Psychological Research
https://doi.org/10.1007/s00426-023-01879-9

RESEARCH

Planning lane changes using advance visual and haptic information

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Received: 27 June 2022 / Accepted: 17 September 2023

Abstract
Taking a motor planning perspective, this study investigates whether haptic force cues displayed on the steering wheel are more effective than visual cues in signaling the direction of an upcoming lane change. Licensed drivers drove in a fixed-base driving simulator equipped with an active steering system for realistic force feedback. They were instructed to make lane changes upon registering a directional cue. Cues were delivered according to the movement precuing technique employing a pair of precues and imperative cues which could be either visual, haptic, or crossmodal (a visual precue with a haptic imperative cue, and vice versa). The main dependent variable was response time. Additional analyses were conducted on steering wheel angle profiles and the rate of initial steering errors. Conditions with a haptic imperative cue produced considerably faster responses than conditions with a visual imperative cue, irrespective of the precue modality. Valid and invalid precues produced the typical gains and costs, with one exception. There appeared to be little cost in response time or initial steering errors associated with invalid cueing when both cues were haptic. The results are consistent with the hypothesis that imperative haptic cues facilitate action selection while visual stimuli require additional time-consuming cognitive processing.

Keywords Motor preparation · Steering control · Haptic cueing · In-vehicle haptics

Introduction

As we are starting to witness the transition from manually operated cars to autonomous cars, we also recognize the inevitable need for effective modes of communication between humans and automated operators (Duthoit et al., 2018). One of these modes, which has received a lot of attention, entails the sense of touch, or more generally, haptics. The sense of touch is often divided into passive touch and active touch (Ziat 2023). Passive touch usually involves tactile stimulation of the skin without any particular action on the part of the recipient (e.g., a vibration to the index finger). Active touch, also known as haptics, *does* involve active engagement with the environment and consequently also engages the motor system and the kinesthetic senses. Thus, unlike traditional interfaces that rely on visual and auditory channels, haptic interfaces generate signals that stimulate the tactile and kinesthetic senses. Exploiting the senses of touch is understandable because they are less important to the immediate driving task as vision and hearing are and, therefore, have the potential to be a channel of communication that is much less likely to interfere with the driving task (e.g., Meng et al., 2015).

There are now numerous empirical accounts (reviewed below) of the potentially beneficial effects of introducing haptics in terms of response times, error rates, gaze control, mental load, lane excursions, and many other driving-specific parameters. At the same time, these accounts do not always address the underlying psychomotor processes that could help in explaining how the beneficial effects come about. This study aims to take a step toward such an explanation. To this end, the study adopts the perspective of planning a motor response for an upcoming lane change in a simulated driving environment and compares how visual and haptic cues affect the nature of the planned motor response.

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Published online: 06 October 2023

Functions and outcomes of in-vehicle haptics

Recent years have seen several literature reviews offering organizational schemes of the many ways in which the application of haptics in cars has been explored. These reviews take various perspectives, ranging from the technological (Gaffary & Lécuyer, 2018; Noubissie Tientcheu et al., 2022), the methodological (Petermeijer et al., 2015), and the psychological (Breitschaft et al., 2019). They typically aim at identifying the types of function for haptics, how the haptic information is conveyed, and what kind of benefits have been demonstrated. We briefly summarize the main takeaways for these topics.

Gaffary and Lécuyer (2018) and Petermeijer et al. (2015) identify two types of function for in-vehicle haptics, assistance/guidance and warning. Assistance/guidance systems provide feedback signals that assist the driver in taking appropriate action. The feedback typically consists of forces exerted on a control interface (e.g., the steering wheel) and can convey the direction and the magnitude of the recommended action. Warning systems inform the driver about potentially dangerous situations related to maneuvering (e.g., impending collisions, lane departures, speeding, cars in blind spots) and vehicle control (e.g., curve negotiation, lane keeping) without enforcing any kind of appropriate action on the driver. Meng et al. (2015) categorize haptic warnings into non-directional warnings that can be used to attract a driver's attention, directional warnings that can be used to direct a driver's attention to a specific location, and meaningful warnings that can be used to convey abstract messages to the driver.

The most common channels for conveying haptic signals are the steering wheel, brake or gas pedal, seat, and seat belt, although some work has looked at the dashboard (Pitts et al., 2012) and the driver's clothes (e.g., waist belts; Asif et al., 2012). In terms of stimulation, a distinction is made between vibrotactile stimulation and force stimulation. Vibrotactile stimulation tends to be used in warning systems and is implemented using (arrays of) simple actuators, such as eccentric rotating mass vibration motors (a.k.a. ERMs), mounted on the steering wheel, seat belt, or in the seat. Force stimulation tends to be used in assistance/guidance systems and is typically implemented using forces displayed on the steering wheel or on a pedal.

Collectively, the literature on in-vehicle haptics suggests that both in-vehicle guidance and warning systems can improve driver performance. Plenty of studies have demonstrated that in-vehicle haptic stimuli elicit faster reactions than auditory and visual stimuli. Response times are typically measured on the basis of steering responses (Navarro et al., 2007, 2010; Straughn et al., 2009), brake responses (e.g., Chun et al., 2012; De Rosario et al., 2010; Krüger et al., 2021; Lylykangas et al., 2016; Mohebbi et al., 2009), or gas pedal responses (e.g., Adell et al., 2008). Compared to auditory stimuli, faster responses have been demonstrated for haptic stimuli on the steering wheel (Itoh et al., 2012; Kozak et al., 2006; Navarro et al., 2007, 2010; Straughn et al., 2009), on the pedal (Adell et al., 2008), on the seat (Stanley, 2006), and on the seat belt (Adell et al., 2008; Mohebbi et al., 2009; Scott & Gray, 2008). Compared to visual stimuli, faster responses have been demonstrated for haptic stimuli on the steering wheel (Hoc et al., 2009; Kozak et al., 2006; Navarro et al., 2007, 2010) and on the pedal (Adell et al., 2008; De Rosario et al., 2010; Lylykangas et al., 2016).

Dual route hypothesis

Some in-vehicle haptics studies made comparisons to multimodal stimuli that combined haptic stimuli with auditory (Itoh et al., 2012; Navarro et al., 2007, 2010; Stanley, 2006; Ziat et al., 2015) or visual stimuli (Lylykangas et al., 2016; van Erp & van Veen, 2004), which generally speaking produced responses faster than (Itoh et al., 2012), or as fast as (Navarro et al., 2007, 2010), haptics only. For instance, Navarro et al., (2007, 2010) developed and tested a haptic hybrid warning-guidance device called motor priming (MP) designed to help drivers keep their lane. The MP device generates asymmetrical movements on the steering wheel such that the amplitude in the direction of the lane center is larger than the amplitude in the direction of lane departure (see also Van Baelen et al., 2021). In a series of experiments (Navarro et al., 2007, 2010), the efficacy of the MP device was compared with a range of warning systems, consisting of an auditory warning (a rumble strip sound), symmetrical (i.e., directionless) steering wheel oscillations, lateral vibrations on the steering wheel (two vibrators were inserted in the upper part of the steering wheel, one on each side), and lateral vibrations on the seat (a set of vibrators was placed in the right and left sides of the base and back of the seat). Generally speaking, the greatest benefits were recorded for the motor priming mode alone, or for the combination of MP with the auditory warning, which produced an average reduction in the duration of lateral excursion by as much as 40%. The beneficial effect of the MP device was further elaborated in follow-up studies by Deroo et al., (2012, 2013) that demonstrated a reduction in mean steering response times between 12.5 and 155 ms, depending on the conditions.

In an attempt to explain *how* haptic cues often outperform warning signals in other sensory modalities, Navarro et al., (2007, 2010) proposed that the haptic benefits can be attributed to a "dual route sceneario". According to this hypothesis, haptic cues are encoded directly at the sensorimotor level, whereas visual cues require additional time-consuming

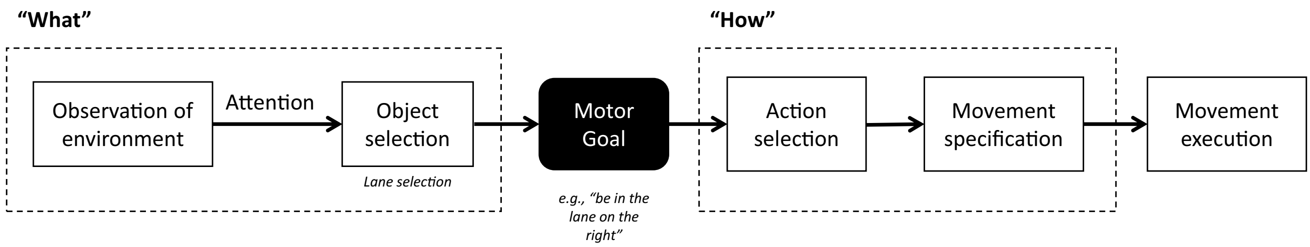

Fig. 1 General framework for motor planning, as suggested by Wong et al. (2015), adapted slightly for the lane change task

cognitive processing. This hypothesis is generally consistent with earlier basic (non-driving) experiments suggesting that kinesthetic and/or vibrotactile information can be used as quickly and accurately as a vision to elicit movements, and sometimes even show a clear advantage (e.g., Bell & Macuga, 2019; Crevecoeur et al., 2016; Flanders & Cordo, 1989; Flanders et al., 1986; Gielen et al., 1983; Jordan, 1972; Kamen & Morris, 1988; Klein, 1977; Klein & Posner, 1974; Ng & Chan, 2012; Prewett et al., 2012).

Changing lanes

The dual route hypothesis was prompted by a task that requires online compensations for deviations from the lane. Much of steering control in driving, however, also involves anticipatory processes (e.g., Donges, 1978; Frissen & Mars, 2014; Land & Horwood, 1995). Indeed, one motivation for many of the in-vehicle systems—and warning systems in particular—is to support anticipatory processes by better preparing a driver for a particular action (e.g., braking) through the display of pertinent information in advance of when that action is required. This study therefore adopts a real-world driving maneuver that requires anticipation and planning; changing lanes (Böffel & Müsseler, 2015; Macuga et al., 2007; Wallis et al., 2002, 2007; Yan et al., 2020). Specifically, the lane-changing maneuver represents a tactical decision that determines which lane the vehicle will be moving to in the immediate future (Gong & Du, 2016).

The conceptualization of lane change as a decision-making process accords with the general framework for motor planning put forward by Wong et al. (2015) (see Fig. 1). At the core of the framework is the idea that all actions are centered on a motor goal (e.g., "being in the right lane"). The control of movement is conceptualized as a decision-making problem (Wolpert & Landy, 2012) in which the problem is to decide *what* the motor goal should be and *how* it can be achieved.

The what part of the problem is addressed by three processes that are collectively referred to as the *selection of motor goals*. The first process is observing the environment, which is concerned with the acquisition of sensory information in order to identify and localize objects (e.g., available lanes). Attention assists in the selection and exclusion of objects. The second process concerns the application of pertinent task roles common to many motor actions (e.g., traffic rules, or experimental task demands). The third process is the selection of the object of interest (e.g., the lane on the right).

The how part turns motor goals into concrete courses of action. It includes processes that are concerned with movement trajectories that are independent of the end-effector (action selection) and with the concrete specification of motor command parameters (movement specification). The central position of the framework is that the decision-making processes of selecting motor goals consume the bulk of processing time, while the how part consumes only a fraction.

From the perspective of the motor planning framework, the selection of motor goals for a lane change can be characterized as follows. A possible motor goal would be "being in the lane to my right". Observing the environment would involve the lanes of the road. The application of pertinent task roles could be observing pertinent traffic rules. Finally, the selection of the target of interest would be discerning the actual lane to move into.

Preparing lane changes based on visual cues

Only a handful of studies have investigated how drivers plan for lane changes (Chapman, 2017; Hofmann & Rinkenauer, 2013; Hofmann et al., 2010). All these studies employed visual signals and variations of the movement precuing technique (Rosenbaum, 1980, 1983; Rosenbaum & Kornblum, 1982). The technique introduces a straightforward task. When a signal—referred to as the *imperative cue*—is presented, the participant is supposed to perform an associated response as quickly as possible. A little time before the presentation of the signal a precue is presented. This precue can be a non-informative "get ready" signal (*neutral* precue), or it can provide advance information about the upcoming required response. Moreover, this advance information is typically valid but can on occasion be invalid. *Valid* precues inform the participant to prepare for a response (e.g., prepare to change to the lane on your left) that corresponds to the required response (i.e., change to the lane on your left). *Invalid* precues inform the participant to prepare for a response (e.g., prepare to change to the lane on your left) that is different from the actually required response (change to the lane on your right). The typical finding—the cue-validity effect—is that valid and invalid precues result in, respectively, faster and slower responses when compared to when no (or a non-informative) precue is available (e.g., Tan et al., 2003).

Hofmann et al. (2010) had participants drive a simulated car—moving at a constant speed of 60 km/h—with a cued lane change occurring, on average, once every ten seconds. Visual precues and imperative cues were, respectively, green and red colored arrows presented just below the horizon. On a given trial, a 300 ms precue was followed, after an interval of 1200 ms, by a 300 ms imperative cue. The precue was either neutral or it was congruent with the upcoming lane change. In other words, if the precue indicated a direction, then that direction was always a valid indicator of a required lane change. In 50% of the trials, the precue was an arrow pointing in the direction of the upcoming lane change. On the remaining 50% of the trials, the precue was neutral (i.e., a line without an arrow head). There was, therefore, an incentive to use precue information to prepare imminent actions. In a follow-up study, Hofmann and Rinkenauer (2013) included a relatively small set of trials with invalid precues as well. Across different blocks, two different distributions of valid as well as invalid precues were used: 90:10 or 75:25. Since the vast majority of trials were valid, there was still considerable incentive for the participants to prepare in accordance with the precue. Together the two studies consistently demonstrated the typical precuing effect: valid cues yielded a significant speeding up of the response and invalid cues incurred a cost in response time.

Most recently, Chapman (2017) conducted an experiment very similar to the one by Hofmann and Rinkenauer (2013) but added a secondary distractor task with the aim of better understanding how distraction affects information processing. The secondary task consisted of a visual search task which was to simulate common in-vehicle activities such as interactions with a navigation system. The distractor task added about 5–15 ms to overall response times. While there was again a benefit of having valid advance information (about 15 ms), there was no significant additional cost from having invalid advanced information, which was partially attributed to the absence of time pressure in the task and learning effects.

Reinterpreting the movement precuing technique

The original logic behind the precuing technique (Rosenbaum, 1980, 1983; Rosenbaum & Kornblum, 1982) was to supply, in advance of a motor response, *partial* information about the defining characteristics of that motor response (e.g., the extent, but not the speed, of an arm movement) and then observe how long it takes to perform the response after a reaction signal is presented. The assumption was that the time to perform the response includes the time to specify those parameters that were not precued in advance. From the perspective of the motor planning framework, the logic appears to have been targeting the how part.

Here, the precuing technique is reinterpreted as a tool for experimentally separating planning a movement and triggering a (planned) movement. First, the neutral precue condition provides an approximation of how long it takes to execute an unprepared action; that is, how long it takes to fully plan (what + how) and execute an action. Since the neutral precue merely serves as a ready signal to prime an observer's attention, only upon the imperative cue is the requisite information to select a motor goal (what) and specify a movement (how) available.

Second, the valid precue condition provides an approximation of how long it takes to execute a prepared action once it is triggered by an imperative cue. Response times, when compared to those in the neutral precue condition, can be taken as a gauge of the time required by the what part of motor planning (given that the how part presumably requires a negligible amount of time; Wong et al., 2015).

Third, the invalid precue condition provides an approximation of how long it takes to override a prepared action and prepare and execute a new action. It was previously assumed that the typically observed slower responses in invalid conditions reflect the cost of having to reprogram the parameters for a new movement (e.g., Larish & Frekany, 1985). However, rather than with fast motor processes, these costs are now thought to be associated with slow perceptual-cognitive processes (Leuthold, 2003); that is again, with the what part of motor planning.

The present study

The objective of the present study is to appreciate the dual route hypothesis within the perspective of the motor planning framework using the reinterpreted precuing technique. We recall that the dual route hypothesis is based on the proposition that visual cues require time-consuming cognitive processing whereas haptic cues effectively bypass cognitive processing by virtue of being encoded directly at the sensorimotor level. We take this to mean that any action will be faster when triggered by a haptic cue irrespective of its state of preparedness. Here, the dual route hypothesis is addressed in a number of ways. The resulting hypotheses are summarized in Table 1.

The first way pertains to *triggering unprepared* lane changes. Using a neutral cue condition, we expect to see

Table 1 Hypotheses for the current study

Hypothesis		Precue	Expected outcome
Triggering (unprepared)	H_{1a}	Neutral	Responses for haptic imperative cues are faster than for visual imperative cues
	H_{1b}		No difference in response times between haptic and visual precues
Triggering (prepared)	H_{2a}	Valid	Gains in response times for haptic imperative cues are larger than for visual imperative cues
	H_{2b}	Invalid	Costs in response times for haptic imperative cues are smaller than for visual imperative cues
Planning	H_3	Valid/invalid	Responses are faster when the precue and imperative cue match in modality, compared to when they do not match

faster responses for haptic than for visual imperative cues (hypothesis H_{1a}). This situation is most comparable to those in the above-reviewed literature producing faster movements with haptic than with visual stimuli. Moreover, we do not expect to see any effect of the sensory modality of the neutral precue since it merely functions as a call on the participant to pay attention (H_{1b}).

The second way pertains to *triggering prepared* lane changes. Here two different effects combine: The cue validity effect and the time-saving effect of triggering an action with a haptic cue. When the precue is valid these two effects are expected to add up differently for the haptic and visual imperative cues. Specifically, the *gains* in response time will be larger for prepared lane changes triggered by a haptic cue than those triggered by a visual cue (H_{2a}). When the precue is invalid these two effects are again expected to add up differently for the haptic and visual imperative cues. Specifically, the *costs* in response time will be smaller for prepared lane changes triggered by a haptic cue than those triggered by a visual cue (H_{2b}). In a sense, costs associated with the invalid cue are (partially) offset by the time-saving effect of triggering an action with a haptic cue.

The third way pertains to *planning* a lane change and is speculative in nature. Specifically, we ask whether an action prepared based on visual information is in any way different from an action prepared based on haptic information. To explore this issue of crossmodality, we compare conditions in which the pre- and imperative cues are of the same modality, with conditions in which they are of different modalities. Crossmodal interference effects have been reported in several perceptual and motor tasks. For instance, numerous studies have been conducted using a "crossmodal congruency task" that show that the spatial discrimination of a stimulation on the body (e.g., a vibration on the index finger or thumb) that requires attending to one modality (e.g., touch) can nevertheless show interference from stimulation in another modality (e.g., visual), even when that stimulation merely serves as a distractor and is otherwise irrelevant to the task (e.g., Spence et al., 2004). The kind of tasks used in these congruency tasks, however, are difficult to compare with the preparation of motor actions and only allow for naïve expectations. And even the dual route hypothesis or the motor planning framework does not allow for clear expectations. In fact, the motor planning framework does not clearly address sensory modalities, although it is reasonable to assume that only planning within the visuo-motor system is implied. We therefore speculate that if the precue modality is somehow determinant in preparing an action, then we can expect faster responses when the precue and imperative cue match in modality, compared to when they do not match (H_3).

Method

Participants

Twelve participants, four females and eight males, between the age of 24 and 39 (mean = 30; SD = 5.4), volunteered for the experiment. They had been licensed drivers for a minimum of 3 years. The experiment was conducted in accordance with the ethical standards specified by the 1964 Declaration of Helsinki, and all participants gave informed consent.

Apparatus and Material

The study took place in a fixed-base driving simulator, consisting of a single-seat cockpit with full instrumentation (See Fig. 2; Frissen & Mars, 2014). It was equipped with an active steering system for realistic force-feedback. The visual environment was displayed on three 32-inch LCD monitors, one in front of the driver and two laterals, inclined at 45° from the front one. The monitors were viewed from a distance of about 1 m and covered 115° of visual angle in width and 25° in height. The SCANeR™ Studio software package (OKTAL) was used for creating the track and controlling the experiment. The virtual track was a 20 km long straight road with 31 lanes, each 3.5 m wide without any traffic. At any given time, only a subset of the lanes was visible to the participant (about 4–5 on either side). The track was set in a grassy, but otherwise flat and featureless, terrain.

The visual stimuli, illustrated in the left column of Fig. 3, were arrows that pointed to the left or to the

Fig. 2 The fixed-base driving simulator

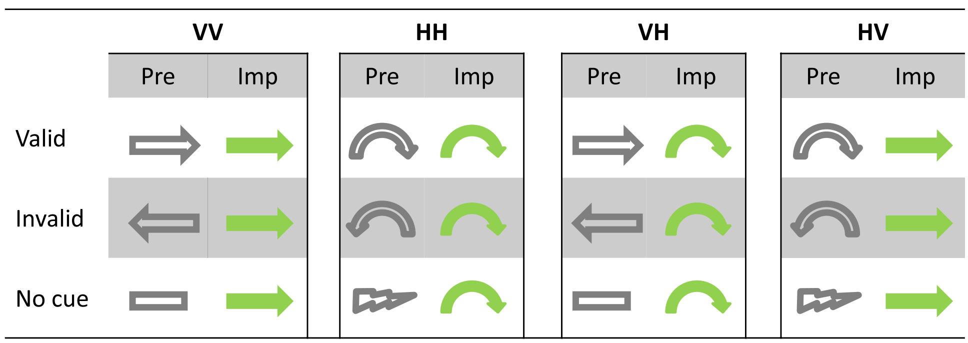

Fig. 3 Schematic overview of the conditions. The 'flash' in the HH and HV neutral conditions represents a directionless rumble of the steering wheel (see method)

right, and extended 6.1° horizontally, and 0.9° and 2.0° vertically, for the narrow and wide parts of the arrow, respectively. For those cases in which a neutral cue was necessary (see the section on Procedure and Design) the stimulus was a rectangle (5.3° horizontally, and 0.9° vertically). Precues were rendered in outline only (i.e., they were hollow) and grey arrows and imperative cues were solid bright green arrows. The stimuli were, superimposed on the far part of the track, presented directly in front of the driver and just below the horizon so that the participants did not have to take their eyes off the road.

The haptic stimulus was a brief tug on the driver's hands delivered by the steering wheel. The tug either had a clearly identifiable leftward (i.e., counterclockwise) or rightward (clockwise) direction. Specifically, the haptic stimulus was a suprathreshold 'jerk' created by issuing a bang-bang type biphasic torque control signal that moved the steering wheel with a 300 ms triangular movement profile. The force of the stimulus was 7 N on the unloaded steering wheel. For the haptic neutral condition, the precue was a 'rumble', consisting of a 300 ms long sequence of a 20 Hz oscillation of the steering wheel with a force of 4 N (unloaded steering wheel). Pretesting established that the rumble was suprathreshold and that it had no discernible direction to it.

Design and procedure

The experimental design (see also Fig. 3) was the factorial combination of the following factors. *Precue Modality:* The precue could be in the visual or haptic modality. *Imperative Cue:* The cue which signaled the lane change could be in the visual or haptic modality. The resultant four cue combination conditions are denoted by the letter pairs VV, HH, HV, and VH, where the first letter denotes the modality of the precue and the second is the modality of the imperative cue. *Cue Validity*: The relative distribution of valid, invalid, and non-informative cues was 6:1:1. In other words, the precue was valid on 75% of trials, invalid on 12.5%, and non-informative (i.e., neutral) on the remainder 12.5%. Finally, *Direction of Lane Change*: Participants were either to turn into the lane on the left or on the right.

Each participant completed 96 trials for each of the four cue combination conditions, evenly split up into two runs of 48 trials (36 Valid, 6 Invalid, 6 Neutral), summing up to 384 trials. The resulting eight runs were administered according to an ABCD-DCBA scheme with the order of the four cue combination conditions counterbalanced using a Latin square. A run typically lasted around 5 min in which the participant completed the 48 trials consecutively. The speed of the car was controlled by the simulation. At the start of a run, the car accelerated to 60 km/h while in third gear and maintained that speed until all trials were completed (i.e., the car did not stop between trials). There were short breaks in between runs while the experimenter loaded the next run; although participants were free to take longer breaks if so desired. The experiment was typically completed in a single session and never lasted more than 75 min (only one of the participants was tested into two consecutive days due to scheduling/availability issues).

Each trial consisted of a sequence of two events. First, a precue was presented for 300 ms followed by an inter-stimulus interval (ISI). The ISI was randomly sampled from a uniform probability distribution between 600 and 1200 ms, at 50 ms intervals. At the end of the cue interval, the imperative cue was presented for 300 ms. After the offset of the imperative cue, there was a random inter-trial interval of between 3500 and 5000 ms for the participant to complete the lane change before the next sequence of a pre and an imperative cue was started.

Participants were instructed to make the correct lane change as quickly as possible upon registering the imperative cue. They were also instructed to keep both hands on the steering wheel at all times at either the 22:10 or 21:15 position, depending on preference. The experimenter, who was in the lab with, but out of sight of the participant, monitored, and enforced proper hand position.

Before the experiment proper, there was a period of practice during which participants drove along another track that included numerous turns; they drove until they became comfortable driving the simulator and their driving performance had stabilized (which took never more than 10 min). Participants next received four short sets of practice trials, one for each of the four cue combination conditions, always in the same order: VV, HH, HV, and VH. Each practice set featured eight valid, four invalid, and two neutral trials, in that order, with the cue interval fixed at 1200 ms. During the practice, the experimenter explained the conditions as they occurred. On rare occasions, the practice session was repeated upon request of the participant or if the experimenter deemed it necessary.

Data analysis

All dependent variables were calculated from the angular position of the steering wheel (see also Fig. 4). Position data were recorded at 500 Hz but down-sampled to 20 Hz for the analyses (Frissen & Mars, 2014). Steering wheel angle profiles were rectified such that, irrespective of direction, a correct response first shows a positive peak followed by a negative peak. In other words, data were analyzed without regard for the instructed direction of lane change, as this was only an experimental necessity to create uncertainty about the steering motion (see also, Hofmann et al., 2010).

Preprocessing and analyses of the data were done in MATLAB (R2019b) and inferential statistical analyses with IBM SPSS (version 23). All ANOVAs were repeated measures. Effects were considered statistically significant if p-values were less than 0.05; violations of sphericity were corrected for by using the Huyn-Feldt correction. Effect sizes are quantified using partial-η^2. Common guidelines for interpreting η^2 suggest that values larger than 0.14 can be considered to reflect “large” effects (Cohen, 1988).

Empirical bootstraps with 10,000 replications were used to estimate 95% confidence intervals for response times analyses.

Response times

Response time was defined as the time difference between the onset of the imperative cue and the onset of the steering movement. Movement onset time was calculated on the basis of two points along the steering wheel’s angular velocity profiles (the first derivative of the angular position of the steering wheel). The first point was the peak velocity and the second was the point where the profile first reached 10% of the peak velocity. To project backward in time, a linear extrapolation was done between these two points to $v = 0°/s$.[1]

For each participant, individual averages were calculated by taking the median across trials. Trials with response times that were anticipations (4.8% of all trials) or that were longer than 1s (0.6%) were excluded from further response time analyses.

Delta plots: distributional response time analysis

Additional analyses of response times were conducted using an adaptation of the delta plot analysis (de Jong et al., 1994). Delta plots, as they are applied here, show the magnitude of cueing effects as a function of response times. Rather than calculating overall mean response times for any particular condition, response times are first binned in quartiles, and gains/losses are calculated for each quartile (the logic of the current adaptation of the delta plot analysis is further explained in Fig. 5a). This way, cueing effects can be compared across the time epochs spanned by the quartile bins; e.g., from relatively fast responses (first quartile) to relatively slow responses (fourth quartile). Such a breakdown allows for more fine-grained insights into any transient or lasting characteristics of cue validity effects as they unfold over time.

Initial steering errors

While participants virtually always ended up in the correct lane, many would, on occasion, initially steer into the wrong

[1] Teasdale et al. (1993) proposed a more sophisticated method for determining the movement onset time. A two-stage algorithm first determines the sample at which the time series first exceeds 10% of its maximum value. Then, working back it looks for the first sample at which speed reaches 10% of the speed of the first point. The final step locates the onset as this second point minus the standard deviation of the time between the first and second points. In our case, however, this method could not distinguish between the early parts of the peak that were due to the participant’s movement and those that were due to the haptic cue.

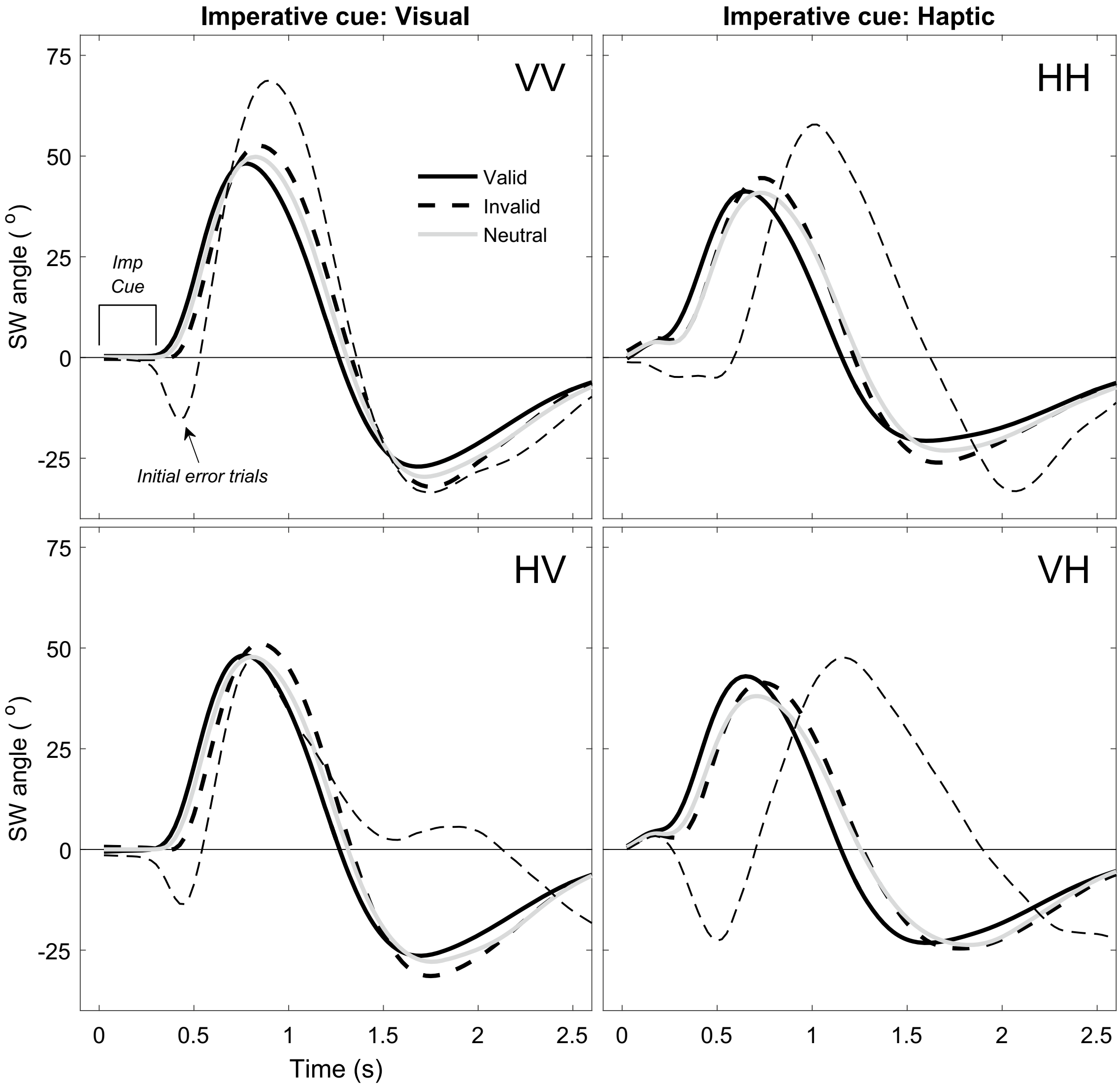

Fig. 4 Group mean steering wheel profiles for the four conditions. Profiles were standardized with respect to the instructed lane change direction; that is, a correct response, irrespective of direction, first shows a positive peak followed by a negative one. The top left panel illustrates how an initially incorrect response (thin dotted lines) can be identified by a small early negative peak

lane. Such an initial error was identified by the first (negative) peak in the rectified steering wheel profile (see Fig. 4, panel VV) and constituted 10.4% of all trials. The number and distribution of initial steering errors themselves were outside of the purview of the hypotheses but were considered in a secondary descriptive analysis.

Results

Figure 6 shows the means for response times (panel a) and the gains and costs associated with valid and invalid precue conditions (panel b). Initial steering errors are also shown (panel c).

Hypothesis 1: Triggering unprepared lane changes

Visual inspection of the response times in the neutral cue condition appears to confirm hypothesis H_{1a} that haptic imperative cues allowed for faster motor planning than visual cues. In addition, there was no apparent difference between visual and haptic precues (H_{1b}). This visual appreciation of the results was supported by a 2 (Imperative Cue: Visual vs. Haptic) × 2 (Precue: Visual vs. Haptic) ANOVA. The main effect of Imperative Cue was significant (F (1, 11) = 12.84, MSE = 0.042, p = 0.004, η_p^2 = 0.54). The main

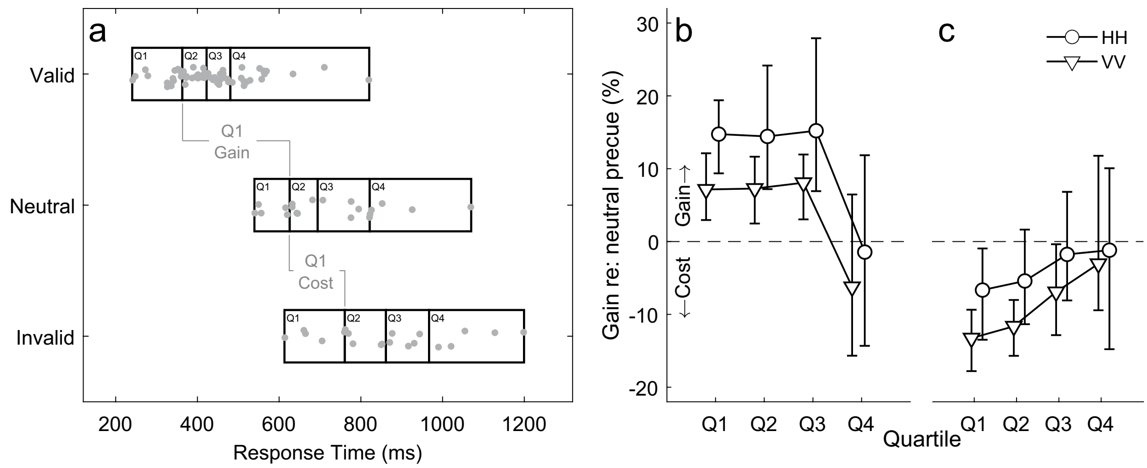

Fig. 5 Delta plot analysis. **a** Illustration of the current adaptation of the delta plot analysis using fictitious individual-trial response times (small grey dots). For each participant, response times are divided into quartiles (solid line boxes) and for each quartile, the difference is calculated between the valid and the neutral precue conditions (ΔRT valid), and between the invalid and neutral precue conditions (ΔRT invalid). Positive and negative ΔRT values indicate gains and costs in response time, respectively. **b** Group mean delta plot for the HH and VV conditions for ΔRT valid, and **c** for ΔRT invalid. All error bars represent 95% empirical bootstrap confidence intervals based on 10,000 bootstrap samples

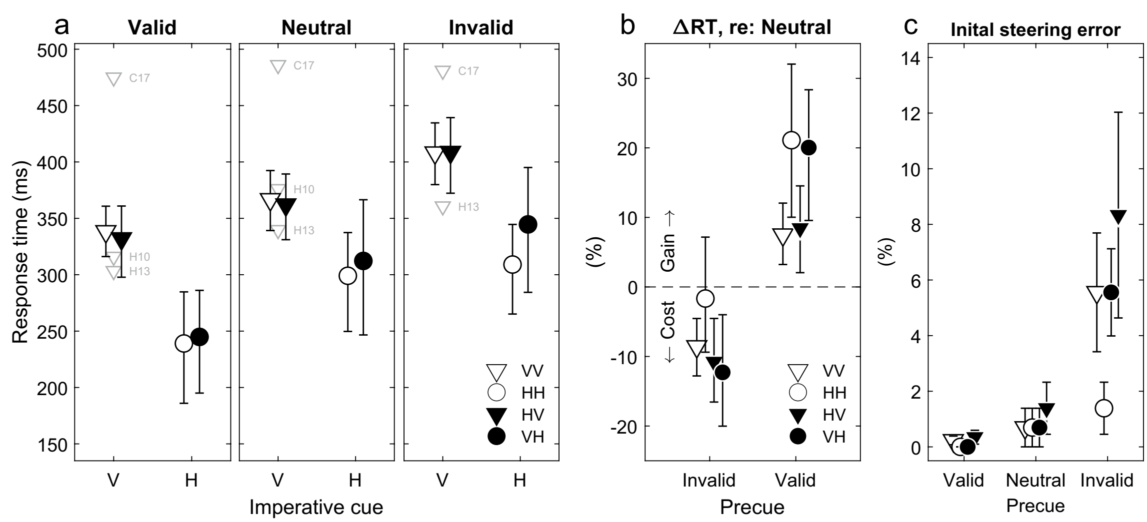

Fig. 6 Summary of the main results. **a** Response times. Marker types are organized by imperative cue (filled inverted triangle for visual, filled circle for haptic), and by whether stimuli were unimodal (white symbols) or crossmodal (black symbols). For reference, the grey markers show the pertinent results from earlier studies with visual cues (C17: Chapman, 2017; H10: Hofmann et al., 2010; H13: Hofmann & Rinkenauer, 2013). **b** The effect of valid and invalid cueing in terms of gain with respect to the neutral cue condition. Positive and negative values indicate a decrease (gain) and increase (cost) in response time, respectively. **c** Percentage of trials a participant initially steered in the wrong direction. Error bars in panels a and b represent 95% empirical bootstrap confidence intervals based on 10,000 bootstrap samples and the SEM in panel **c**

effect of Precue and the interaction were not significant (both F's < 1). Collapsed across precues, the mean response times (and 95% confidence intervals) were 364 ms (332–397) for the visual and 305 ms (247–363) for the haptic imperative cue.

Hypotheses 2 and 3: Triggering prepared lane changes, and crossmodal precues

Response times were submitted to a 2 (Imperative Cue: Visual vs. Haptic) × 3 (Validity: Valid, Neutral, Invalid) × 2 (Precue: Visual vs. Haptic) ANOVA. The results are reported as they pertain to the various hypotheses.

Hypothesis 3: Crossmodal precues

The main effect of Imperative Cue ($F(1, 11) = 32.68$, MSE = 0.225, $p < 0.001$, $\eta_p^2 = 0.75$) was significant while the effect of Precue ($F(1, 11) = 2.04$, MSE = 0.003, $p = 0.181$, $\eta_p^2 = 0.16$) was not. The interaction between Imperative Cue and Precue was not significant ($F < 1$). The non-significant interaction is inconsistent with our speculation (H_3) that responses are faster when the precue and imperative cue match in modality.

Hypotheses 2a and b: Triggering prepared lane changes

In addition to the main effect of Imperative Cue (see above), the main effect of Validity ($F(2, 22) = 17.52$, MSE = 0.105, $p < 0.001$, $\eta_p^2 = 0.61$) was significant, although their interaction was not ($F\ (2, 22) = 2.86$, MSE = 0.004, $p = 0.079$, $\eta_p^2 = 0.21$).

While the p-value for the interaction did not warrant a conclusion of statistical significance, it was less than 0.1 and the corresponding effect size was substantial. The interaction between Imperative Cue and Validity was therefore further explored with a separate 3 (Validity) × 2 (Precue) ANOVA for each Imperative Cue.

For the *visual imperative cue*, the main effect of Validity was significant ($F\ (2, 22) = 21.08$, MSE = 0.047, $p < 0.001$, $\eta_p^2 = 0.66$). Follow-up within-subjects contrasts revealed significant differences between Valid and Neutral cues ($F\ (1, 11) = 9.40$, MSE = 0.021, $p = 0.011$, $\eta_p^2 = 0.46$) and between Invalid and Neutral cues ($F\ (1, 11) = 32.2$, MSE = 0.40, $p < 0.001$, $\eta_p^2 = 0.75$). Neither of these contrast effects interacted with Precue (all F's < 1).

For the *haptic imperative cue*, the main effect of Validity was significant ($F\ (2, 22) = 11.02$, MSE = 0.058, $p = 0.02$, $\eta_p^2 = 0.50$). Follow-up within-subject contrasts revealed significant differences between Valid and Neutral cues ($F\ (1, 11) = 7.63$, MSE = 0.096, $p = 0.018$, $\eta_p^2 = 0.41$), but not between Invalid and Neutral cues ($F\ (1, 11) = 1.65$, MSE = 0.005, $p = 0.225$, $\eta_p^2 = 0.13$); neither of these contrast effects interacted with Precue (all F's < 1).

At face value, these ANOVA results are consistent with our hypothesis that the visual imperative cue is associated with larger *costs* than the haptic cue (Hypothesis H_{2b}). However, before we can fully entertain this interpretation, we want to consider the costs for the VH and HH conditions more closely (see Fig. 6). First, the confidence interval for the VH condition *does not include zero*; in fact, on average its costs are very similar (around 10%) to those in the HV condition. It appears then that the lack of a significant effect of the invalid cue should be attributed to the HH condition, which indeed shows an average cost of around 0%.

To further precise this apparent lack of costs, the cost (and gain) functions for HH condition were submitted to delta plot analyses. The results, shown in Fig. 5b, c, allow for three observations. First, on average the gains due to valid precues (Fig. 5b) were consistently larger in the HH condition than in the VV condition. This is in accordance with the above ANOVA results and with hypothesis H_{2a}. Second, the gains showed relatively little transience: Gains were consistent across Q1 to Q3 and dissipated only for the slowest of responses, in Q4. Third, and most pertinent here, just like the VH condition, the HH condition *can* incur costs. However, these costs were small (about 7%) and limited to only that subset of trials in which participants responded very quickly (i.e., all confidence intervals included zero, except for Q1). For comparison, a different time course was evident for the VV condition in which costs were on average larger than in the HH condition. Only the confidence intervals for Q4 included zero, showing that any costs associated with invalid cues lasted up to, and including, Q3. It can be concluded therefore that costs associated with the HH condition do exist but that they are transient and subject to much more rapid decay than costs associated with the VV condition.

Initial steering errors

Visual appreciation of Fig. 6c allows a number of observations about the effect of cueing conditions on initial steering errors. First, the Invalid cueing conditions produced most of the errors by far. Second, the number of errors in the Invalid conditions depended on the particular modality: On average, the crossmodal HV condition produced the largest number of errors, followed by the VV and VH conditions. The HH condition produced the smallest number of errors, comparable to the neutral precue conditions.

Discussion

The objective of this driving simulation study was to compare the motor planning for imminent lane changes with advanced visual, haptic, and crossmodal information. Beyond assessing the effectiveness of haptic and visual cues in facilitating the preparation of steering responses, the goal was to determine which underlying processes are impacted by these cues in the theoretical framework of motor preparation.

Haptic cues are more effective at triggering steering responses

In the neutral precue conditions, haptic imperative cues produced significantly faster responses than visual imperative cues. This finding is consistent with hypothesis H_{1a}. Since the response times for the crossmodal conditions were essentially the same as in the unimodal conditions, the findings also lend support to hypothesis H_{1b}. In other words, the response times for conditions in which the *imperative* cues were in the haptic modality (HH and VH) produced faster responses than conditions in which the imperative cues were in the visual modality (VV and HV). Thus, the potential for haptic cues to reduce response times is mostly, if not entirely, driven by the modality of the imperative cue and not by any particular modality combination of pre- and imperative cues.

When considered from the perspective of the theoretical framework of motor preparation by Wong et al. (2015), these results could be reinterpreted to mean that the advantage of haptic cues lies in the fact that they intervene at the level of the selection of the action ("how" part) by indicating to the effector of the response (i.e., the hands) the direction of the response to be made, whereas a visual cue acts upstream on the selection of the motor goal ("what" part).

These results are consistent with those reported by Mars and colleagues in near-lane departure situations where drivers had to make a lane correction (Deroo et al., 2012, 2013; Navarro et al., 2007, 2010). For instance, Deroo et al. (2013) showed that drivers very quickly inhibit responses triggered by haptic cues when they are in the opposite direction to the required response (i.e., when the context contradicts the haptic prompt to move). This held true even when the cue was strong enough to trigger a reflexive counterreaction. The advantage associated with haptic cueing of the corrective movement compared to indications delivered in other sensory modalities was interpreted as the consequence of a direct encoding at the sensorimotor level. By contrast, visual stimuli require additional time-consuming cognitive processing.

Effect of cue validity on response time and initial steering errors

We now turn to the effects of valid and invalid precues. The results from our visual cues-only condition were in agreement with—and therefore replicate—those reported by Hofmann and colleagues (Hofmann & Rinkenauer, 2013; Hofmann et al., 2010). Moreover, *all* conditions produced the typical gains associated with valid precues irrespective of the modality of the cues. The *magnitude* of the gains, however, did depend on modality in accordance with hypothesis H_{2a}. In conditions with a visual imperative cue, gains in response time were on average around 8%. In contrast, in conditions with a haptic imperative cue gains were on average more than twice as large (around 20%). Irrespective of their magnitude, the gains establish that drivers can, and do, use the information afforded by a valid cue to prepare for a lane change (Rosenbaum & Kornblum, 1982). It seems that the decrease in reaction times associated with imperative haptic cues, which were already observed with a neutral precue, is potentiated by a preliminary indication of the direction of the steering response. Again, the sensory modality of the precue is not decisive.

Overall, invalid precues produced the expected costs in response times (hypothesis H_{2b}), which reflects the ability of drivers to discard and reprogram planned actions (e.g., Hartwigsen & Siebner, 2015; see also Chapman, 2017). The apparent outlier was the HH condition since it did not appear—at first sight—to produce a cost in response time in response to an invalid precue. However, the delta plot analysis showed that a cost did exist, but that it was of small magnitude and transient (i.e., it was only detected for the fastest responses). It appears that by virtue of it acting downstream in the motor planning process, the imperative haptic cue may partially offset the negative effect of an invalid precue. However, the offsetting effect was only observed when the precue was also delivered via the haptic modality. In the VH condition, the cost was clearly observed to suggest that the ability of a haptic cue to offset erroneous preparatory information does not extend to crossmodality.

In terms of initial steering errors, virtually all errors were made in response to invalid cueing, in about 5% of all trials. It is noted that this error rate is an order of magnitude higher than the 0.3% reported by Hofmann and Rinkenauer (2013); however, finding substantial numbers of errors is the more common finding in studies of fast manual reaching tasks (e.g., Marinovic et al., 2010). Indeed, our average is close to a 2.1% error rate reported by Rosenbaum and Kornblum (1982). We suppose, therefore, not that our error rate was high, but that Hofmann and Rinkenauer's was very low. The source of the discrepancy is currently a matter of speculation.

More importantly, the rate of initial steering errors showed some dependency on the particular combination of modalities: when both the pre- and imperative cues were haptic there were virtually no errors, whereas the other cue modality combinations did produce errors. This result is similar to the observation made on the reaction times. It seems then that the imperative haptic cue is associated with an ability to offset the effect of an invalid haptic precue. This could be interpreted as another demonstration that the effectiveness of haptic cues lies in their intervention in the action selection process, overriding the influence of the precue on motor preparation.

Effect of crossmodal cueing on response time

If we exclude the very small effect of the invalid precue in the HH condition, the response times produced by the crossmodal condition with a visual precue and a haptic imperative cue (VH) were not different from the response times in the HH condition. Similarly, response times produced by a haptic precue and a visual imperative cue (HV) were not different from the response times in the VV condition. Hence, hypothesis H_3, which proposed that HV and VH could give rise to a form of crossmodal interference, is not validated. Rather, it would seem that it is congruence in the haptic modality alone that facilitates the execution of a correct steering response in the presence of an incorrect precue.

Limitations

There are a number of design elements in the study that may qualify the conclusions drawn above. These elements pertain to the relative comparability of the visual and haptic stimuli, the fact that participants could have access to supplemental visual cues in the haptic condition, and the absence of inertial cues because of the use of a fixed-base driving simulator. We address these elements in turn.

Besides the obvious difference in sensory modalities, the visual and haptic stimuli were not necessarily matched and differed in a number of ways. First, the haptic cue involves movement whereas the visual cue is static; that is, they were not matched in terms of movement dynamics. One can imagine, for instance, a visual analog in which a cartoon steering wheel with hands is shown to rotate. At the same time, “linear” arrows, like the ones used in the current work, are arguably highly familiar symbols and unambiguous. Second, visual and haptic stimuli were not matched in terms of salience. While both stimuli were suprathreshold and entirely unambiguous there remains the possibility that the haptic stimulus was somehow more salient than the visual stimulus, which could have been a contributing factor to the faster responses.

While driving in the simulator, participants had a plain view of (their hands on) the steering wheel. It is therefore possible that they had access to visual cues generated as a consequence of the haptic stimulus, potentially transposing the haptic cue to a visual-haptic multisensory one. Multisensory cues generate more robust neural responses and generally lead to faster and more accurate behavioral responses (e.g., Holmes & Spence, 2005; Rowland et al., 2007; Stevenson et al., 2014). It remains to be seen whether any such multisensory benefit is at play in the current paradigm where the effective cue was the direction of the jerk, which was designed to be suprathreshold and unambiguous.

A final note can be made about the lack of pertinent inertial cues concomitant with making a lane change due to the use of a fixed-base driving simulator. With such a platform, a driver’s main sources of sensory information are the visual feedback from observing the consequences of moving through the (simulated) environment and the efference copy information from effecting movements on the steering wheel. While the absence of inertial cues affects drivers’ ability to sense how their steering actions might affect vehicle position as well as their ability to execute an accurate lane change (Macuga et al., 2007), it remains to be explored if, and how, it affects their planning of the lane change.

Implications for practice and research

This study is in line with the development of vehicle automation at levels 1 (driver assistance) and 2 (partial driver automation) according to the classification drawn up by the Society of Automotive Engineers (2021). However, the aim of the study was not to provide an empirical demonstration of the effectiveness and benefits of a system that could be implemented in a commercial vehicle. For that, further ergonomic studies under more realistic driving conditions would be required. However, the question of using the haptic modality to initiate trajectory correction movements is an open one. This study focused on the psychomotor processes that could be important in achieving this goal. This involved evaluating these processes in the context of a task that relies on skills acquired in real-life driving while maintaining strict experimental control.

The all-round superior performance in the condition with only haptic cues provides further empirical support for the introduction of haptic steering wheel feedback in vehicle automation (Breitschaft et al., 2019; Gaffary & Lécuyer, 2018; Petermeijer et al., 2015). Not only did we observe a gain in response time of about 60 ms relative to having only visual cues (i.e., a gain of about 1 m, at 60 km/h), but also there were virtually no initial steering errors. Contrary to vibrotactile alerts, which are not effective replacements for visual direction cues (Prewett et al., 2012), force feedback on the steering wheel does allow for unambiguous directional cues. Arguably, the combination of gaining time and making appropriate steering actions will be a positive contribution toward accident prevention.

In spite of the demonstrated potential of in-vehicle haptics, a number of issues need to be acknowledged and investigated. There are reasons to be concerned about whether a driver would pick up the haptic stimulus as well as they should. For instance, there is evidence that active movements can suppress tactile perception in the moving body part (Chapman 1994; Vitello et al., 2006; Ziat et al., 2010; but see Frissen et al., 2012). Similarly, haptic stimuli have been shown to be susceptible to masking by sudden presentations of auditory or visual stimuli (Spence & Ho, 2008) or by ambient vibration (Meng et al., 2015). One approach to appreciating the robustness of the benefits of in-vehicle haptics is by extending the ecological validity of studies by considering more realistic scenarios. Increased ecological validity yields the facility of adding potentially important factors. One such factor would involve including moving traffic or static obstacles in order to elicit more compelling reasons (i.e., pressure) for the participant to perform correctly. After all, while the current lane change task was speeded through instruction, there were no (simulated) consequences associated with a late or incorrect response. A related factor would be to strategically vary the perceptual (e.g., Meng et al., 2015) and cognitive (e.g., Gaffary & Lécuyer, 2018) workload for the driver. On a more practical side, studies will need to be conducted that are dedicated to understanding the long-term effects of driving with haptic assistance and/or warning systems.

A final consideration made here is that, even when controlled experiments are able to demonstrate objective benefits this does not necessarily translate into *subjectively experienced* benefits. The effects of in-vehicle haptics have been assessed with a large array of subjective measures, including the NASA-TLX (e.g., Katzourakis et al., 2014), task difficulty ratings (e.g., Fitch et al., 2011), satisfaction (e.g., Chun et al., 2012, 2013), perceived usefulness/helpfulness (e.g., Chun et al., 2012, 2013; Kozak et al., 2006), and user preference (Dass et al., 2013; Huang et al., 2015; Navarro et al., 2010). Navarro et al. (2010), for instance, found that their motor priming device was the least preferred when compared to a range of other warning devices, despite producing the best performance. Participant interviews revealed that the motor priming device was judged to be less helpful, less acceptable, and more intrusive, than the other devices. Similarly, participants in a study by Kozak et al. (2006) reported that they found a directional steering wheel torque device less helpful and less acceptable than an auditory warning or a simple steering wheel vibration. In other words, developing an objectively effective in-vehicle haptic device does not mean that drivers will like it, potentially leading to disuse (Parasuraman & Riley, 1997).

Conclusion

This study used the movement precuing technique to tap into the psychomotor processes underlying the motor planning for imminent lane changes with advanced visual, haptic, and crossmodal information. One main result was that response to haptic imperative cues produced considerably faster responses than conditions with a visual imperative cue, irrespective of the precue modality. Another finding was one particular exception to the typical cue validity effect associated with the precuing technique. There appeared to be little cost in response time or steering errors associated with invalid cueing when both cues were haptic.

As the catalog of in-vehicle haptic devices keeps growing, the real-world use of haptic warning and assistance systems is becoming a tangible reality. But with every new addition to the catalog comes a potentially new way in which the haptic perceptual system is engaged. Indeed, the catalog is becoming big enough that it apparently warrants three different typologies (Breitschaft et al., 2019; Gaffary & Lécuyer, 2018; Petermeijer et al., 2015). If the modes of communication between the human and the car are to be properly supported, there is a need for research that goes beyond adding empirical demonstrations of the efficacy and benefits of any particular device to our catalogs. Instead, there is a need for a new lane of fundamental research aimed at understanding the psychomotor processes that are at play when haptic devices are employed. With the current study, we hope to have changed into that lane.

Acknowledgements We would like to thank Ewen Carcreff for helpful contributions to the analysis of the movement profiles, and all the participants who volunteered their time. We have no conflicts of interest to disclose.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by IF. The first draft of the manuscript was written by IF and all authors commented on, and wrote for, previous versions of the manuscript. All authors read and approved the final manuscript.

Funding No funding was received for conducting this study.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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