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Takeover requests for automated driving: The effects of signal direction, lead time, and modality on takeover performance

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ABSTRACT

Vehicle-to-driver takeover will still be needed in semi-autonomous vehicles. Due to the complexity of the takeover process, it is important to develop interfaces to support good takeover performance. Multimodal displays have been proposed as a candidate for the design of takeover requests (TORs), but many questions remain unanswered regarding the effectiveness of this approach. This study investigated the effects of takeover signal direction (ipsilateral vs. contralateral), lead time (4 vs. 7 s), and modality (uni-, bi-, and trimodal combinations of visual, auditory, and tactile signals) on automated vehicle takeover performance. Twenty-four participants rode in a simulated SAE Level 3 vehicle and performed a series of takeover tasks when presented with a TOR. Overall, single and multimodal signals with a tactile component were correlated with the faster takeover and information processing times, and were perceived as most useful. Ipsilateral signals showed a marginally significant benefit to takeover times compared to contralateral signals. Finally, a shorter lead time was associated with faster takeover times, but also poorer takeover quality. Findings from this study can inform the design of in-vehicle information and warning systems for next-generation transportation.

1. Introduction

Vehicle automation is expected to appear in a variety of forms for the next several decades (e.g., Hedlund, 2016; Kyriakidis et al., 2019), ranging from Levels 0 – 2, where drivers must monitor the driving environment at all times, to Levels 4 – 5, where most of the driving is controlled by automation (SAE International, 2018). For intermediate levels of automation, such as Level 3, one of the most safety–critical issues relates to the need for takeover, whereby drivers resume control of the vehicle due to unexpected situations, such as missing lane boundary lines or the presence of a construction zone (McDonald et al., 2019).

This transitional process usually involves two phases that are comprised of multiple steps (as shown in Fig. 1): 1) a signal response phase: the vehicle issues a takeover request (TOR) and the driver must quickly perceive the TOR and process information in the driving environment, while at the same time preparing for the takeover by moving hands to the steering wheel and feet to the pedal; 2) a post-takeover phase: once the transfer of control is complete, drivers should select the most appropriate course of action and then execute that decision by manually maneuvering the controls of the vehicle (Huang & Pitts, 2022; McDonald et al., 2019; Petermeijer et al., 2016; Zeeb et al., 2015). Here, the TOR is presented only a few seconds prior to the event requiring the takeover. In other words, if the driver does not take over within the length of the lead time or time-to-collision (TTC), which is defined as the time between the presentation of the TOR and the critical event (McDonald et al., 2019), a collision may occur. Therefore, it will be critical to develop effective human–machine interfaces (HMIs) that support drivers in successfully transitioning from automated to manual control of vehicles (e.g., Carsten & Martens, 2019; National Science and Technology Council and the United States Department of Transportation, 2020).

1.1. Types and forms of takeover requests (TORs)

Currently, TORs are presented using the visual (V), auditory (A), and/or tactile (T) sensory modalities. Often, visual signals are presented either on the vehicle's windshield using a heads-up display (HUD) or an augmented reality (AR) interface (e.g., Lindemann et al., 2019), or on the in-vehicle display (center) console (e.g., Petermeijer et al., 2017a,b), represented as abstract icons or messages in text form. Auditory TORs are played through in-vehicle speakers as abstract sounds (e.g., a beep)

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and/or verbal messages (e.g., Petermeijer et al., 2017a). Finally, tactile alerts are generally presented using vibrotactile/haptic interfaces embedded into drivers' seat (e.g., Yoon et al., 2019). In many cases, a single modality TOR may not be effective since drivers may engage in non-driving-related tasks (NDRTs), which may use the same perceptual resource that is needed to perceive the TOR (Naujoks et al., 2018; Roche et al., 2019; Yoon et al., 2019). For example, drivers may not notice an auditory TOR if they are listening to music or holding a phone conversation. Thus, researchers have investigated the benefits of multimodal TORs, which are combinations of visual, auditory, and/or tactile signals.

TORs can be used as alerts to inform drivers of the need to take over or as aids to guide them on how to takeover. For alerting purposes, studies have found that takeover performance is often better with multimodal signals than unimodal signals (e.g., Huang & Pitts, 2022; Huang et al., 2019; Petermeijer et al., 2017a,b; Politis et al., 2017; Roche et al., 2019; Salminen et al., 2019; Yoon et al., 2019). For example, within the signal response phase, Yoon et al. (2019) compared all seven types of signals (single V, A, and T, combinations of two: VA, VT, and AT, and combination of all three: VAT), and found that multimodal signals (i.e., VT, VT, AT, and VAT) were associated with shorter takeover times compared to single modal stimuli (i.e., V, A, and T). Similarly, Huang and Pitts (2022) found that multimodal signals that contained a tactile cue had faster response times for both younger and older drivers. In contrast, fewer studies have measured the effects of signaling modality on takeover driving performance within the post-takeover phase. Politis et al. (2017) compared the impacts of all seven signal types (i.e., V, A, T, VA, VT, AT, and VAT) on lateral deviation when controlling the vehicle in the same lane after a takeover, and found the single visual cue to have the greatest lateral deviation compared to all other six signals. Roche et al. (2019) measured the influence of an auditory speech-based alert (A) and a bi-modal text-audio (VA) combination on both standard deviation of lateral position (SDLP) as well as on maximum change of steering wheel angle (∂max) when performing a lane change takeover task (i.e., moving into the left lane after a TOR). The single speech-based signal was associated with better takeover performance (i.e., smaller SDLP and ∂max) compared to the text-audio pair. Currently, it is difficult to synthesize the literature on the effects of multimodal signals on the post-takeover performance, given that the few initial studies employed different signal types, instructions to drivers (in response to TORs), and post-takeover performance metrics (e.g., Politis et al., 2017; Roche et al., 2019). One unanswered question is whether the benefits of multimodal TORs (compared to unimodal TORs) persist throughout the post-takeover phase when complex maneuvers are required, such as lane changes to avoid road obstacles.

1.2. Directional TORs

In terms of using TORs to instruct drivers on how to take over, two commonly used HMIs have been employed: 1) Ipsilateral display: the interface presents a signal that is spatially compatible with the required action, based on the stimulus–response compatibility (SRC) (Proctor & Vu, 2006); and 2) contralateral display: the signal is incompatible with the required action (reversed SRC) (e.g., Chen et al., 2020; Cohen-Lazry et al., 2019; Petermeijer et al., 2017a,b). For example, an ipsilateral signal shown on the left side of the vehicle's windshield instructs the driver to move into the left lane to avoid a possible collision with an adjacent vehicle in the right lane, while a contralateral signal shown on the left side informs the driver of a potential obstacle in the left lane, and thus the driver should instead steer away from the direction of the signal and move into the right lane.

The effectiveness of ipsi- and contralateral approaches have been explored in semi-autonomous driving (e.g., Chen et al., 2020; Cohen-Lazry et al., 2019; Petermeijer et al., 2017a,b). These studies often compare time-related metrics, such as response times to TORs between the two directional signals without measuring actual driving performance, such as maximum lateral acceleration. Cohen-Lazry et al. (2019) reported that drivers responded faster to ipsilateral TORs, while Chen et al. (2020) found contralateral signals to be associated with shorter response times. However, no differences between these signal directions were found in Petermeijer et al. (2017a,b), where drivers could choose which action to make based on their own intuitive interpretation of the signals. Two possible factors may explain these conflicting findings, namely the warning lead time/TTC and signaling modality.

For warning lead time, Chen et al. (2020) evaluated five discrete lead times between 2 and 4 s, but did not find significant differences in response times between ipsilateral and contralateral signals. The lead times used in this study are considered to be short, based on a review that summarized findings from a series of takeover studies (Eriksson & Stanton, 2017) and classified times shorter than 4 s as short, whereas 7 s (or longer) were labeled as relatively longer takeover time budgets. With a longer lead time, the effects of the two directional signals on response times may be different. For example, Petermeijer et al. (2017a,b) used 7 s and did not find significant differences between the signal types, while Cohen-Lazry et al. (2019) employed a 4-second lead time and reported that response times to ipsilateral (compared to contralateral) signals were shorter. A similar reversed effect of lead time was found in manual driving. Specifically, one study showed that drivers who were given a longer time allotment to make responses to auditory alerts, used to inform them about pedestrians walking across the road, responded faster to contralateral signals, but with a shorter time budget, they responded faster to ipsilateral signals (Straughn et al., 2009). The authors propose that with longer times, people had more time to evaluate the driving situation and make timely decisions. However, it is unclear whether longer vs. shorter lead times have this reversed effect on responding to directional signals during automated driving.

Secondly, signal modality can also impact drivers' responses to the two directional signals, as they showed different effects on time-related metrics. For example, Cohen-Lazry et al. (2019) and Chen et al. (2020) employed single tactile and auditory signals, respectively, with a relatively short takeover lead time, and showed two opposite relationships between ipsi- and contralateral signals. Ipsilateral signals were associated with shorter reaction times in Cohen-Lazry et al. (2019), but with longer reaction times in Chen et al. (2020), compared to contralateral signal. Also, Petermeijer et al. (2017a,b) compared V, A, and VA signals, but the interaction between signal type and direction was not reported. In order to resolve these contradicting findings, additional research is needed to more comprehensively examine the effects of signal modality/type on the responses to the two directional signals.

1.3. The current study

This study aimed to examine the effects of signal directions, lead

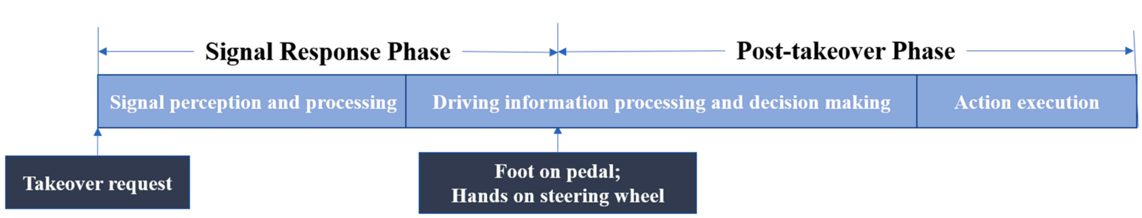

Fig. 1. The takeover model (Huang and Pitts (2022), adapted from Petermeijer et al. (2016) and Zeeb et al. (2015)).

time, and signal modality on takeover performance. Particularly, participants rode in an SAE Level 3 vehicle (i.e., a vehicle that automatically controls most vehicle dynamics, including speed and lane keeping control, except under difficult conditions when human intervention is needed) using a driving simulator and took over control of the vehicle in response to TORs that varied in terms of direction (ipsilateral and contralateral), lead time (4 and 7 s), and modality (uni-, bi-, and tri-modal combinations of visual, auditory, and tactile signals). Performance in both the signal response and post-takeover phases were measured. Our expectation was that with a shorter lead time, takeover performance would be better with ipsilateral compared to contralateral signals, but the benefits of ipsilateral signals would dissipate as the lead time increased. We also expected that the benefits of multimodal signals would be observed in the post-takeover phase and would be associated with better vehicle takeover quality. Research findings can inform the design of next-generation in-vehicle HMI that facilitate communications between drivers and vehicles.

2. Methods

2.1. Participants

Twenty-four volunteers, ranging between the ages of 20 – 29 years (mean age = 24.0, standard deviation (SD) = 3.0), i.e., sixteen males (mean age = 23.6, SD = 2.9) and eight females (mean age = 24.7, SD = 3.2), participated in this study. The average number of years of driving experience across participants was 4.9 years (SD = 3.2). All participants were students from Purdue University, West Lafayette, IN. Eligibility requirements included: 1) possession of a valid driver's license for at least one year, 2) regular driving at least once per week, 3) normal/correct-to-normal vision, and 4) no impairments to the senses of hearing and touch. Participants were compensated at a rate of $30 per hour. The study received approval from the Purdue University Institutional Review Board (IRB protocol #: 1802020214).

2.2. Apparatus/stimuli

The experiment was conducted in a fixed-base driving simulator – miniSim – developed by National Advanced Driving Simulator (NADS). This system consists of three 42-inch monitors (which display the main driving scene; resolution 1920 × 1080) and one 18.5-inch monitor (which serves as the vehicle dashboard display). Additional system accessories include driving foot pedals, a steering wheel, a control panel, and a driver seat (see Fig. 2). Driving data was collected at 60 Hz.

The visual signal (V) was a 200 × 200 pixel yellow circle presented either on the left or right lane of the highway (e.g., visual signals on the left lane required drivers to move into the left lane for ipsilateral signals or the right lane for contralateral signals). The auditory signal (A) was a 400 Hz beep presented via a headset, with an intensity range from 0 to 100 dB. The tactile signal (T) was presented using four C-2 tactors (by Engineering Acoustics, Inc.) attached to a belt and fastened around participants' upper waist. In particular, two tactors were placed on each side of the participant's lower back area (Fig. 2). The intensity range of tactile signals was 30 – 48 dB. A crossmodal matching task was performed wherein each participant adjusted the intensities of the auditory and tactile signals to match that of a reference visual cue (Pitts et al., 2016). All visual, auditory, and tactile signals lasted for one second.

2.3. Driving scenario

Participants rode in a simulated SAE Level 3 automated vehicle, which automatically controlled lane position and speed. The automated vehicle traveled in the middle lane of a three-lane highway at a constant speed of 60 mph (e.g., He et al., 2021; Huang & Pitts, 2022). A leading vehicle was continuously present either 4 or 7 s ahead of the subject vehicle (4 and 7 s represent short and long lead times, respectively; see summary in Eriksson & Stanton, 2017). Also, two fleets of vehicles, also traveling at 60 mph in both left and right adjacent lanes, trailed the subject vehicle at a constant following distance of 176 feet, see Fig. 3 (a). Occasionally, during the drive, a construction zone would appear in the center lane, which precipitated a sudden stop of the lead vehicle. When this happened, the subject vehicle detected the obstacle (road construction) 352 or 616 feet ahead (corresponding to a 4- or 7-second lead time, respectively) (Eriksson & Stanton, 2017), and initiated a takeover request (TOR) using one of the seven signal types. Simultaneously, the trailing distances of the two fleets of adjacent vehicles (with respect to the subject vehicle) randomly changed from 176 feet to either 88 or 264 feet away (correspondingly to 1- or 3-second headway, respectively; see Fig. 3 (b) for an example). This was done to increase the complexity of driving task and environment. Here, in addition to avoiding the obstacle ahead, drivers also needed to avoid possible rear-end collisions with trailing vehicles. After receiving a TOR, participants were told to move into the lane with the most available space (in this case, the 264-feet distance). To do this, they needed to first deactivate the automation by stepping on the brake pedal, and then position their hands on the steering wheel and their foot on the accelerator pedal to maintain the speed. Directional TORs were used to guide drivers to the correct adjacent lane. After processing the TOR and information in the driving environment, participants needed to change lanes and manually control the vehicle at 60 mph, just as they would in real-life driving until they passed the construction zone. Once they were clear of this zone, they needed to move back into their original lane and reactivate the

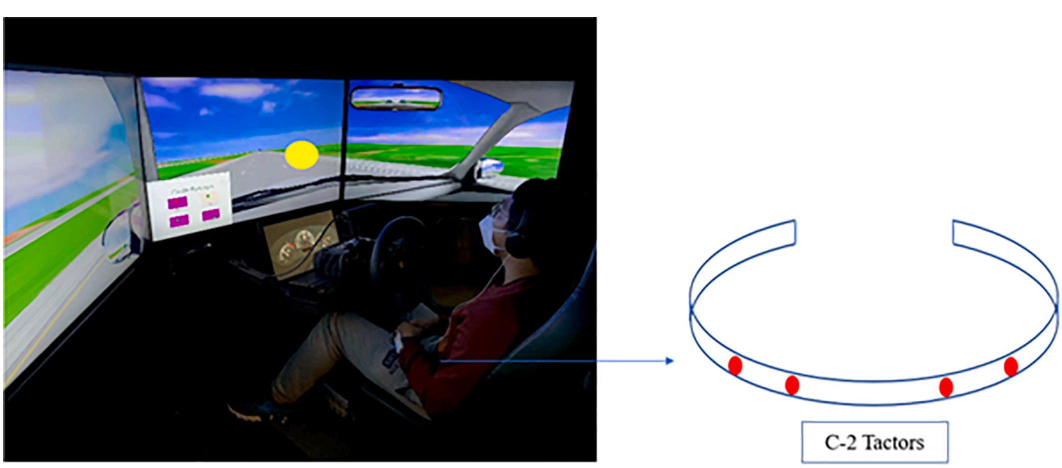

Fig. 2. Experiment setup and apparatus/stimulus.

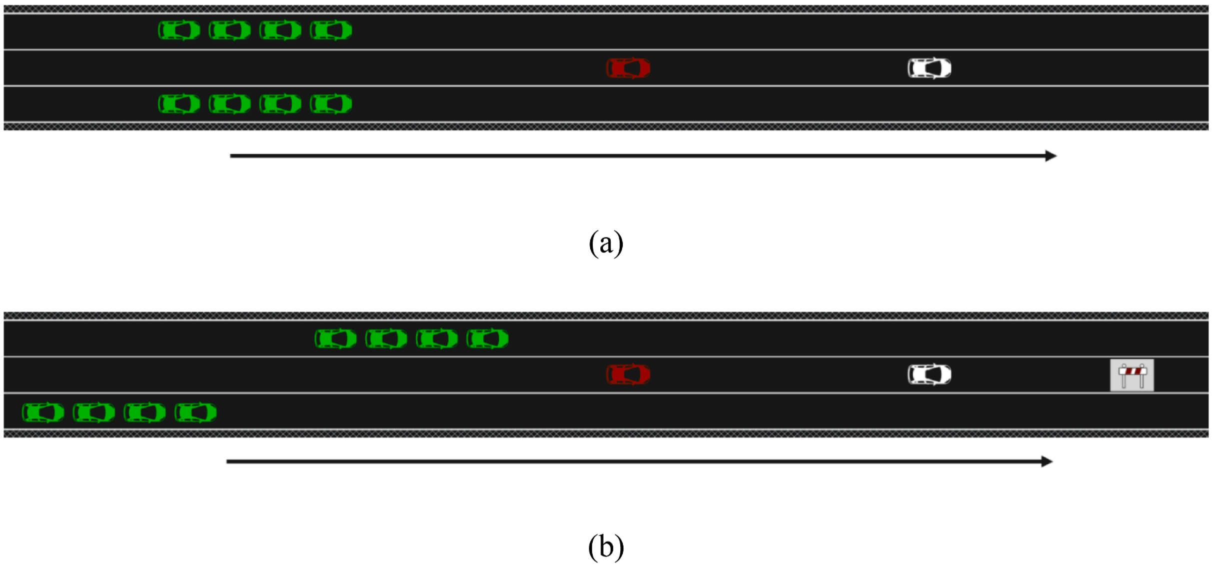

Fig. 3. Example bird's eye-view of the driving scenario: (a) absence of a takeover event: the subject vehicle (red) is following a leading vehicle (white), which is being followed by two fleets of vehicles (green) in both left and right adjacent lanes with equal distances; (b) during a takeover event: the subject vehicle (red) was expected to move into the right adjacent lane to avoid a collision with the leading vehicle (white), which was hindered by a construction zone (grey and red sign) in front, as well as with the approaching vehicles in the left lane (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

automation by pressing a button on the steering wheel.

2.4. Procedure

Upon arrival, participants first signed the study's consent form and completed a demographic data form. Then, each participant performed the crossmodal matching task and a 10-minute training session where they practiced takeover procedures and maneuvering the vehicle with all signal types and lead times, which was the same as those needed in the actual experiment. For the experiment, similar to Petermeijer et al. (2017a,b), each participant completed a total of four driving blocks, with two blocks using ipsilateral signals (i.e., ipsilateral condition) and two blocks employing contralateral signals (i.e., contralateral condition). With respect to Fig. 3 (b), where the right lane had the most available space, in the ipsilateral condition, the visual signal was presented on the right side of drivers' screen (in the right lane), the auditory signal was presented only in the right side of the headset, and the tactile signal was presented as vibrations only of the two tactors on the right side, - all of which indicated that the driver should move to the right lane after the TOR. In contrast, in the contralateral condition, all visual, auditory, and tactile signals were instead presented on the left side. For bi- and trimodal combinations, signals were presented concurrently. In each condition, 14 takeover requests with two lead times (i.e., 4 and 7 s) were presented, with each of the seven signal types randomly presented once in each block. The average interval between each takeover request was 2 min (Li et al., 2019; Petermeijer et al., 2017a,b). To prevent potential order effects, the two ipsi- and contralateral conditions and the two lead times were counterbalanced. For example, if a participant completed the ipsilateral condition first and the contralateral condition second, then the next participant would begin with the contralateral condition followed by the ipsilateral condition. For lead time, if a 4-second lead time was used for the first VAT signal presentation in the first half of the 14 takeover requests, then the 7-second lead time would be employed for the VAT signal in the second half of the 14 takeover requests. Additionally, 5-minute breaks were given to avoid task fatigue caused by the experiment.

To control drivers' attention allocation and prevent them from preparing for a TOR in advance, participants were required to interact with a game - "Spot the Difference," located in the (right or left, counterbalanced) corner of the main display. This task was used to represent engagement in non-driving-related tasks during naturalistic automated driving. As shown in Fig. 4, the game consisted of four separate items, and participants needed to identify the one that was different from the other three based on the cue (i.e., color, location, shape, or spelling of words) presented at the top of the game interface. For example, in Fig. 4 (b), the cue indicates that a "word" is different. Participants should identify the box containing the word "Late," which is different from the other boxes labeled "Mate" by simply telling the experimenter the location of the box. The experimenter selected the answer provided by participants. This approach aimed to minimize participants' physical demands during the driving session. Once the selection was made, a new trial would begin. The game was automatically paused during a takeover and then automatically resumed once participants reactivated the automation.

During each block, drivers were required to keep their feet on the base of the simulator and hands in their laps, and continuously interact with and focus on the game task until the onset of a TOR. After the four blocks, participants engaged in a 10-minute debriefing session where they completed a post-experiment questionnaire about their preferences of TOR signal types and directions. The experiments lasted approximately 75 min.

2.5. Dependent measures

Post-takeover driving performance metrics included takeover time, information processing time, and maximum resulting acceleration. Also, perceived usefulness and satisfaction of each type of signal as well as preference for signal direction were assessed.

Takeover time: Takeover time (in seconds) measures the time between the presentation of a TOR and the first conscious input to the vehicle (McDonald et al., 2019). Here, conscious input is defined by a 2-degree change of the steering wheel or 10% change of gas pedal input. This particular measure is used as an indicator of how quickly drivers prepare to control the vehicle.

Information processing time: Information processing time (in seconds) measures the time between the onset of a TOR and the initiation of a lane change (absolute deviation from the lane center larger than 6 feet, Petermeijer et al., 2017a,b). It is used to determine how quickly drivers

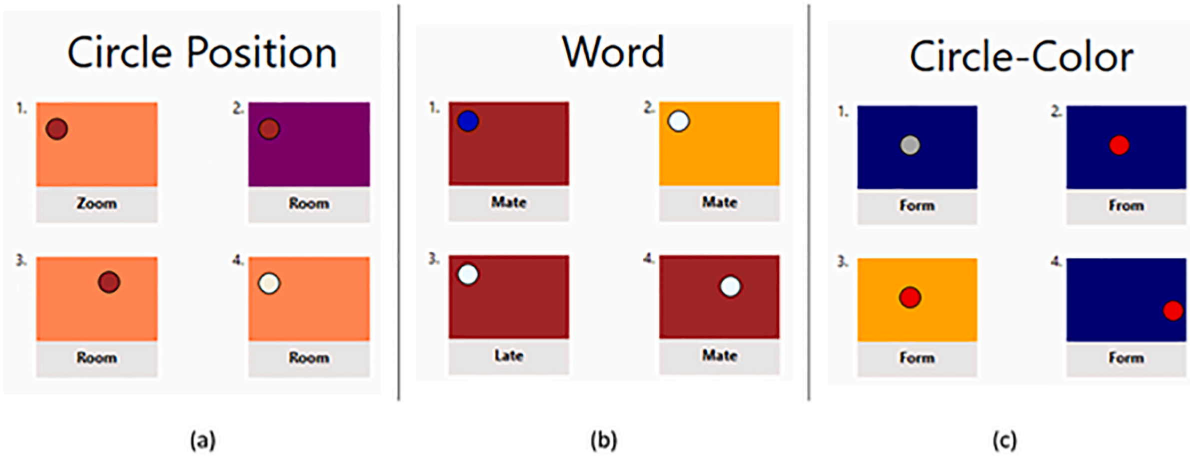

Fig. 4. Three example trials of the Spot the Difference game (circle position, the spelling of words, and circle color, respectively).

perceive and process takeover requests, and make appropriate decisions to avoid possible collisions.

Maximum resulting acceleration: Maximum resulting acceleration (in m/s^2) is calculated based on longitudinal and lateral accelerations during the post-takeover phase (see the equation below). This particular metric was chosen because it encompasses a broader set of longitudinal and lateral aspects of vehicle handling, such as maximum longitudinal/lateral accelerations, steering wheel angle and velocity, and standard deviation of vehicle speed. In general, it serves as an indicator of takeover quality and comfort (e.g., Hergeth et al., 2017; Li et al., 2019), such that a smaller value represents better takeover quality.

$$\text{Max resulting acceleration} = \sqrt{\text{max longitudinal acceleration}^2 + \text{max lateral acceleration}^2} \quad (1)$$

Subjective measures: To examine the potential influence of drivers' perceptions of the TOR signals on takeover performance, a qualitative approach was employed that assessed subjective attitudes towards the signal types. Particularly, perceived usefulness and satisfaction of each signal type was measured using a 9-item technology acceptance questionnaire, where participants rated each item using a 5-point Likert scale that ranges from −2 to 2 (Petermeijer et al., 2017a; Petermeijer et al., 2017b; Van Der Laan et al., 1997); see Table 2 in the Results section for a summary of the scores for each signal type. The overall usefulness and satisfaction scores were computed based on the scores of the nine items. The preference of signal direction was assessed using a question in the post-experiment questionnaire: “What type of directional signal do you prefer?” The answer was either “ipsilateral” or “contralateral.” The definitions of the two terms were provided.

2.6. Data analysis

A 2 (direction: ipsilateral and contralateral) × 2 (lead time: 4 and 7 s) × 7 (signal type; V, A, T, VA, VT, AT, and VAT) full factorial design was employed in this study. Performance variables were analyzed using a three-way repeated-measures analysis of variance (ANOVA), where signal direction, lead time, and signal type were within-subject factors. For violations of sphericity tests, the degrees of freedom were corrected using Greenhouse–Geisser estimates. Bonferroni corrections were applied for multiple comparisons. For all statistical tests, results were considered significant at $p < 0.05$. Partial eta squared (η_p^2) was used as a measure of effect size.

3. Results

3.1. Takeover time

There was a significant main effect of lead time ($F(1, 23) = 5.068$, $p = .034, \eta_p^2 = .181$) and signal type ($F(6, 138) = 24.838, p < .001, \eta_p^2 = .519$) on takeover times. For lead time, takeover times for the 4-second lead time (M = 1.749 s, standard error of mean (SEM) = 0.057) were shorter compared to the 7-second lead time (M = 1.789 s, SEM = 0.063; $p = 0.034$). For signal type (Fig. 5), signals that included a tactile cue, i.e., T (M = 1.714 s, SEM = 0.069), VT (M = 1.625 s, SEM = 0.068), AT (M = 1.707 s, SEM = 0.067), and VAT (M = 1.632 s, SEM = 0.063), had shorter takeover times compared to those without a tactile signal, i.e., V (M = 1.899 s, SEM = 0.071), A (M = 1.995 s, SEM = 0.061), and VA (M = 1.810 s, SEM = 0.056). Also, takeover times were marginally affected by signal direction ($F(1, 23) = 3.200, p = .087, \eta_p^2 = .122$). Specifically, takeover times for ipsilateral signals (mean (M) = 1.746 s, standard error of mean (SEM) = 0.058) were marginally shorter ($p = 0.087$) compared to contralateral signals (M = 1.791 s, SEM = 0.064).

Fig. 6 (a) shows the average takeover trajectories for each of the seven signal types, lasting for 20 s from the presentation of each takeover request. This 20-second time window was determined by the time needed to complete each takeover trial. The trajectories indicate that after receiving a TOR that included a tactile cue, drivers both initiated the lane change and centered themselves in the adjacent lanes faster than with TORs that did not contain a tactile signal.

There was also a significant direction × signal type interaction on takeover times ($F(3.5, 80.872) = 2.776, p = .038, \eta_p^2 = .108$). As shown in Fig. 5, a difference between the two takeover directions was present only for the V and AT signal types. For these two signal types, takeover times were faster with ipsilateral signals (for V: M = 1.804 s, SEM = 0.062; for AT: M = 1.658 s, SEM = 0.068) compared to contralateral signals (for V: M = 1.993 s, SEM = 0.093; for AT: M = 1.756 s, SEM = 0.072) ($p = 0.010$ and 0.024).

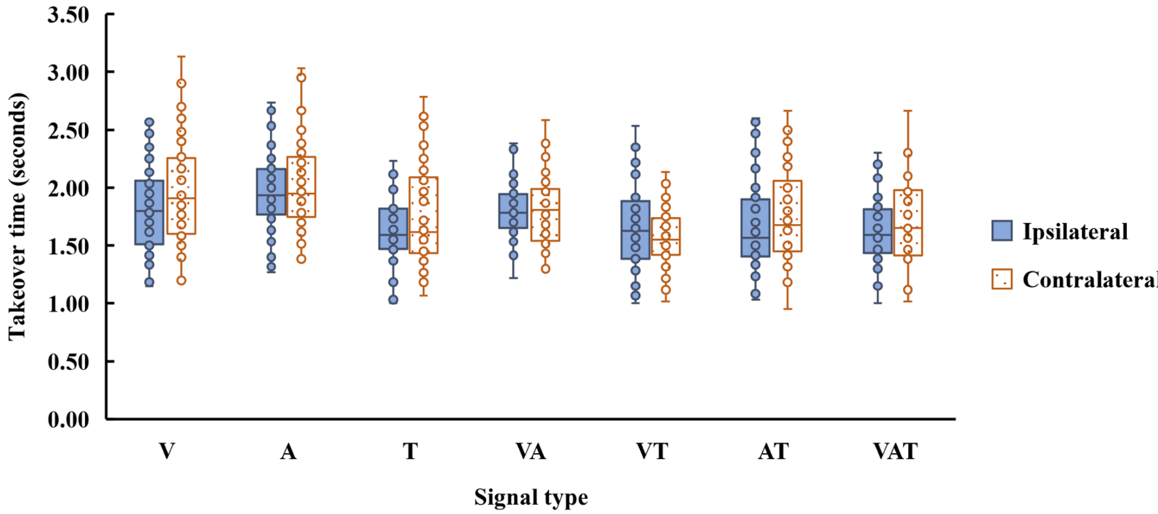

Fig. 5. Takeover time as a function of signal direction and type.

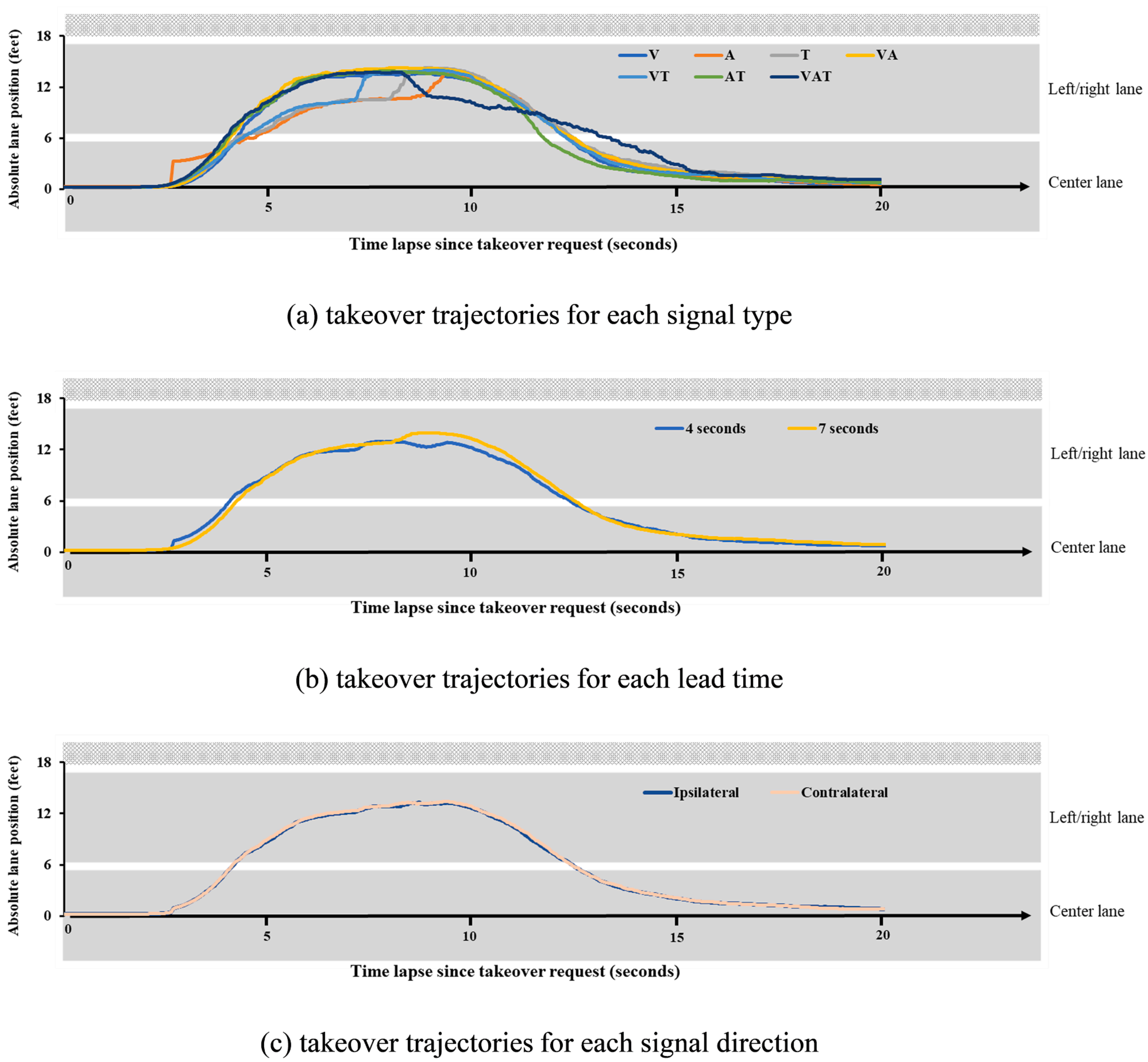

Fig. 6. Takeover trajectories 20 s within takeover request.

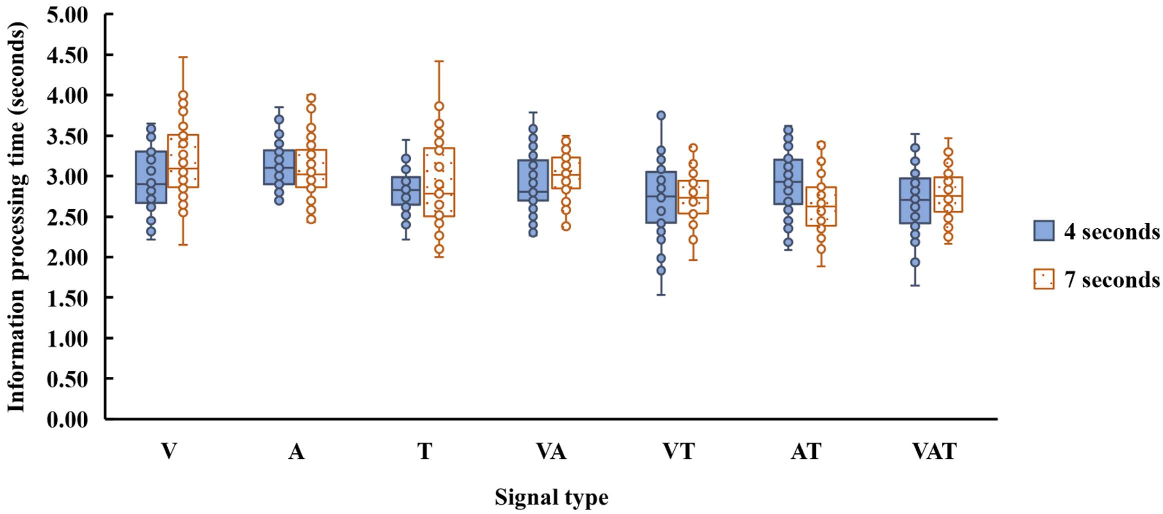

Fig. 7. Information processing time as a function of lead time and signal type.

3.2. Information processing time

There was a significant main effect of signal type ($F(6,138) = 21.528, p < .001, \eta_p^2 = .484$) on information processing time (Fig. 7). Similar to takeover times, signals using the tactile modality, i.e., T (M = 2.880 s, SEM = 0.073), VT (M = 2.765 s, SEM = 0.072), AT (M = 2.802 s, SEM = 0.066), and VAT (M = 2.748 s, SEM = 0.062), had shorter information processing times compared to signals without a tactile cue, i.e., V (M = 3.080 s, SEM = 0.061), A (M = 3.092 s, SEM = 0.051), and VA (M = 2.955 s, SEM = 0.048). However, no significant main effect of signal direction ($F(1,23) = 2.260, p = .146, \eta_p^2 = .089$) nor lead time ($F(1,23) = .059, p = .810, \eta_p^2 = .003$) on information processing time was found.

3.3. Maximum resulting acceleration

Lead time had a significant main effect on maximum resulting acceleration ($F(1,23) = 8.601, p = .007, \eta_p^2 = .272$), see Fig. 8. Here, the 4-second lead time was associated with a larger maximum resulting acceleration (M = 11.23 m/s^2, SEM = 0.340) compared to the 7-second lead time (M = 10.67 m/s^2, SEM = 0.347). The average takeover trajectories for each lead time (Fig. 6(b)) suggest that with a longer lead time, the trajectory was smoother. No significant main effect of direction ($F(1,23) = 2.245, p = .148, \eta_p^2 = .089$) nor signal type ($F(6,138) = .453, p = .842, \eta_p^2 = .019$) was observed. As shown in Fig. 6(c), the average takeover trajectories of ipsilateral and contralateral signals were overlapping.

See Table 1 for summary statistics for all data listed in Sections 3.1-3.3.

3.4. Subjective measures

Table 2 summarizes the average scores for each of the nine items in the technology acceptance questionnaire, as well as the overall scores for usefulness and satisfaction. A one-way ANOVA was employed to compare the means of usefulness and satisfaction ratings between each

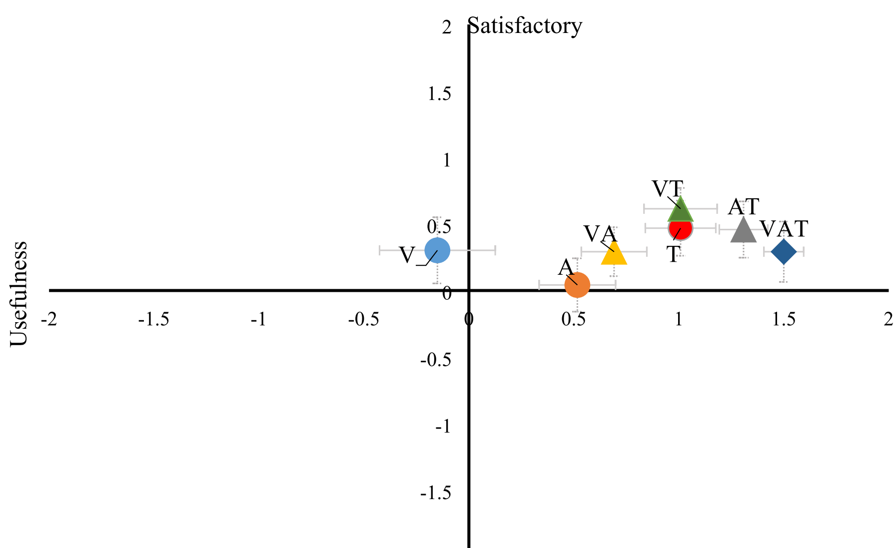

Fig. 8. Perceived usefulness and satisfaction for each signal type.

Table 1
Summary statistics of the dependent measures for all independent variables.

		Takeover time (seconds)				Information processing time (seconds)				MRA (m/s^2)			
		Mean	SE	Min.	Max.	Mean	SE	Min.	Max.	Mean	SE	Min.	Max.
SiD	Ipsilateral	1.75	0.058	0.25	3.15	2.88	0.058	1.13	4.92	10.80	0.342	2.52	21.52
	Contralateral	1.79	0.064	0.43	3.68	2.93	0.058	1.53	4.63	11.10	0.349	1.62	24.80
SiM	V	1.90	0.071	1.15	3.68	3.08	0.061	2.15	4.92	11.07	0.382	3.33	20.84
	A	2.00	0.061	0.87	3.03	3.09	0.051	1.90	4.00	10.80	0.422	4.21	21.04
	T	1.71	0.069	1.00	3.15	2.88	0.073	2.00	4.42	10.99	0.440	3.44	19.92
	VA	1.81	0.056	1.17	2.58	2.96	0.048	2.27	3.78	11.25	0.432	2.68	21.22
	VT	1.63	0.068	0.25	2.77	2.77	0.072	1.13	4.17	10.71	0.419	2.88	21.52
	AT	1.71	0.067	0.95	2.67	2.80	0.066	1.88	3.63	10.96	0.380	2.52	24.80
	VAT	1.63	0.063	0.43	2.67	2.75	0.062	1.65	4.50	10.86	0.401	1.62	20.33
LT	4 s	1.75	0.057	0.43	3.68	2.90	0.056	1.53	4.63	11.23	0.340	1.62	24.80
	7 s	1.79	0.063	0.25	3.15	2.91	0.057	1.13	4.92	10.67	0.347	2.68	21.52

Note: SiD = signal direction; SiM = signal modality; LT = lead time; MRA = maximum resulting acceleration.

Table 2
Average usefulness and satisfaction scores for each signal type.

Negative (− 2)	Positive (+2)	V	A	T	VA	VT	AT	VAT
Useless	Useful	0.04	0.71	1.13	1.00	1.33	1.58	1.92
Bad	Good	−0.08	0.38	0.79	0.58	0.92	1.21	1.21
Superfluous	Effective	−0.17	0.42	1.00	0.71	0.96	1.13	1.29
Worthless	Assisting	0.00	0.38	0.92	0.58	0.88	1.13	1.38
Sleep-inducing	Raising Alertness	−0.54	0.71	1.21	0.58	0.96	1.50	1.71
Overall usefulness score		**−0.15**	**0.52**	**1.01**	**0.69**	**1.01**	**1.31**	**1.50**
Unpleasant	Pleasant	0.54	0.17	0.38	0.46	0.50	0.21	0.00
Annoying	Nice	0.33	−0.13	0.08	−0.08	0.38	0.17	0.04
Irritating	Likeable	0.17	0.04	0.67	0.33	0.71	0.54	0.42
Undesirable	Desirable	0.17	0.08	0.75	0.46	0.88	0.92	0.71
Overall satisfaction score		**0.30**	**0.04**	**0.47**	**0.29**	**0.61**	**0.46**	**0.29**

signal type.

There was a significant main effect of signal type on usefulness ($F(2.537, 58.340) = 14.443, p < .001, \eta_p^2 = .386$), but not on satisfaction ($F(2.498, 86.612) = 1.274, p = .291, \eta_p^2 = .053$). Also, as shown in Fig. 8, the VAT signal (M = 1.50, SEM = 0.095) was perceived to be comparably the most useful signal type, followed by AT (M = 1.31, SEM = 0.115), VT (M = 1.01, SEM = 0.174), and T (M = 1.01, SEM = 0.168). The single visual signal was reported to be the least useful signal (M = -0.15, SEM = 0.276).

Finally, for the preference between ipsilateral and contralateral signals, 92% of participants preferred ipsilateral signals, compared to only 8% percent for contralateral signal.

4. Discussion

This study investigated the effects of signal direction, lead time, and signal modality on semi-autonomous vehicle takeover performance. Within the signal response phase of the takeover process, single and multimodal signals that included a tactile cue were associated with shorter takeover and information processing times, while signal direction and lead time only showed differences in takeover times. Additionally, better takeover quality within the post-takeover phase was observed when drivers had a longer lead time. In terms of drivers' perception of the signals, takeover requests (TORs) that contained a tactile signal also received the highest usefulness rating, and ipsilateral signals were preferred compared to contralateral signals.

4.1. Signal response phase

Takeover time indicates how quickly a driver prepares to take over, while information processing time indicates the speed at which a driver initiates a lane change after receiving a TOR. Overall, both takeover time and information processing times were faster with modality signals that consisted of a tactile cue. Previous research has shown multimodal signals to be associated with faster response times and higher detection accuracy compared to unimodal signals (Diederich & Colonius, 2004; Hecht & Reiner, 2009; Hecht et al., 2006; Ho et al., 2007; Lu et al., 2013, 2012; Pitts & Sarter, 2018; Wickens et al., 2011), but in our study, we also found that even the single tactile cue had better performance compared to bi-modal signal – VA. This further confirms findings from prior work in the semi-autonomous environment that suggested that tactile signaling may benefit takeover transitions in terms of speed (e.g., Huang & Pitts, 2022; Huang et al., 2019), which could reduce accident risks. One possible reason for this finding could be that the tactile channel was most available for receiving information, since the visual and auditory channels were already occupied by continuous input from the road and secondary task (Meng & Spence, 2015; Wickens, 2008). Alternatively, tactile stimuli may be processed faster compared to visual and auditory information (suggested in Pitts & Sarter, 2018). This advantage also infers that tactile cueing may be useful for communicating a broader range of information to drivers. For example, structured tactile patterns can be used to indicate the location and speed of adjacent vehicles to support situation awareness after the TOR.

Different from our expectations, signal direction produced only a marginally significant effect on takeover time, suggesting that ipsilateral signals, where the vehicle instructs the driver on what action(s) to take, may be more beneficial for guiding drivers through a takeover situation. In contrast, Petermeijer et al. (2017a,b) did not find a difference between signal directions. In their study, drivers were not informed that signals were directional and were instead able to make driving maneuvers based on their own interpretation of the meaning of signals. But, in our study, participants were informed of the signal direction and needed to act based on this knowledge. However, the outperformance of ipsilateral signals did not last throughout the entire signal response phase, since there were no differences in the information processing time measurement (which is the time length of the entire signal response phase). This is consistent with previous work (Cohen-Lazry et al., 2019) that also found drivers to respond faster to ipsilateral signals compared to contralateral signals. However, Cohen-Lazry et al. (2019) did not use the longer time range measurement, i.e., information processing time. Our study shows empirically that the benefits of ipsilateral signals may only be present in the initial signal response phase of the takeover process. One plausible explanation for this finding could be that when takeover requests were presented, participants, whose attention was not focused on the road since they were engaged in a non-driving-related task, followed instinctual responses that fit the stimulus–response compatibility phenomenon (Proctor & Vu, 2006) to deactivate the automation and take hold of the steering wheel as quickly as possible (Cohen-Lazry et al., 2019). However, the benefits of ipsilateral, or instructional, signals in terms of takeover time could have been diluted given the time allotted (i.e., 4 and 7 s). With the longer headway (i.e., 7-second lead time), drivers may have not felt obligated to change lanes immediately, but rather when a possible collision was imminent (e.g., Chen et al., 2020; Petermeijer et al., 2017a,b). In other words, when drivers received the TOR, and after assessing the time-to-collision, they might have voluntarily delayed executing their action in order to take time to determine the most appropriate maneuver to make. On the other hand, drivers in the shorter lead time condition (4 s) only had faster takeover times, but not information processing times (when compared to the 7-second lead time). This may be attributable to the urgency of the situation (Muttart, 2005; Scott & Gray, 2008), where drivers judged the urgency level using the distance between their and the lead vehicle.

The interaction between signal direction and modality on takeover time revealed that the effect of signal direction only existed for the V and AT signals. Takeover times were faster with ipsilateral compared to contralateral signals for V and AT, but no differences were found between other signal types. This finding supported our speculation that different signal modalities used in previous studies may be one of the reasons why findings between the two signal directions were conflicting (e.g., Chen et al., 2020; Cohen-Lazry et al., 2019; Petermeijer et al., 2017a,b). While prior work only used one or two signal modalities to examine the effects of signal direction on takeovers, our study compared all seven signal types. Contrary to our expectations that differences between the two signal directions would be found with unimodal signals, only the single visual and bimodal auditory-tactile signals were associated with differences in takeover times. The reasons for these differences are unclear and future research should seek to delineate explanations.

4.2. Post-takeover phase

Takeover quality was compared among the levels for signal direction, lead time, and signal modality after drivers successfully resumed control of the vehicle, measured by maximum resulting acceleration. Here, maximum resulting acceleration was only affected by lead time. Specifically, the 7-second time was associated with a smaller maximum resulting acceleration, thus a better takeover quality, which is in line with previous studies (Mok et al., 2015; Wan & Wu, 2018; see reviews: McDonald et al., 2019; Zhang et al., 2019). No differences were found in vehicle handling between the signal direction and signal modality factors. This potentially indicates that the effects of signal direction and modality only existed in the signal response phase, but did not last long enough to impact post-takeover performance. In other words, after processing the TOR, drivers focused their attention on making decisions about which course of action to pursue and executing that action. Thus, the effects of signal direction and modality quickly decayed as time lapsed beyond the signal response phase. With a longer lead time, drivers have more time to process information in the driving environment and better prepare to respond to the TOR (Wan & Wu, 2018).

To improve takeover quality, Wan & Wu (2018) recommend using a minimum of 10-second lead time after they compared driving performance among different six takeover lead times, ranging from 3 to 60 s. Alternatively, the lead time can be designed to be context-dependent based on the urgency of the situation. Studies have found that a mismatch between the timing of a warning and the urgency of that situation may be incorrectly interpreted (Abe & Richardson, 2004; Jamson et al., 2008; Parasuraman et al., 1997). For example, if the lead time is too long, drivers may disregard an urgent signal as a false alarm and/or forget that a warning signal was presented. On the other hand, if the lead time is too short, drivers may not have enough time to process it, respond, and achieve a smooth transition of control. In this case, a system may adapt the warning lead time to fit the urgency of the situation.

4.3. Users' preferences

The usefulness and satisfaction comparisons among signal modalities revealed that the combined visual-auditory-tactile (VAT) cue was perceived to be most useful, followed by AT, VT, and T. This finding is consistent with our previous work that assessed participants' subjective perceived ease of detecting signals and found younger drivers to rate VAT, VT, and AT as the easiest to perceive (Huang & Pitts, 2020). Combining this finding and results from objective measures, we infer that signals with a tactile component, may be most helpful to drivers during takeover. This may be explained by the demographics of participants in our study. It is possible that younger adults are more frequently exposed to technology that contains some form of vibration (alerts). In fact, 25% of our study participants reported that their current vehicles were equipment with some type of tactile displays, such as lane departure or collision warning systems. With high utilization of visual and auditory resources in automated driving, e.g., due to engaging in NDRTs, drivers may find tactile signaling to be the most useful display. Additionally, 92% of participants preferred the ipsilateral over the contralateral signal. One explanation for this result could be that contralateral signals are designed based on the reverse SRC phenomenon, which is not instinctual. Thus, it may be more challenging for drivers to first identify the signal direction and then think about an action in the opposite direction of the signal. This additional step could have resulted in less satisfaction. However, a more systematic qualitative study on signal direction preferences should be conducted.

4.4. Limitations and future work

Participants in this study experienced a total of 28 takeover events on an average 120-second time interval. Even though our goal was to comprehensively compare all seven modality types, and we intentionally divided the experiment into four separate blocks to prevent task fatigue, this frequency of takeovers may not be completely representative of real-life semi-autonomous driving. Future work may seek to reduce the number of repeated trials per participant. Similarly, variations in the situations requiring a takeover transition should be explored. We only used one type of takeover event – a construction zone. Follow-up studies on takeover may also consider varying elements of the driving environment, such as traffic density, weather, and road type. We also focused mainly on driving-related metrics, but additional work should consider the use of psychophysiological measurements to verify findings. For example, eye tracking can reveal how drivers allocate their attention between ipsi- and contralateral signals. Our study used a fixed-based driving simulator, which may limit our complete understanding of how drivers behave during semi-autonomous driving. Future researchers should replicate our work in a real-world driving scenario in order to determine the external validity of our findings. Finally, study participants were all college students, who do not necessarily represent the broader driver population. Follow-on work may seek to increase the study sample size by including other age groups with varying driving experiences.

5. Conclusion

This study examined the effects of signal direction, lead time, and signal modality on takeover performance in the signal response and post-takeover phases of an automated vehicle takeover process. Single and multimodal signals with tactile components showed the greatest benefits in terms of takeover and information processing times, and were also perceived as most useful. Signal direction presented only a marginally significant benefit to takeover time, particularly for ipsilateral signals that instructed drivers on which action(s) to take. Finally, the shorter lead time was associated with a faster takeover time, but worst takeover quality. These findings may help to inform the design of human–machine interfaces for next-generation passenger vehicles and guide automotive manufacturers in determining the most appropriate warning signal modality, format, and time. In particular, during semi-autonomous driving, one sensory modality (especially visual channel) may be overloaded with information. When a takeover is needed, drivers need to quickly adhere to the information conveyed by the takeover signal to transition to manual driving. This study provides empirical data on the effectiveness of multimodal takeover requests, which can ultimately contribute to improved occupant and traffic safety.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abe, G., Richardson, J., 2004. The effect of alarm timing on driver behaviour: an investigation of differences in driver trust and response to alarms according to alarm timing. Transp. Res. Part F: Traffic Psychol. Behav. 7 (4–5), 307–322. https://doi.org/10.1016/j.trf.2004.09.008.

Carsten, O., Martens, M.H., 2019. How can humans understand their automated cars? HMI principles, problems and solutions. Cogn. Technol. Work 21 (1), 3–20. https://doi.org/10.1007/s10111-018-0484-0.

Chen, J., Šabić, E., Mishler, S., Parker, C., Yamaguchi, M., 2020. Effectiveness of lateral auditory collision warnings: should warnings be toward danger or toward safety? Hum. Factors. https://doi.org/10.1177/0018720820941618.

Cohen-Lazry, G., Katzman, N., Borowsky, A., Oron-Gilad, T., 2019. Directional tactile alerts for take-over requests in highly-automated driving. Transp. Res. Part F: Traffic Psychol. Behav. 65, 217–226. https://doi.org/10.1016/j.trf.2019.07.025.

Diederich, A., Colonius, H., 2004. Bimodal and trimodal multisensory enhancement: effects of stimulus onset and intensity on reaction time. Percept. Psychophys. 66 (8), 1388–1404. https://doi.org/10.3758/BF03195006.

Eriksson, A., Stanton, N.A., 2017. Takeover time in highly automated vehicles: noncritical transitions to and from manual control. Hum. Factors 59 (4), 689–705. https://doi.org/10.1177/0018720816685832.

He, D., Kanaan, D., Donmez, B., 2021. In-vehicle displays to support driver anticipation of traffic conflicts in automated vehicles. Accid. Anal. Prev. 149, 105842. https://doi.org/10.1016/j.aap.2020.105842.

Hecht, D., Reiner, M., Halevy, G., 2006. Multimodal virtual environments: response times, attention, and presence. Presence: Teleoperators Virtual Environ. 15 (5), 515–523.

Hecht, D., Reiner, M., 2009. Sensory dominance in combinations of audio, visual and haptic stimuli. Exp. Brain Res. 193 (2), 307–314. https://doi.org/10.1007/s00221-008-1626-z.

Hedlund, J., 2016. Autonomous Vehicles Meet Human Drivers: Trafic Safety Issues for States. Spotlight on Highway Safety (Vol. 722). Retrieved from https://www.ghsa.org/sites/default/files/2017-01/AV 2017 - FINAL.pdf.

Hergeth, S., Lorenz, L., Krems, J.F., 2017. Prior familiarization with takeover requests affects drivers' takeover performance and automation trust. Hum. Factors 59 (3), 457–470. https://doi.org/10.1177/0018720816678714.

Ho, C., Reed, N., Spence, C., 2007. Multisensory in-car warning signals for collision avoidance. Hum. Factors 49 (6), 1107–1114. https://doi.org/10.1518/001872007X249965.

Huang, G., & Pitts, B. (2020). Age-related differences in takeover request modality preferences and attention allocation during semi-autonomous driving. In International Conference on Human-Computer Interaction (pp. 135–146). Springer, Cham. doi:10.1007/978-3-030-50252-2_11.

Huang, G., Pitts, B.J., 2022. The effects of age and physical exercise on multimodal signal responses: implications for semi-autonomous vehicle takeover requests. Appl. Ergon. 98, 103595. https://doi.org/10.1016/j.apergo.2021.103595.

Huang, G., Steele, C., Zhang, X., Pitts, B.J., 2019. Multimodal cue combinations: a possible approach to designing in-vehicle takeover requests for semi-autonomous driving. Proc. Hum. Factors Ergonomics Society Annual Meeting 63 (1), 1739–1743. https://doi.org/10.1177/1071181319631053.

Jamson, A.H., Lai, F.C.H., Carsten, O.M.J., 2008. Potential benefits of an adaptive forward collision warning system. Transp. Res. Part C: Emerging Technol. 16 (4), 471–484. https://doi.org/10.1016/j.trc.2007.09.003.

Kyriakidis, M., de Winter, J.C.F., Stanton, N., Bellet, T., van Arem, B., Brookhuis, K., Martens, M.H., Bengler, K., Andersson, J., Merat, N., Reed, N., Flament, M., Hagenzieker, M., Happee, R., 2019. A human factors perspective on automated driving. Theoretical Issues Ergonomics Sci. 20 (3), 223–249. https://doi.org/10.1080/1463922X.2017.1293187.

Li, S., Blythe, P., Guo, W., Namdeo, A., Edwards, S., Goodman, P., Hill, G., 2019. Evaluation of the effects of age-friendly human-machine interfaces on the driver's takeover performance in highly automated vehicles. Transp. Res. Part F: Traffic Psychol. Behav. 67, 78–100. https://doi.org/10.1016/j.trf.2019.10.009.

Lindemann, P., Muller, N., & Rigolll, G., 2019. Exploring the use of augmented reality interfaces for driver assistance in short-notice takeovers. in: IEEE Intelligent Vehicles Symposium, Proceedings (Vol. 2019-June, pp. 804–809). Piscataway, NJ, USA: Institute of Electrical and Electronics Engineers Inc. doi:10.1109/IVS.2019.8814237.

Lu, S.A., Wickens, C.D., Sarter, N.B., Thomas, L.C., Nikolic, M.I., Sebok, A., 2012. Redundancy gains in communication tasks: a comparison of auditory, visual, and redundant auditory-visual information presentation on NextGen Flight Decks. Proc. Hum. Factors Ergonomics Society Annual Meeting 56 (1), 1476–1480.

Lu, S.A., Wickens, C.D., Prinet, J.C., Hutchins, S.D., Sarter, N., Sebok, A., 2013. Supporting interruption management and multimodal interface design: Three meta-analyses of task performance as a function of interrupting task modality. Hum. Factors 55 (4), 697–724. https://doi.org/10.1177/0018720813476298.

McDonald, A.D., Alambeigi, H., Engström, J., Markkula, G., Vogelpohl, T., Dunne, J., Yuma, N., 2019. Toward computational simulations of behavior during automated driving takeovers: a review of the empirical and modeling literatures. Hum. Factors 61 (4), 642–688. https://doi.org/10.1177/0018720819829572.

Meng, F., Spence, C., 2015. Tactile warning signals for in-vehicle systems. Accid. Anal. Prev. 75, 333–346. https://doi.org/10.1016/j.aap.2014.12.013.

Mok, B. K. J., Johns, M., Lee, K. J., Ive, H. P., Miller, D., & Ju, W., 2015. Timing of unstructured transitions of control in automated driving. in: IEEE Intelligent Vehicles Symposium, Proceedings (Vol. 2015-Augus, pp. 1167–1172). Center for Design Research, Department of Mechanical Engineering, Stanford University, Stanford, CA 94043, United States: Institute of Electrical and Electronics Engineers Inc. doi: 10.1109/IVS.2015.7225841.

Muttart, J.W., 2005. Quantifying Driver Response Times Based upon Research and Real Life Data. In: Driving Assessment Conference. Public Policy Center, pp. 9–17.

National Science and Technology Council and the United States Department of Transportation. (2020). *Ensuring American Leadership in Automated Vehicle Technologies, Automated Vehicles 4.0*. Retrieved from https://www.transportation.gov/av/4.

Naujoks, F., Befelein, D., Wiedemann, K., Neukum, A., 2018. A review of non-driving-related tasks used in studies on automated driving. Adv. Intelligent Syst. Comput. 597 (November), 525–537. https://doi.org/10.1007/978-3-319-60441-1_52.

Parasuraman, R., Hancock, P.A., Olofinboba, O., 1997. Alarm effectiveness in driver-centred collision-warning systems. Ergonomics 40 (3), 390–399. https://doi.org/10.1080/001401397188224.

Petermeijer, S., Bazilinskyy, P., Bengler, K., de Winter, J., 2017a. Take-over again: Investigating multimodal and directional TORs to get the driver back into the loop. Appl. Ergon. 62, 204–215. https://doi.org/10.1016/j.apergo.2017.02.023.

Petermeijer, S.M., de Winter, J.C.F., Bengler, K.J., 2016. Vibrotactile Displays: A Survey with a View on Highly Automated Driving. IEEE Trans. Intell. Transp. Syst. 17 (4), 897–907. https://doi.org/10.1109/TITS.2015.2494873.

Petermeijer, S., Doubek, F., De Winter, J., 2017b. Driver response times to auditory, visual, and tactile take-over requests: A simulator study with 101 participants. In: 2017 IEEE International Conference on Systems, Man, and Cybernetics. https://doi.org/10.1109/SMC.2017.8122827.

Pitts, B.J., Sarter, N., 2018. What You Don't Notice Can Harm You: Age-Related Differences in Detecting Concurrent Visual, Auditory, and Tactile Cues. Hum. Factors 60 (4), 445–464. https://doi.org/10.1177/0018720818759102.

Pitts, B.J., Riggs, S.L., Sarter, N., 2016. Crossmodal matching: a critical but neglected step in multimodal research. IEEE Trans. Hum.-Mach. Syst. 46 (3), 445–450. https://doi.org/10.1109/THMS.2015.2501420.

Politis, I., Brewster, S., Pollick, F., 2017. Using multimodal displays to signify critical handovers of control to distracted autonomous car drivers. Int. J. Mobile Hum. Computer Interaction 9 (3), 1–16. https://doi.org/10.1016/j.bbapap.2014.08.013.

Proctor, R., & Vu, K. (2006). *Stimulus-response compatibility principles: Data, theory, and application*. CRC press. Retrieved from https://books.google.com/books?hl=en&lr=&id=NISHh4ZJV4AC&oi=fnd&pg=PP1&dq=Stimulus-+response+compatibility+principles:+Data,+theory,+and+application&ots=mnEBDhHIV1&sig=q2KkUY7YmaRLrnLaLHc_FYenc5I.

Roche, F., Somieski, A., Brandenburg, S., 2019. Behavioral changes to repeated takeovers in highly automated driving: effects of the takeover-request design and the nondriving-related task modality. Hum. Factors 61 (5), 839–849. https://doi.org/10.1177/0018720818814963.

SAE International. (2018). SAE J3016: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. *SAE International*, 1.

Salminen, K., Farooq, A., Rantala, J., Surakka, V., & Raisamo, R. (2019). Unimodal and multimodal signals to support control transitions in semiautonomous vehicles. In *11th ACM International Conference on Automotive User Interfaces and Interactive Vehicular Applications, AutomotiveUI 2019* (pp. 308–318). Tampere University of Applied Sciences, Tampere University, Tampere, Finland: Association for Computing Machinery, Inc. doi:10.1145/3342197.3344522.

Scott, J.J., Gray, R., 2008. A comparison of tactile, visual, and auditory warnings for rear-end collision prevention in simulated driving. Hum. Factors 50 (2), 264–275. https://doi.org/10.1518/001872008X250674.

Straughn, S.M., Gray, R., Tan, H.Z., 2009. To go or not to go: stimulus-response compatibility for tactile and auditory pedestrian collision warnings. IEEE Trans. Haptic 2 (2), 111–117. https://doi.org/10.1109/TOH.2009.15.

Van Der Laan, J.D., Heino, A., De Waard, D., 1997. A simple procedure for the assessment of acceptance of advanced transport telematics. Transp. Res. Part C: Emerg. Technol. 5 (1), 1–10. https://doi.org/10.1016/S0968-090X(96)00025-3.

Wan, J., Wu, C., 2018. The effects of lead time of take-over request and nondriving tasks on taking-over control of automated vehicles. IEEE Trans. Hum.-Mach. Syst. 48 (6), 582–591. https://doi.org/10.1109/THMS.2018.2844251.

Wickens, C.D., 2008. Multiple resources and mental workload. Hum. Factors 50 (3), 449–455. https://doi.org/10.1518/001872008X288394.

Wickens, C., Prinet, J., Hutchins, S., Sarter, N., Sebok, A., 2011. Auditory-visual redundancy in vehicle control interruptions: two meta-analyses. Proc. Hum. Factors Ergonomics Society Annual Meeting 55 (1), 1155–1159. https://doi.org/10.1177/1071181311551241.

Yoon, S.H., Kim, Y.W., Ji, Y.G., 2019. The effects of takeover request modalities on highly automated car control transitions. Accid. Anal. Prev. 123, 150–158.

Zeeb, K., Buchner, A., Schrauf, M., 2015. What determines the take-over time? An integrated model approach of driver take-over after automated driving. Accid. Anal. Prev. 78, 212–221. https://doi.org/10.1016/j.aap.2015.02.023.

Zhang, B., de Winter, J., Varotto, S., Happee, R., Martens, M., 2019. Determinants of take-over time from automated driving: a meta-analysis of 129 studies. Transp. Res. Part F: Traffic Psychol. Behav. 64, 285–307. https://doi.org/10.1016/j.trf.2019.04.020.