, 2015). At this critical moment, the driving task primarily occupies the visual channel, while non-driving-related tasks and take-over requests occupy various channels including auditory, visual, and tactile modalities. Consequently, the driver' s attentional resources are distributed across different sensory inputs to varying degrees. When two or more tasks simultaneously occupy the same channel, attentional resource competition may occur (Scott & Gray, 2008), affecting the take-over process. For instance, when both the take-over request and driving task occupy the visual channel, resource competition can impair take-over performance.

2.2 The Take-Over Process and Situation Awareness

Situation awareness is defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1995). Endsley (1995) divided situation awareness into three continuous levels: Level 1—perceiving information in the environment, Level 2—integrating perceived information into a coherent understanding, and Level 3—projecting the future implications of that understanding.

During automated driving take-over, drivers acquire situation awareness through these same three continuous levels. Establishing situation awareness is particularly crucial for the take-over process (Lu, Coster, & De Winter, 2017). However, because the automated system replaces most driving tasks, drivers' situation awareness is often impaired to varying degrees. Lower situation awareness can lead to: (1) failure to complete the take-over, resulting in traffic collisions; or (2) degraded take-over performance even when successful, manifested as longer take-over reaction times and poorer take-over quality metrics such as minimum time-to-collision (TTC) and lane deviation (Wan et al., 2018; Zeeb, Buchner, & Schrauf, 2016). Situation awareness impairment stems from two sources: first, from automation itself—the higher the automation level, the lower the driver' s involvement in the driving task, and consequently the lower the situation awareness (Endsley, 1995; Gugerty, 1997). Second, non-driving-related tasks consume cognitive resources that would otherwise be used for acquiring situation awareness (De Winter, Happee, Martens, & Stanton, 2014).

3. Take-Over Requests in the Take-Over Process

As an effective Advanced Driving Assistant System (ADAS), the warning system is responsible for providing timely information about dangerous situations and serves as an important pathway to help drivers shift attention and acquire situation awareness. The effectiveness of take-over requests is a key research focus, influenced by the request' s modality and content, as well as its lead time.

3.1 Modality and Content of Take-Over Requests

Take-over requests primarily utilize three human sensory channels: visual, auditory, and tactile. Research shows that visual, auditory, tactile, and multimodal take-over requests can all effectively provide situation-relevant information, capture driver attention, enhance situation awareness, and assist drivers in successfully taking over (Meng et al., 2015; Petermeijer, Bazilinskyy, Bengler, & De Winter, 2017; Politis, Brewster, & Pollick, 2015; Wan & Wu, 2017).

3.1.1 Visual Take-Over Requests During driving, 90% of information comes from the visual system (Summala, Lamble, & Laakso, 1998). The greatest advantage of visual warnings is their ability to provide large amounts of information quickly, helping drivers rapidly detect dangers in the surrounding environment (Wege, Will, & Victor, 2013). In automated driving, common visual warning methods present take-over request information on the central dashboard, such as current vehicle status and the location and distance of hazards (Bazilinskyy et al., 2018; Eriksson, Banks, & Stanton, 2017; Zeeb et al., 2016). When the request is issued, drivers must shift their gaze between the driving scene and the dashboard, increasing take-over reaction time. Head-up display (HUD) technology avoids this drawback by superimposing warning information directly onto the real-world scene, reducing gaze transition time and helping drivers quickly establish situation awareness (Langlois & Soualmi, 2016).

Lorenz, Kerschbaum, & Schumann (2014) found that presenting AR take-over request information in different colors on HUDs affected take-over quality. Additionally, people have different preferences for various HUD information presentation formats, with text displaying "Please take over" being more popular than warning lights on windshields (Bazilinskyy & De Winter, 2015). However, most take-over requests that occupy central visual field can cause visual load. Ambient displays can utilize peripheral vision to convey situation-relevant information, reducing attention time and load on central vision (Bazilinskyy et al., 2018). For example, using LED flashing light strips on the steering wheel for take-over requests can not only accelerate reaction times but also enhance situation awareness and support appropriate decision-making (Borojeni, Chuang, Heuten, & Boll, 2016). Furthermore, well-designed visual human-machine interfaces on various displays can improve information comprehensibility and effectiveness (Naujoks, Forster, Wiedemann, & Neukum, 2017). For instance, an icon of hands holding the steering wheel visually conveys that the vehicle is in a take-over pending state, while different icon colors and dynamic progress bars can indicate take-over urgency (Eriksson et al., 2017; Naujoks et al., 2017). Nevertheless, single-modality visual warnings have significant limitations. Driver attention to the interface may compete with the driving task for visual resources (Scott et al., 2008), impairing driving performance. Moreover, when non-driving-related tasks occupy the same visual channel, resource competition may cause drivers to ignore warning information (Bazilinskyy et al., 2018).

3.1.2 Auditory Take-Over Requests Unlike visual warnings, auditory warnings are omnidirectional and do not occupy visual resources, allowing drivers to quickly focus attention on dangerous objects or the road ahead. Consequently, they are widely used in driving warnings (Bazilinskyy et al., 2015; Forster, Naujoks, Neukum, & Huestegge, 2017). Speech, natural sounds, and auditory icons can all effectively convey driving warning information through the auditory channel. Common natural sounds such as "beep" or "click" tones can effectively alert drivers and improve take-over performance while also communicating different levels of situational urgency through variations in presentation frequency (Bazilinskyy et al., 2018). Bazilinskyy et al. (2015) compared user preferences for four different natural take-over sounds and found that two consecutive "beep" sounds were most preferred. Körber, Gold, Lechner, and Bengler (2016) also confirmed the effectiveness of this natural sound in take-over research. In contrast, speech can convey more information and is important for improving take-over quality (Politis et al., 2015). Generally, female voices are preferred over male voices (Bazilinskyy et al., 2015), and declarative sentences are considered more appropriate than interrogative sentences for conveying situational urgency (Bazilinskyy & De Winter, 2017). However, this preference is also influenced by voice tone and content, with male voices delivering direct commands like "immediately" perceived as more urgent, while female voices are more suitable for suggestive phrases containing words like "please" (Bazilinskyy et al., 2017). However, speech requests themselves can cause driving distraction due to language, cultural, and time cost constraints. As sound information that can convey specific event or object characteristics within a short time, auditory icons are often more easily recognizable than other sound signals and cause less driving distraction (Belz, Robinson, & Casali, 1999). Driving-related auditory icons are typically sounds associated with dangerous events such as collisions or tire skidding. These sounds are easier to understand and more effective than other auditory information at shortening driver reaction times and reducing collisions (Beattie, Baillie, & Halvey, 2015; Belz et al., 1999). Additionally, mixing sound information with different advantages may yield better warning effects. Forster et al. (2017) found that compared to presenting only "natural sounds," a mixed "natural sound + speech" auditory take-over request resulted in better take-over performance and higher subjective usefulness ratings. However, auditory warnings are not always effective. The auditory channel has limited capacity and can be interfered with by other environmental sounds. Furthermore, auditory warnings and non-driving-related tasks occupying the same channel may cause resource competition, leading to missed or incomplete information reception and affecting the take-over process.

3.1.3 Tactile Take-Over Requests Tactile warnings deliver signals directly to the skin, are less susceptible to external interference, and do not increase auditory or visual load (Prewett, Elliott, Walvoord, & Coovert, 2012). Although less common in take-over research, tactile take-over requests have proven effective at helping distracted drivers redirect visual attention forward (Petermeijer, De Winter, & Bengler, 2016), enhancing situation awareness (Telpaz, Rhindress, Zelman, & Tsimhoni, 2015), and improving take-over performance in emergency situations (Wan et al., 2017). In driving, vibrotactile stimulators are typically installed in the seat, steering wheel, seatbelt, or on the driver' s waist (Petermeijer et al., 2016; Petermeijer, Doubek et al., 2017; Scott et al., 2008; Wan et al., 2018). Maximizing tactile warning effectiveness requires careful design of vibration amplitude, frequency, timing, and location (Petermeijer et al., 2016). Petermeijer, Hornberger, Ganotis, De Winter, & Bengler (2017) found that increasing the distance between vibrators helped drivers better distinguish vibration location, while the number of simultaneously activated vibrators affected subjective experience—more simultaneous activations yielded higher satisfaction with vibration patterns. Additionally, the presentation sequence of vibration stimuli affects take-over performance. Wan et al. (2017) found that when the vibration sequence was "back-back-seat-seat," drivers' take-over reactions were faster than with other sequences. Directional vibration stimuli have also been shown to assist rapid driver response and provide spatial orientation (Meng et al., 2015). Petermeijer, Cieler, & De Winter (2017) further classified directional vibration information and found that drivers responded faster to static vibration patterns (vibration only on the left or right side of the seat) than to dynamic patterns (alternating left-right vibration). Despite the potential of tactile requests to support cognitive processing and response selection during take-over, single-modality tactile warnings have inevitable drawbacks. Perceived vibration intensity is limited by clothing thickness (Meng et al., 2015), and bumpy roads increase the likelihood of information being ignored. Moreover, while changing vibration frequency can convey different levels of situational urgency, excessive vibration can cause annoyance, and vibrations in close temporal proximity reduce information comprehensibility (Petermeijer et al., 2016).

3.1.4 Multimodal Take-Over Requests Given the limitations of single-channel requests, researchers have increasingly proposed multimodal take-over approaches. Multimodal take-over requests, which combine two or more sensory channels, have been shown to convey more information per unit time, demonstrate superior warning effectiveness compared to single-channel requests (Bazilinskyy et al., 2018; Politis et al., 2015), and are more preferred by users (Petermeijer, Bazilinskyy et al., 2017). From a cognitive resource perspective, information occupying the same channel as the driving task causes resource competition, while complementary advantages across different channels can further enhance take-over request effectiveness. Auditory warnings do not occupy visual resources, reducing competition with the visual demands of driving, while visual warnings can present sound information that is easily interfered with by the environment through a visual interface. Additionally, since common non-driving-related tasks occupy visual and auditory channels, utilizing the less-used tactile channel can effectively warn distracted drivers through vibration, while the auxiliary role of audio-visual channels can reduce the risk of tactile information being ignored. However, which multimodal combination is most effective and the applicable scenarios for multimodal requests remain unclear. For example, Petermeijer, Bazilinskyy et al. (2017) found that for lane-change take-over tasks, audio-tactile requests elicited faster driver responses than single tactile requests. Politis et al. (2015) found that three-channel combinations were more effective than single visual or auditory requests, particularly in emergency situations.

Both single-channel and multimodal take-over requests can help drivers shift attention and acquire situation awareness to some extent. Single-channel requests have certain limitations, while multimodal requests can leverage complementary advantages across channels but carry higher risks of increasing cognitive load. Moreover, automated driving take-over is a dynamic and complex process of human-machine-environment interaction. The effectiveness of different channel requests may vary with changes in the driving environment, and the optimal channel for take-over requests may differ depending on task difficulty. Furthermore, the effectiveness of each channel may also change with driver characteristics and the non-driving task being performed.

3.2 Lead Time of Take-Over Requests

In addition to modality, the timing of request issuance—known as lead time —is another important factor affecting take-over request effectiveness. Lead time is typically set based on Time-to-Collision (TTC), which refers to the time required for a vehicle to collide with a lead vehicle or obstacle given their current trajectories and speed differential (Kiefer, Flannagan, & Jerome, 2006). The lead time of a take-over request is the advance warning time before a potential collision.

Numerous studies have demonstrated that lead time significantly affects the take-over process in hazardous scenarios. Regarding take-over performance, different lead times influence both reaction time and quality. Mok et al. (2015) found that while most drivers could successfully take over with a 5-second lead time, performance was better with 8 seconds. Gold, Damböck, Lorenz, and Bengler (2013) found that compared to 7 seconds, a 5-second lead time resulted in shorter reaction times but poorer take-over quality. Wan et al. (2018) suggested that lead times exceeding 10 seconds are necessary for optimal take-over performance. From a cognitive mechanism perspective, longer lead times enable higher levels of situation awareness. Vlakveld, van Nes, de Bruin, Vissers, and van der Kroft (2018) found that drivers achieved higher situation awareness with a 6-second lead time than with 4 seconds. Samuel, Borowsky, Zilberstein, and Fisher (2016) compared lead times of 4, 6, 8, and 12 seconds and found that at least 8 seconds were required for drivers to achieve complete situation awareness.

These findings on lead time are inconsistent for several reasons. First, the take-over scenarios varied across studies. For example, Gold et al. (2013) used a highway collision scenario, Wan et al. (2018) employed six different hazard scenarios on highways (including collisions, sudden lead vehicle stops, and obstacles), while Vlakveld et al. (2018) used eight different hazard events in urban, rural, and highway settings. Differences in scenario complexity and urgency affect situation awareness acquisition and processing, resulting in varying required take-over times. Second, the non-driving-related tasks used were not standardized. Vlakveld et al. (2018) used everyday gaming tasks, while Gold et al. (2013) used a standardized visual search task (SuRT). Since non-driving tasks impose varying cognitive loads, higher loads require longer lead times to maintain equivalent take-over performance and situation awareness levels. Therefore, in automated driving human factors research, lead time settings must fully consider the effects of current take-over scenarios and non-driving-related tasks.

4. Take-Over Scenarios in the Take-Over Process

Unlike manual driving, where drivers maintain attention on the driving scene and vehicle status, drivers in automated vehicles focus on non-driving-related tasks, causing their situation awareness to continuously decline. When the system issues a take-over request, drivers begin perceiving the situation (Ito et al., 2016), and their level of understanding affects take-over performance.

Scenario complexity influences situation awareness acquisition (Radlmayr, Gold, Lorenz, Farid, & Bengler, 2014). Simple scenarios are easier for drivers to quickly understand and achieve complete situation awareness than complex ones. In conditional automated driving, take-over scenarios include both task-related situations and the broader driving context. Common task-related situations include sudden lead vehicle stops, road construction, obstacles, and disappearing lane markings (Petermeijer, Doubek et al., 2017; Wan et al., 2017), which require braking or lane-change responses. Petermeijer, Doubek et al. (2017) simulated six different types of take-over scenarios but found no performance differences, possibly because the long lead times used (all >10 seconds) gave drivers sufficient time to understand each scenario and respond appropriately. Additionally, traffic density—an indirect contextual factor typically measured as vehicles per unit distance—affects take-over performance. High traffic density prolongs reaction times and reduces take-over quality (Gold, Körber, Lechner, & Bengler, 2016; Radlmayr et al., 2014), likely because high-density scenes are more complex, requiring drivers to perceive and monitor more surrounding vehicles and incorporate them into driving decisions (Körber et al., 2016).

Radlmayr et al. (2014) also found that when the take-over task involved lane changing, the positions of surrounding vehicles were important factors affecting scenario complexity and urgency.

Most automated driving take-over studies investigate how other factors affect performance under one or several fixed take-over tasks, rarely finding differences across task types. This may be because automated driving will first be implemented on highways, where most research is conducted, and where event types are relatively uniform, so task type itself does not significantly affect the take-over process. Additionally, research on contextual factors beyond the immediate task has mostly focused on traffic density, without exploring other scene elements, primarily because driving scenes comprise various complex factors that are difficult to categorize systematically.

5. Non-Driving-Related Tasks in the Take-Over Process

As automation levels increase, drivers have more discretionary time and engage in non-driving-related tasks such as listening to music, making calls, playing games, or even sleeping with varying levels of engagement (Gold et al., 2016; Jamson, Merat, Carsten, & Lai, 2013). Most research shows that performing non-driving-related tasks during automated driving impairs driver performance, likely because these tasks consume attentional resources, impose varying cognitive loads (Bueno et al., 2016), and may compete with driving activities for resources, thereby affecting take-over time and quality. Additionally, non-driving tasks reduce situation awareness (De Winter et al., 2014), forcing drivers to rapidly acquire situation awareness when a take-over request is issued to ensure safe take-over.

Different types of non-driving-related tasks impair take-over performance to varying degrees, though findings are inconsistent. Gold, Berisha, and Bengler (2015) found that cognitive tasks impaired take-over performance less than visual and motor tasks, while Radlmayr et al. (2014) found similar impairment levels between cognitive and visual tasks. The workload of non-driving-related tasks may be the underlying mechanism for these differences. Zeeb et al. (2016) found that non-driving tasks with different visual-cognitive loads impaired take-over performance, but this effect appeared only in take-over quality rather than reaction time, possibly because take-over quality is more affected by visual-cognitive processing, while reaction time in their experiment depended more on reflexive action speed. Additionally, the attentional resources occupied by non-driving-related tasks may be important. Wan et al. (2018) found that monitoring the automated system resulted in shorter take-over reaction times than reading, typing, watching videos, or playing games. This may be because monitoring tasks occupy fewer attentional resources compared to other tasks that consume visual, auditory, and cognitive resources, requiring minimal attention shifting and thus enabling faster reactions.

However, non-driving-related tasks do not exclusively have negative effects.

Some automated driving studies found that simply monitoring the automated system produced more drowsiness than watching videos or reading tasks (Miller et al., 2015). Although this drowsiness did not impair take-over performance, Neubauer, Matthews, and Saxby (2012) found that performing non-driving-related tasks actually yielded better take-over performance than no task at all. This may be because engaging in non-driving activities creates an "involvement" effect that helps drivers maintain alertness during automated driving and promotes faster reactions (Miller et al., 2015). Additionally, research found that younger drivers performing certain non-driving tasks could switch attention back and forth, maintaining more flexible attention states that facilitated take-over responses (Clark, McLaughlin, Williams, & Feng, 2017).

Therefore, the impact of non-driving-related tasks on take-over performance remains inconclusive. On one hand, task types differ: standardized tasks like n-back allow good experimental control but have low ecological validity, while ecologically valid tasks like gaming or reading lack strict control and vary significantly between studies. On the other hand, the impact of non-driving-related tasks is also limited by driver capabilities, with different driver types affected to varying degrees and showing different response speeds and operational strategies. Furthermore, task characteristics such as workload level may be another important factor causing inconsistent results. There may exist a workload threshold below which non-driving-related tasks activate the driver for take-over, but above which they impair take-over performance.

6. Driver Factors in the Take-Over Process

Take-over is an interactive process between humans and both the environment and the system. As the responder in conditional automated driving take-over, the driver plays a critical role, making it important to investigate how driver characteristics affect the process.

Age and driving experience are important factors affecting take-over. With increasing age, drivers' information processing speed, task-switching ability, attention allocation, hazard perception, and reaction speed all decline (Körber et al., 2016). Regarding take-over performance, older drivers' average reaction times are at least 1.2 seconds longer than younger drivers (Körber et al., 2016), and their post-take-over driving speeds are lower (Clark et al., 2017). In subjective evaluations, older drivers report higher satisfaction with conditional automated systems than younger drivers (Gold, Körber, Hohenberger, Lechner, & Bengler, 2015), possibly because age-related declines in cognitive and behavioral responses increase the need for automated assistance. Additionally, driving experience affects the take-over process, with experienced drivers better able to predict hazardous situations requiring take-over and faster at acquiring situation awareness (Wright, Samuel, Borowsky, Zilberstein, & Fisher, 2016).

Furthermore, driver attitudes toward automated driving, such as trust, significantly affect take-over. Trust influences automated driving usage, but both overtrust and lack of trust are detrimental—overtrust leads to misuse of automated systems, while lack of trust hinders adoption and use (Choi & Ji, 2015; Parasuraman & Riley, 1997). Conversely, the take-over process also affects trust, as take-over experiences and effective requests can increase driver trust in conditional automated systems (Gold, Körber, et al., 2015; Körber, Prasch, & Bengler, 2018; Wintersberger, Von Sawitzky, Frison, & Riener, 2017).

Compared to other factors affecting take-over, driver characteristics have received relatively less research attention in conditional automated driving, possibly because the automated system assumes much of the safe driving responsibility, causing driver factors to be overlooked. Additionally, driver factors may be treated as individual differences and considered extraneous variables. However, research on drivers' physiological characteristics and attitudes confirms their impact on the take-over process, demonstrating that driver factors are an essential and non-negligible component throughout automated driving, especially during take-over.

7. Summary and Outlook

This article discusses factors affecting take-over performance in conditional automated driving from the perspective of driver cognitive mechanisms, including take-over requests, non-driving-related tasks, take-over scenarios, and driver characteristics, and analyzes the influences of these factors and their interactions.

7.1 Cognitive Mechanisms of How Different Factors Affect the Take-Over Process

Attention and situation awareness are two important cognitive mechanisms affecting take-over. Existing research on influencing factors has primarily focused on driving behavioral performance, with few studies exploring the cognitive mechanisms behind these effects. However, cognitive mechanisms can explain the reasons underlying behavior, making it urgent to further investigate the internal cognitive mechanisms through which factors affect take-over. (1) Research has shown that effective take-over requests can facilitate attention shifting and rapid situation awareness acquisition, but this conclusion is mainly inferred from good take-over performance (Langlois & Soualmi, 2016). From a cognitive principle perspective, investigating the time required for drivers to shift attention and acquire situation awareness can provide a basis for setting lead times, and exploring how different modalities affect driver attention and situation awareness can inform human-centered take-over request interface design. (2) Non-driving-related tasks occupy driver attentional resources, but whether this occupation facilitates (Gold et al., 2016) or inhibits (Miller et al., 2015) the take-over process remains inconclusive. Clarifying attentional resource allocation before and after take-over requests can help identify the internal reasons for differential effects of non-driving-related tasks. (3) Scenario complexity is an important factor affecting take-over performance. Radlmayr et al. (2014) and Gold et al. (2016) have investigated how traffic density—a dimension of complexity—affects take-over performance, but whether traffic density and other scenario factors affect driver attention and situation awareness acquisition remains to be verified. (4) Drivers play a critical role throughout the take-over process. Körber et al. (2016) and Wright et al. (2016) have confirmed that driver factors such as age and experience affect take-over performance. Investigating how individual cognitive abilities like attention allocation and reaction speed affect take-over performance can better explain individual differences in the take-over process.

7.2 Interactions Among Factors in the Take-Over Process

Take-over requests, non-driving-related tasks, take-over scenarios, and driver characteristics collectively influence the automated driving take-over process, with each factor' s effect often moderated by others. Therefore, interactions in the take-over process warrant in-depth investigation. As driving warnings, take-over requests can timely alert distracted drivers. Although numerous studies have proven that take-over request design can improve performance, most previous research has investigated request modality and lead time effectiveness based on single take-over scenarios and specific non-driving-related tasks. For example, Petermeijer, Bazilinskyy et al. (2017) concluded request effectiveness under lane-change tasks and visual search non-driving tasks, but these limited conditions restrict generalizability. Therefore, the applicability of request types across different driving scenarios requires further exploration. Additionally, non-driving-related tasks and take-over requests may interactively affect the process. When both occupy the same channel, attentional resource competition occurs. Future research could investigate how these two factors affect take-over performance and physiological indicators when occupying the same channel and provide solutions for potential resource competition.

Moreover, existing research has mostly considered take-over request effectiveness only from a safety perspective. Beyond safety, drivers' subjective attitudes such as comfort, satisfaction, and acceptance should also be important considerations in request design, and these subjective attitudes may be interactively influenced by other factors such as scenario complexity. Take-over is a process of human-machine and human-environment interaction, offering extensive exploration space for interaction effects.

7.3 Effects of Individual Driver Differences on the Take-Over Process

Drivers are the main participants in conditional automated driving take-over, yet empirical research on how individual differences affect the process is limited. A few studies have preliminarily explored driver factors such as age and experience (Körber et al., 2016; Wright et al., 2016), but other potential driver factors require further verification. For example, driver factors from manual driving may also affect automated driving take-over—Wiedemann et al. (2018) found that higher blood alcohol concentration impaired take-over performance. Additionally, although driver trust is closely related to automated driving technology, balancing insufficient and excessive trust to facilitate conditional automated driving operation remains an urgent issue. Previous trust research has mostly used questionnaires (Kyriakidis et al., 2015), while some researchers like Wintersberger et al. (2017) have used simulated driving to investigate factors causing trust deficiencies. Future research could also examine trust as a driver factor to explore how different trust levels affect the take-over process.

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