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Tactile encoding of directions and temporal distances to safety hazards supports drivers in overtaking and intersection scenarios

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ABSTRACT

Safe traffic participation requires continuous monitoring of the environment for potential safety hazards. Here we investigate, to what extent an interface using directed tactile stimuli to communicate temporal distances to approaching objects can make drivers feel supported and influence their driving safety. In contrast to previous studies, we focus on conditions in which the driver has relatively high levels of control over the criticality of evolving hazards as well as on scenarios with laterally approaching hazards. In a dynamic driving simulator experiment, 33 participants completed a selection of overtaking and intersection scenarios with and without sensory support. Furthermore, two novel variants of the interface which differed in the resolution of the temporal distance encoding were utilized. We measured safety, quantified as minimum time-to-contact (mTTC) and rate of critical situations, and assessed the participants' subjective understanding, acceptance and perceived helpfulness of the support functions. Participants understood the system in both variants after brief exposure. The subjective evaluation was positive with regard to helpfulness, acceptance, and custom questionnaire responses. While mTTC values did not differ between supported and baseline drives, the availability of the system reduced the occurrence of safety–critical situations in intersection scenarios. Driving statistics further reveal that the availability of the system increased the likelihood for entering system-relevant signaling ranges in overtaking scenarios. In sum, the presented work extends previous findings by showing that the subjective utility of the investigated tactile interface applies beyond critical situations and that it can also provide a safety advantage at intersections.

1. Introduction

In dynamic environments, the task of driving a vehicle requires drivers to continuously monitor the surroundings in order to identify potential safety hazards and navigate successfully. Drivers thereby primarily rely on visual cues as these can quickly and accurately provide information about nearby as well as distant objects and events. Furthermore, invariants in dynamic visual features such as laterally stable points of optical expansion might enable us to recognize our direction of movement and identify approaching objects with little cognitive effort (Gibson, 1979; Lee, 1976; Todd, 1981). Nevertheless, peoples' visual sampling rate and bandwidth are bounded. Especially when a large spatial coverage with rear- and side monitoring is required, such as for driving, the sequential nature of saccade-driven visual sampling puts limits on how many objects or directions can be monitored within a given time interval.

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Nomenclature

TTC	time-to-contact/time-to-collision: the time it would take for two objects to collide when assuming that velocities and trajectories are maintained
mTTC	minimum time-to-contact: smallest value in a set of TTC estimates
THW	time headway: distance to the current location of another object measured in time
LLI	Lateral Line Interface: interface that utilizes a belt of tactile actuators to create stimuli that encode direction and TTC information
continuous LLI	LLI with a continuous TTC-intensity encoding
binary LLI	LLI with a binary TTC-intensity encoding

This limitation becomes noticeable when the complexity of a situation increases, which typically results in a velocity reduction (Ludwig et al., 2018; Marciano and Yeshurun, 2012b; Marciano and Yeshurun, 2012a) to cope with the high perceptual load. For trucks and other large vehicles, also distance and visual occlusion pose typical challenges to scene perception that create a need for perceptual assistance.

1.1. Related Work

Attempts to support a driver's scene understanding have been made by utilizing various visual interfaces (Garesche, 2000; Hinninger et al., 2012; Wang et al., 2014). Such interfaces however, have the inherent property of competing with the actual visible scene for the driver's visual attention and, accordingly, can even increase visual load. Assuming the existence of parallel processing streams for distinct sensory modalities (Sarter, 2007; Wahn et al., 2016), a more suitable strategy to improve people's ability to navigate through complex dynamic environments consists of interfacing with other sensory modalities like hearing and touch.

There are a variety of examples in which auditory stimuli are used to alert drivers about safety-relevant events (Graham, 1999; McKeown, 2005; Glatz et al., 2014), such as for frontal collision warnings (Sugimoto and Sauer, 2005; Stein et al., 2016) and for parking support (Yasui and Iisaka, 2002; Iwama, 2006). Also tactile (Pielot et al., 2008; Kern et al., 2009) and kinesthetic stimuli (Maag et al., 2015) have been investigated as a potential informative medium and are a popular stimulus choice for lane departure warnings (Motoyama et al., 2000; Beruscha et al., 2011; Deroo et al., 2013) and lane-keeping assistance (Ishida and Gayko, 2004; Roozendaal et al., 2020).

Tactile stimuli have multiple properties that make them eligible for use in driver assistance (see Krüger et al., 2018). During driving, the tactile sense is not utilized for most body parts, resulting in a large available surface area for tactile communication. Tactile perception further does not rely on active scanning (Sarter, 2000) and is intuitively localizable (Fitch et al., 2007), which can make it suitable for input that encodes spatial information and requires alerting characteristics. The lack of competition with information sampling from other sensory modalities (Sarter, 2007; Hancock et al., 2013; Wahn et al., 2016) further entails the possibility to use it for a transmission of complementary information. Both De Rosario et al. (2010) and Lylykangas et al. (2016) found that vibrotactile frontal collision warnings delivered through the accelerator pedal were more effective than visual signals and resulted in faster driver reactions. Ho et al. (2005) discovered that spatially-predictive vibrotactile cues speed up responses to potential emergency situations, suggesting advantageous properties in spatial encodings. Petermeijer et al. (2015) who have surveyed 70 studies on haptic driver assistance concluded that haptic feedback can improve driving performance, reduce reaction time and mental workload. Yet they identified a lack of research on their potential for conveying dynamic temporal and spatial patterns.

1.2. The Lateral Line Interface

The presented work aims at filling this gap. As initial steps towards that goal, Krüger et al. (2018, 2019, 2020b) have introduced a concept for driver assistance that uses directed tactile stimuli around the core of a driver's body in order to inform the driver about approaching objects. While the stimulus location encodes the direction towards an approaching object, the stimulus intensity encodes the *temporal proximity* to the respective object. Here the temporal proximity is defined as the complement of the time-to-contact (TTC) within a fixed temporal range. The use of a temporal encoding makes the stimulus intensity a function of both distance and relative velocity. This dependence on two variables allows for a generation of meaningful stimuli for arbitrary spatial distance ranges (see Krüger et al., 2020b) and thus a large diversity of scenarios in which the assistance can be applicable. In reference to the lateral line, a system of organs used by many aquatic vertebrates to sense local changes in water pressure (Pitcher et al., 1976; Coombs et al., 2001), the authors labeled this concept *Lateral Line Interface* (LLI). They evaluated effects of this form of assistance in simulated highway situations of high criticality and found that participants were able to utilize it to improve their perceived and objective safety after only a few minutes of exposure.

The LLI stimuli have at least two properties which can account for such effects: 1. The presence or absence of a stimulus encodes whether or not a safety hazard approaches from a given direction (binary presence information). This information alone may suffice to speed up hazard detection. 2. The intensity of a stimulus informs about how close or urgent an approaching hazard is (continuous urgency information). This has the additional value of facilitating prioritization of actions, especially in the presence of multiple hazards. Furthermore, it has been suggested that people are already utilizing TTC information during movement (Lee, 1976; Cavallo

and Laurent, 1988; Hoffmann and Mortimer, 1994). For instance, Van der Horst (1991) found that drivers' braking response follows a TTC threshold.

1.3. Open Questions

Although questionnaire and interview responses reported by Krüger et al. (2018) indicated that participants understood and utilized the stimulus intensity, the practical contribution of the time-contingent stimulus intensity has not yet been addressed. With the present work we investigate the role of the time-contingent stimulus intensity explicitly by a comparison of binary and continuous signal variants.

Such a comparison can be particularly insightful in situations in which the time information gives the driver a theoretical advantage. An example for such a situation is a scenario in which multiple vehicles are simultaneously approaching the ego-vehicle but are predicted to collide with it at different times. In this scenario a variable intensity could help a driver to prioritize the most urgent of multiple concurrent stimulus sources. Scenarios with laterally crossing traffic such as intersections can provide an appropriate basis for addressing the value of a continuous encoding.

Another open question is whether the reported safety advantages generalize to scenarios that differ from the tested highway overtaking scenarios. Krüger et al. (2020a) found that, on average, LLI-usage increased the safety by more than 2 s in highway scenarios with strongly limited visibility and thus even higher inherent criticality. An investigation of cases with reduced criticality, in which the LLI may be utilized outside the scope of a warning device, has not yet been reported and constitutes another contribution of the present work. The earlier drivers become aware of potential upcoming hazards, the more foresighted their driving behavior can be. Assistance utility in situations of reduced criticality could thus even have the potential to reduce the occurrence of more critical situations.

In the context of the LLI, we define scenarios of reduced initial criticality (compared to previous studies) as scenarios in which a driver can manage to avert a collision already near the edge of the stimulus onset threshold of 5 s without falling into a 0-3 s TTC range.

With the information provided by an LLI, drivers should be able to more accurately assess the safety of situations and adjust their behavior accordingly. By basing predictions on present conditions, the LLI assumes a function within a feedback loop (Carver and Scheier, 1990; Fuller, 2011) that tells a driver whether the last action leading to the current state was safety-reducing or safety-increasing. The safety increase in critical situations reported by Krüger et al. (2020b) supports this perspective. Additionally, driving adjustments may be efficiency-driven (Kapeller et al., 2021). Typically, a driver implicitly balances a safety- and an efficiency objective on the way to a destination.

An example in which the two objectives are weighted against each other is a situation on a multi-lane road with a decelerating vehicle in the front. Maintaining the own speed, with an intention to overtake once a gap opens on the fast lane, temporarily reduces the safety but not the efficiency. Matching the velocity of the slow front vehicle improves the safety but reduces efficiency due to braking (energy loss) and slowing down (time loss) which in turn reduces the chance of overtaking successfully. For many drivers, decisions might additionally be influenced by a *fairness objective*. In traffic, each action can have consequences for other traffic participants' set of operational possibilities. Selecting actions that maximize this set for all affected traffic participants aids the promotion of safety and efficiency on a wider scope and can hence be a worthwhile objective in foresighted driving (Dietrich and Weisswange, 2019).

We hypothesize that the choice to act one way or another depends on how the driver judges it to affect individual objectives. Thus the driver's ability to correctly assess the consequences of possible actions would be a determining factor. The purpose of the LLI is to support the driver in this assessment.

Here we aim to extend the understanding of the effects of LLI-usage on driving experience, driver behavior and safety.

1.4. Research Hypotheses

Based on the above reasoning about the utilization of encoded time information and behavioral effects of system utilization under reduced criticality, we propose the following research hypotheses:

H1 (subjective benefit): Drivers benefit subjectively from direction and TTC-based urgency information encoded in tactile stimuli to improve safety in
a: highway overtaking scenarios with low criticality
b: intersection scenarios with lateral traffic

H2 (objective benefit): Drivers present higher driving safety levels when assisted by direction and TTC-based urgency information encoded in tactile stimuli in
a: highway overtaking scenarios with low criticality
b: intersection scenarios with lateral traffic

H3 (advantage of time encoding): Continuous tactile TTC-based urgency signaling provides a larger subjective and objective benefit than binary signaling that does not differentiate between different levels of sub-threshold urgency.

To investigate these hypotheses we present a new driving simulator study in which we tested the effects of binary and continuous LLI variants in two classes of driving scenarios.

The remaining article is divided into three parts: *Materials and Methods*, *Results*, and *Discussion*. The *Materials and Methods* section starts with a description of the interface and stimuli of the investigated assistance. This is followed by descriptions of the data

acquisition processes, including participant selection, experimental design, and procedure description. The final part of the *Materials and Methods* section describes the methods of data analysis. The *Results* section contains results descriptions according to the data analysis methods illustrated previously. The section separates results based on subjective reports such as questionnaires and results that refer to driver behavior and performance. Results are interpreted in terms of the research hypotheses specified above this paragraph. Finally, in the *Discussion* section we summarize, critically discuss, and interpret the results. Furthermore, proposals for future work are derived from the discussion.

2. Materials and Methods

This section describes the individual components of the study. First, we introduce the tactile interface and stimuli that were utilized to realize two variants of the previously mentioned *Lateral Line Interface* (LLI). Next we describe the driving simulator setup and the different scenarios in which these interfaces were employed, followed by a description of the data acquisition process. The section concludes with our data analysis procedure.

2.1. Tactile Interface

To generate tactile stimuli we used belt-like interfaces containing 16 equally spaced eccentric rotation mass motors that are triggered with 50 ms latency (feelSpace GmbH, Nagel et al., 2005). These actuators can vibrate with a maximum amplitude of 2.2 g and have a frequency spectrum of 50–240 Hz (0.45–3.3 V). Frequency and amplitude scale almost linearly with voltage. However, this physical stimulus magnitude does not necessarily map linearly to a perceived magnitude. For various senses the relationship between physical and perceived stimulus magnitude can be more accurately expressed in a power law (Fechner, 1860; Stevens, 2017) where exponent values vary across sensory modalities and stimulus sites (Stevens, 2017). As described by Krüger et al. (2018, 2020a, 2020b) who used the same actuators and stimulus locations, the perceived stimulus magnitude for vibrations in the sub 250 Hz range on the body has been found to scale approximately linearly with reference exponents ranging from 0.75 to 0.97 (Merchel et al., 2015). For stimulus intensity scaling, we decided to use an exponent of 0.83 which is the reference value obtained by Merchel et al. (2015).

Because firm contact with the actuators is critical for intensity perception, we used five different belt sizes that can accommodate different body shapes. Depending on the size, the actuators are spaced between 4.9 and 6.5 cm apart. With this setup it is theoretically possible to produce a so-called funneling illusion (Barghout et al., 2009; Kerdegari et al., 2014) which describes a perception of one stimulus which appears to be located between two neighboring actuators that are simultaneously active. However, the design of our scenarios contained no instances of simultaneously signaled objects that were located close enough to each other to induce such an illusion. Therefore, we were able to take advantage of the high spatial resolution of the interface without having to fear a confound from funneling effects. The spacing of actuators also allows for an illusion of apparent motion (Van Erp, 2002) when neighboring actuators are subsequently triggered. In our setup, this case could occur whenever the angle between the ego-vehicle and a signaled object changes. We argue that such a perception of movement is likely to help drivers to correctly attribute stimuli to a moving object in the environment and thus facilitate scene understanding.

2.2. Stimulus Encoding

We mapped two types of information about approaching objects to tactile stimuli. First, the direction of any approaching object relative to the ego-vehicle was mapped to a stimulus location on the belt.

To do so, the angle between the ego-vehicle and an approaching object was calculated in ego-centered coordinates and mapped to one of sixteen ranges of 22.5° that were associated with individual vibromotors.

The angle γ between the ego-vehicle a and an approaching object b was obtained by taking the *arctantwo* function of the difference $\overrightarrow{d}$ between their position coordinates $\overrightarrow{a}$ and $\overrightarrow{b}$ (see Eq. 1).

$$\begin{aligned} \overrightarrow{d} &= \overrightarrow{b} - \overrightarrow{a} \\ \gamma &= arctantwo(d_x, d_y). \end{aligned} \tag{1}$$

Second, a bound temporal proximity between ego-vehicle and the approaching object was mapped to the intensity of tactile stimuli. Here we define the bound temporal proximity as the complement of the time-to-contact (TTC) between the ego-vehicle and another object that is on a collision track with the ego-vehicle within a limited time range. As TTC we understand the time it would take two objects to collide when assuming that they maintain their current velocities and movement directions (Hayward, 1972). Accelerations are not taken into account.

For two vehicles a and b, driving behind each other on the same lane, the TTC between them consists of the distance d_{ab} divided by the relative velocity $v_b - v_a$.

$$TTC_{1D} = \begin{cases} \dfrac{d_{ab}}{v_b - v_a}, & \text{if } v_b > v_a \\ \infty, \text{otherwise.} \end{cases} \tag{2}$$

However, the LLI does not just require TTC information for the front or back directions but for arbitrary directions in the 2D plane.

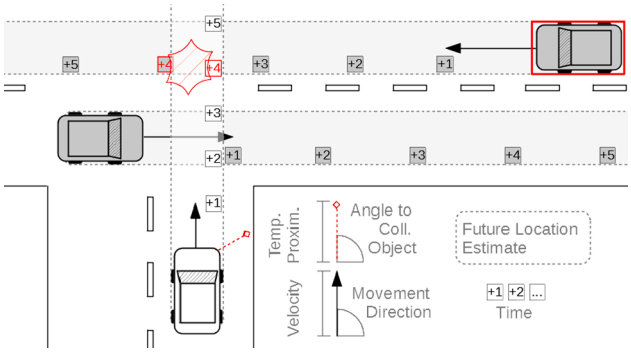


Fig. 1. Illustration of the TTC estimation procedure with two spatial dimensions. Predicted trajectories are annotated with time markers that indicate the predicted vehicle's front position at the respective time. Arrows represent the moving direction (angle) and velocity (length). Vehicles with a predicted collision (spatial and temporal overlap) are highlighted.

Here we therefore implemented a different approach that predicts the TTC based on individual extents and estimated trajectories of objects in the environment.

2.2.1. TTC-2D

In a first step, the positions, orientations, velocities and extents of movable objects in the environment are obtained. Based on these, the future trajectories of the objects are calculated and spatially expanded according to individual object extents, resulting in a set of trajectory polygons. To limit the need of computational resources, trajectories are only estimated up until a specified future point in time t_{max}.

The program then checks for a spatial and temporal overlap between the trajectory polygons of ambient objects and the ego-vehicle. In case of a detected spatiotemporal overlap, the time of the first predicted overlap is taken as the TTC towards that object[1]. Otherwise the TTC for that object is considered to be infinite.

Algorithm 1. TTC_{2D} computation in pseudocode.

for *each object* **do**
  Compute future trajectory from location, orientation and velocity;
  $\forall t \in \{t_0 < t \leq t_{max}\}, pos_t = \begin{pmatrix} x + d_t \cos(\alpha) \\ y + d_t \sin(\alpha) \end{pmatrix}$;
  Create space-time polygon from trajectory and extents;
  if *object == ego vehicle* **then**
    Store *ego-polygon*;
  else
    if *intersects with ego-polygon (in space and time)* **then**
      TTC = time of first intersection;
    else
      TTC = ∞;
    end
  end
end

[1] Our method for collision prediction relies on momentary trajectories and relative velocities to create one predicted path for each vehicle at a time. It does not consider any uncertainty about the future behavior of each vehicle which could result in alternative predictions with varying probabilities for each vehicle. Our method may thus be classified as deterministic. For a probabilistic approach which aims to incorporate some of this uncertainty to derive a broader prediction of a collision risk than the TTC, see Eggert and Puphal (2017).

2.2.2. Intensity

We created two LLI variants which differed in how the stimulus intensity was utilized to encode information.

For objects with a TTC above the threshold θ of five seconds, no stimulus was generated (intensity $= 0$). We chose this threshold because it approximates the limit at which present-day systems can make event predictions (Schmüdderich et al., 2015; Chen and Hsiung, 2018) and because prior research on driver behavior (Van and Hogema, 1994) suggests a TTC of 4.5 to 5 s as an appropriate activation threshold for collision avoidance systems.

For the first LLI variant the stimulus intensity I was set to increase with falling TTC according to Eq. 3. Here s stands for the chosen Stephens' exponent of 0.83. Due to this continuous mapping from TTC to intensity, we term this LLI variant *continuous LLI*.

$$I_{continuous} = max\left(\frac{\theta - TTC}{\theta}, 0\right)^{\frac{1}{s}}. \tag{3}$$

For the second LLI variant, the intensity was not varied for any TTC below that threshold but kept at a constant level μ corresponding to the continuous intensity level at $TTC = 0.5 \cdot \theta$. Due to this binary mapping from TTC to intensity, we term this LLI variant *binary LLI*.

$$I_{binary} = \begin{cases} \mu, & \text{if} TTC < \theta \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

2.3. Driving Simulator

The study took place in the dynamic driving simulator of the Würzburg Institute for Traffic Science (WIVW). The integrated vehicle's console contains commonly available instrumentation with automatic transmission. The simulator's motion system uses six degrees of freedom and can briefly realize a linear acceleration up to 5 m/s^2 or 100°/s^2 on a rotary scale. It consists of 6 electropneumatic actuators (stroke +/- 60 cm; inclination +/- 10°). Three LCD projectors (1920 x 1200 px) are installed in the dome of the simulator and provide the driving scene projection with 240° field-of-view. Exterior and interior mirrors are replaced by LCD displays. The test driver can be observed via a video system and communicate to a system operator via an intercom system. System operation is controlled from a separate operating room. SILAB (WIVW GmbH) was used as driving simulation software.

2.4. Data Acquisition

2.4.1. Participants:

The study included 33 participants, selected from a panel of trained test drivers maintained by the WIVW GmbH. All drivers were trained in simulator driving according to a training procedure specified by Hoffmann and Buld (1960) and had experience with participating in traffic research. All participants were naive to the LLI. 18 drivers were female (9 experienced, 9 inexperienced) and 17 drivers were male (9 experienced, 8 inexperienced). Drivers were categorized as *experienced* if they reported to have driven more than 100000 km in their life and more than 10000 km per year. Drivers who did not meet these criteria where categorized as *inexperienced*. These definitions are in line with previous studies which used similar driving experience classification criteria (Rösler, 2010; Wallis and Horswill, 2007).

2.4.2. Experimental Design:

We carried out a mixed design study with two independent groups of participants, where members of the first group would be driving with the binary LLI and members of the second group with the continuous LLI. Within each group we carried out a repeated measures experiment with the independent variables *assistance* (baseline, assisted) and *scenario* (longitudinal, lateral). In the lateral condition we further distinguished between two scenario variants as described in Section 2.4.3, resulting in the addition of the independent variable *scenario variant* (unidirectional, bi-directional) for trials with lateral traffic. (see Fig. 1).

Figure 2 illustrates the experimental procedure. One experimental session consisted of four blocks. The first block consisted of unassisted drives in highway (longitudinal) and intersection (lateral) scenarios which are further specified in section 2.4.3. The purpose of this block was to obtain baseline driving data prior to any LLI exposure for each participant.

In the second block, the LLI was introduced to the participants and they were given the opportunity to freely explore its functionality in a set of subsequent exploration scenarios which are further specified in section 2.4.3. Accordingly, the purpose of this second block was the introduction and first familiarization with the LLI.

In the third block, participants had to drive again through either the same highway- or the same intersection scenarios as in block one. However, in this block the LLI was enabled for the first 12 trials (assisted) and then disabled again for 12 trials (baseline) in order to also obtain secondary baseline data after LLI exposure for each participant and scenario. For half of the participants within a group, block 3 consisted of intersection trials (lateral), for the other half it consisted of highway trials (longitudinal).

In terms of driving, block 4 had the same conditions as block 3 with the only difference that different driving scenarios were used. Participants who drove through intersection scenarios in block 3 now had to drive in highway scenarios in block 4 and vice versa. Through this last block, assisted and secondary baseline data for each experimental scenario and participant could be acquired.

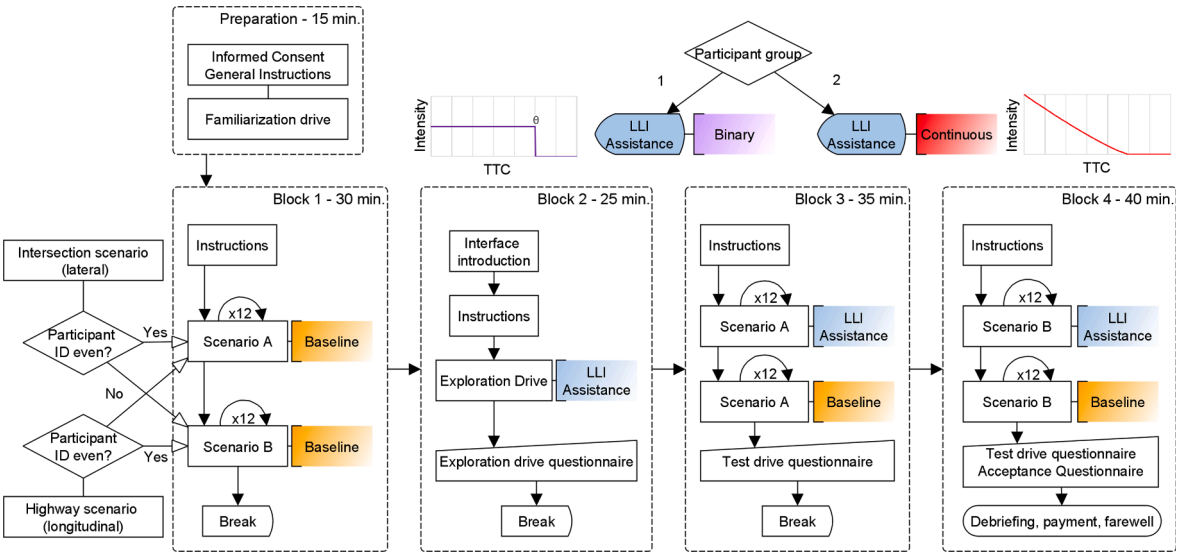


Fig. 2. Experimental procedure with approximate durations for each block. Participants were assigned to one of two groups which differed in the type of LLI assistance (binary or continuous). Within each participant group, for half of the participants scenario A was the longitudinal scenario and scenario B was the lateral scenario. For the other half this assignment was inverted to counter any potential ordering effects. The complete experimental procedure took about 145 min.

For each of the blocks 2, 3, and 4 participants also had to complete a selection of questionnaires further specified in section 2.5.1. The first three blocks concluded with a five minute break.

2.4.3. Driving Scenarios

Exploration Track: An exploration track was included to give participants the opportunity to explore the functionality of the assistance system on their own without prior explanations. It consisted of multiple scenarios which served to gradually familiarize the driver with different aspects of the LLI. Table 1 lists the individual scenarios and corresponding objectives.

Participants were instructed to determine under which circumstances the LLI would be activated and what meaning the stimuli could have.

Longitudinal Scenario: The longitudinal scenario was realized on a two-lane motorway track and consisted of a curved approach section (right-hand bend) and a straight test section. The drivers approached a slightly slower moving front vehicle on the right lane while the left lane was occupied by multiple fast moving vehicles.

The main task for participants was to maintain a target speed (120 to 125 km/h) by overtaking slower moving vehicles when necessary. When the driver reached a time headway (THW) of 2 s the front vehicle decelerated to provoke a faster approach and thereby an activation of the assistance system. When approaching at target speed the corresponding TTC was approximately 7 s at deceleration onset. This gave participants who drove at target speed about 2 s to react prior to stimulus onset in LLI conditions. In the approach phase, the traffic on the left lane developed in a way that either a gap for lane change opened up (4 out of 12 trials) or an existing gap was closed by a rear vehicle (4 out of 12 trials) to avoid scene predictability from experience. Traffic on the left lane was

Table 1
Scenarios and objectives of the exploration track.

Part	Description	Objective
Car following	Two lead vehicles which decelerate one following vehicle	Perceive front and rear activity (longitudinal)
Intersection	Two intersections: 1. vehicle approach from left side 2. vehicle approach from right side	Perceive lateral LLI activity
Gap merge	Driver must enter the motorway and find a gap for merging into traffic	Infer best gap through stimulus intensity
Motorway	Scenario with varying vehicle platoons: 1. cars on right lane 2. cars on both lanes (displaced) 3. bikes on right lane 4. bikes on both lanes	Experience possibility for active manipulation of signals through action

realized as a platoon with an infinite amount of cars. In order to maintain the target speed, participants had to overtake the slowing front vehicle in most trials. The period between the moment of front vehicle brake onset and the moment of successful overtaking defined a valid trial. However, in 4 out of 12 trials the front vehicle would not decelerate and accordingly require no overtaking maneuver. These trials were included as distractor trials and were not considered in the data analysis. During periods between trials the vehicles on the right lane allowed for undisturbed driving at target speed.

Lateral Scenario: The lateral scenario consisted of an inner-city intersection situation. The main task was to cross the stream of vehicles which approached from either the left or right intersection arm. Situation predictability was counteracted through a combination of different gap sizes with different approach speeds (first scenario: v = 8.4 m/s, gap size/ THW = 4.5 s, second scenario: 13.8 m/s, gap size/ THW = 3.0 s). In order to encourage the participants to cross the stream of other road users, the secondary task of the participants was to follow a guidance vehicle driving at 50 km/h, which acted as a navigator and crossed the intersection collision-free already before the participants. We opted for car-following as an implicit, yet effective method of navigation (see e.g. Fulu et al., 2020) which we estimated to interfere less with driver perception than explicit navigation instructions. In addition, the participants were informed that the traffic routing had been changed and therefore the traffic rules at the intersection would be ambiguous for both the participants and the other road users. This instruction offered an explanation for why other road users would not comply with the right-of-way rule or "expect" the participant to do so either.

In addition to situations in which vehicles approached from only one of the intersection arms, for a subset of 4 out of 12 situations per block the scenario was altered to include approaching vehicles from both sides. In these situations two vehicles would initially approach the intersection with the same velocity (v = 13.8 m/s) from opposing directions. However, one of the vehicles would decelerate before reaching the intersection and come to a halt in order to yield to the ego vehicle while the other vehicle would continue crossing the intersection at constant velocity. A driver would need to notice which of the vehicles remains a collision risk and adjust the vehicle speed accordingly during approach and intersection crossing. For both scenario variants we defined a trial as the period during which the vehicle was driving in the region starting 70 meters in front of the intersection and ending at the opposite site of the intersection.

2.4.4. Experiment Procedure:

Upon arrival, participants were welcomed and asked to read and fill out an informed consent form, a privacy statement and a short questionnaire for demographic data. The experimenter then explained that the study is concerned with the evaluation of a new type of driver assistance that utilizes vibrations. These vibrations are transmitted by means of a waist belt that is equipped with vibromotors.

Participants were then instructed to do a familiarization drive for a few minutes before starting the actual experiment according to a procedure specified by Hoffmann et al. (2003). Next, the experimenter explained that multiple driving blocks in and out of town would follow and that participants would need to complete these blocks with and without the tactile assistance while complying with the local road traffic regulations. The blocks were structured according to Section 2.4.2. Between blocks, participants could take a break if desired. After completion of all experimental blocks and questionnaires, participants were debriefed, compensated, and dismissed. One session took about 145 min. Figure 2 illustrates the complete experimental procedure.

2.5. Data Analysis

We used a variety of measures to assess both the subjective experience with the system and the objective driving performance. Here we describe these measures.

2.5.1. Subjective Measures:

Exploration- and Test Drive Questionnaires: For the exploration block and the two test drive blocks (longitudinal and lateral) we used custom questionnaires to assess the participants' experience with the LLI. These questionnaires contained statements for which participants could indicate their agreement on a 7 point Likert scale ranging from *strongly disagree* to *strongly agree*. Following the questionnaire after the exploration drive, participants were asked the following three interview questions targeting aspects which were difficult to capture using Likert-style items: "What do you think does the belt signal mean?", "What did different signals strengths mean?", "What does the signal location indicate?". Because custom questionnaire items only related to assisted drives and not to baseline drives, we analyzed data for custom questionnaire items descriptively based on median responses and interquartile ranges. For interview questions we categorized individual responses based on semantic similarity and used category counts for a descriptive analysis.

Perceived Helpfulness: After each trial with an active LLI, participants were asked to verbally confirm whether or not they had noticed the assistance in the preceding situation and to rate its helpfulness on a 7 point ordinal scale ranging from −3 (*not helpful at all*) to 3 (*quite helpful*). Thus, the helpfulness ratings provide a close to real-time subjective evaluation. We tested the effects of stimulus mode and scenario variant (lateral) on helpfulness ratings using two proportional odds logistic regression models, also known as cumulative link model which are regarded as an appropriate method for the treatment of ordinal data that correctly treat observations as categorical (Agresti, 2003; Christensen, 2018) - one for longitudinal and one for lateral scenarios. To test if ratings were positive we used one-sided one-sample t-tests with Bonferroni adjusted alpha levels for repeated testing.

Acceptance: At the end of the experiment participants completed the Van der Laan acceptance questionnaire (Van Der Laan et al., 1997). This questionnaire utilizes nine items to assess the *acceptance* of the LLI on two dimensions termed *usefulness* and *satisfaction*, both of which range from -2 (worst) to 2 (best). We compared these scores between stimulus modes using Mann–Whitney-U-tests because usefulness and satisfaction scores are derived from ordinal Likert items. To test whether acceptance was positive we used

additional one-sample Wilcoxon signed rank tests with Bonferroni adjusted alpha levels. Because this questionnaire was only used at the end of the experiment, no differentiation between scenarios was possible.

2.5.2. Objective Measures:

We were interested in how LLI usage would affect driver behavior and, in particular, whether and how it affects driving safety. The following measures were used to assess these aspects:

Minimum Time-to-Contact: The *minimum time-to-contact* (mTTC) is a continuous measure that describes the smallest value in a given set of TTC estimates. In our case this set contains TTC values for all recording steps within a trial and across all directions on a 2D plane. The mTTC is thus an expression for how dangerous a trial got at most, with low values indicating high levels of imminence and vice versa. Fluctuations in TTC levels are natural in traffic and dynamic scenarios with moving agents in general (Van der Horst, 1991). However, as the TTC falls, opportunities to avert a collision are increasingly constrained. Below 3 s the TTC approaches dangerous levels which should be avoided for safe driving.

We tested the effects of assistance and stimulus mode on mTTC scores using linear regression models due to their flexibility in terms of predictor types. For the lateral scenario we included additional predictor terms for scenario variant and the interaction between scenario variant and stimulus mode. As we only used categorical predictors, the regression analysis can also be interpreted as analysis of variance (ANOVA).

Critical Situations: The mTTC also served as the basis for our second objective measure, the occurrence of safety–critical situations. We defined such situations as trials in which the mTTC fell below a threshold of one second. While falling below this threshold does not necessarily entail that a collision occurred, doing so is at least a near-miss case and sufficiently critical (Hayward, 1972; Van der Horst, 1991) to be avoided whenever possible. Due to the binary classification of criticality we tested the effects of assistance and stimulus mode on the occurrence of critical situations using binomial logistic regression models. For the lateral condition we added predictor terms for scenario variant and the interaction between scenario variant and stimulus mode.

LLI Activation: The longitudinal condition was designed to contain an evolving hazard in the form of a braking front vehicle but should nevertheless give the driver sufficient time and opportunity to resolve the situation safely. However, this also had the effect that it was not guaranteed that the vehicle would necessarily enter a state that would trigger LLI activation despite a deceleration of a front vehicle. This property of the scenario allowed us to additionally investigate, whether the availability of the LLI would have an effect on the probability to enter a state of system activation. An increase in such cases could be interpreted as an indication for a utilization of the LLI for information sampling whereas a decrease could indicate an increased aversion of either stimulus-triggering conditions or of the stimuli themselves. We tested the effects of assistance and stimulus mode on the occurrence of LLI relevant trials using binomial logistic regression due to the binary nature of LLI presence. For the lateral condition we added predictor terms for scenario variant and the interaction between scenario variant and stimulus mode.

2.5.3. Postprocessing:

Because we are interested in the effects of LLI usage, we had to ensure that data entering the analysis were accompanied by sufficient participant exposure to the LLI. After all, if a participant should drive so carefully that the LLI signaling range of 5-0 s mTTC is never reached, there would be little grounds for any effect by LLI activation on driver behavior or experience. We therefore applied a filter criterion to exclude blocks in which LLI signaling ranges have not been reached in at least 4 out of 12 trials. Distractor trials were excluded from all analysis by default.

This resulted in an exclusion of 167 trials (=49%) in the longitudinal condition and 0 trials in the lateral condition. We applied the exposure criterion to all test drive block measures except for the occurrences of critical situations and LLI activation because these two quantities are by definition only meaningful with a full availability of opposing data.

In the exploration block the scenario design and experimenter instructions ensured sufficient LLI exposure so that no data filtering criterion had to be applied for exploration data. Data from baseline blocks before and after LLI exposure were merged for each scenario to counteract potential learning effects.

All data were processed with *Python* 3.8 using *pandas* data structures for statistical computing (McKinney, 2010). Subsequent statistical analysis was carried out using *R* (R Core Team, 2020).

3. Results

This section contains study results and their consequences for our research hypotheses stated in the introduction. Detailed interpretations and discussions of the results can be found in the discussion section (4).

3.1. Subjective Reports

3.1.1. LLI Perception after Exploration:

Fig. 3 shows the distribution of responses to custom questionnaire items that followed the exploration drive (exploration drive questionnaire). Overall, participants strongly agreed that they perceived stimuli at different belt locations. They agreed that they had noticed signal changes and varying intensities, and that they perceived the influence of their own behavior on the signals. They also agreed with the statement of having understood the meaning of the signals before the exploration period was over. There was slight agreement about the ability to use signals without conscious thought. Participants did not consider the signals as useless or disturbing. These ratings indicate a quick understanding and subjective utility after the free exploration drive.

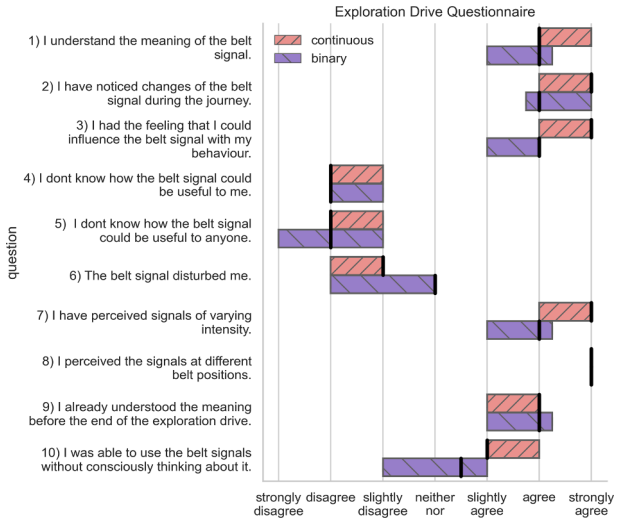


Fig. 3. Exploration drive questionnaire responses (median and interquartile ranges), separated by stimulus mode (binary and continuous LLI).

While a subjective confirmation of understanding reveals that participants may have found a potential explanation for the meaning of LLI signals, it does not confirm that this explanation corresponds to the true meaning. For this reason participants were asked to comment on their understanding of the LLI in their own words. Fig. 4 shows the distribution of responses after a conversion from individual statements into categories that can describe multiple responses. When asked about their understanding of the meaning of signals, participants either attributed the meaning to other vehicles or a risk in the environment. In accordance, stimulus location was linked to the direction of the respective vehicle or danger. Interpretations were similar between the binary and continuous conditions. Signal strength was mainly linked to proximity (mainly continuous LLI) or danger (binary and continuous). One participant thought that it would represent vehicle size and another one understood it as ”speed of approach”. Only one participant in the binary condition reported not perceiving any changes in signal strength. This outcome is in agreement with responses to the corresponding Likert item ”I have perceived signals of varying intensity”. Only one out of 16 participants in the binary LLI group disagreed with this statement, two were neutral, and 13 participants reported having perceived signals of varying intensity. However, this outcome is also surprising as it stands in contrast to the single physical intensity level utilized for the binary LLI.

In summary, the subjective reports after the LLI exploration drive indicate that participants were able to perceive stimuli generated by the LLI and quickly form an understanding about the meaning and utility of these stimuli. Their interpretations largely captured important aspects of the underlying information, suggesting that an uninstructed intuitive utilization can be possible.

3.1.2. LLI Perception after Testing Blocks:

Fig. 5 shows the distributions of responses (median and interquartile ranges) to custom questionnaire items that followed test driving blocks in longitudinal and lateral scenarios (test drive questionnaire). For both scenarios and stimulus modes the participants agreed that LLI signals were pleasant, were helpful in the driving task and made difficult situations easier to resolve. Most participants indicated having used belt signals to adapt their driving behavior to the situations, especially in lateral scenarios where also the perceived usefulness of the directional signal component was higher. These ratings provide first support for our hypothesis H1 (subjective benefit), according to which drivers benefit subjectively from LLI signaling in a) highway overtaking scenarios with low criticality and b) intersection scenarios with lateral traffic.

Participants did not perceive the LLI as distracting or as a negative influence on driving task performance. On average, participants were neutral with respect to having liked to drive with the LLI during the last baseline condition. This may indicate that even though participants recognized the utility of the LLI, in their eyes the longitudinal and lateral scenarios did not necessitate LLI use for safe performance.

For most items there were only small differences between ratings for binary and continuous LLI variants. In the longitudinal scenarios the binary LLI may have higher relative distraction potential than the continuous variant. There was further more agreement about the continuous LLI being usable without conscious thought than the binary variant, albeit only for longitudinal scenarios.

3.1.3. Perceived Helpfulness:

Based on our hypothesis H1 (subjective benefit), we would expect helpfulness ratings to be positive in both scenarios. Hypothesis H3 (advantage of time encoding) would further predict an effect of stimulus mode that indicates higher ratings for the continuous than the binary LLI. Fig. 6 shows the distributions of helpfulness ratings for longitudinal and lateral trials. Table 2 shows the output of the cumulative link models for the longitudinal and lateral conditions (*helpfulness* $\sim$ *stimulus mode* and *helpfulness* $\sim$ *stimulus mode*scenario variant*, respectively). For both longitudinal and lateral trials we found no significant effect for stimulus mode (binary, continuous). For lateral trials we further tested for scenario variants (unidirectional, bi-directional) and

variant-stimulus mode interaction but found no significant effects for either. However, ratings were significantly above 0 (neutral) and thus positive in both longitudinal $t(96) = 10.106, p < 0.001$ and lateral scenarios $t(341) = 26.463, p < 0.001$. These results support our hypothesis H1 (subjective benefit) a) and b). Drivers did benefit subjectively from LLI signaling in both highway and intersection scenarios. Due to the absence of an effect of stimulus mode, the helpfulness ratings provide no support for our hypothesis H3 (advantage of time encoding).

3.1.4. Acceptance:

Based on our hypothesis H1 (subjective benefit), we would expect usefulness and satisfaction scores to be above 0 in both scenarios. Hypothesis H3 (advantage of time encoding) would further predict an effect of stimulus mode that indicates higher ratings for the continuous than the binary LLI.

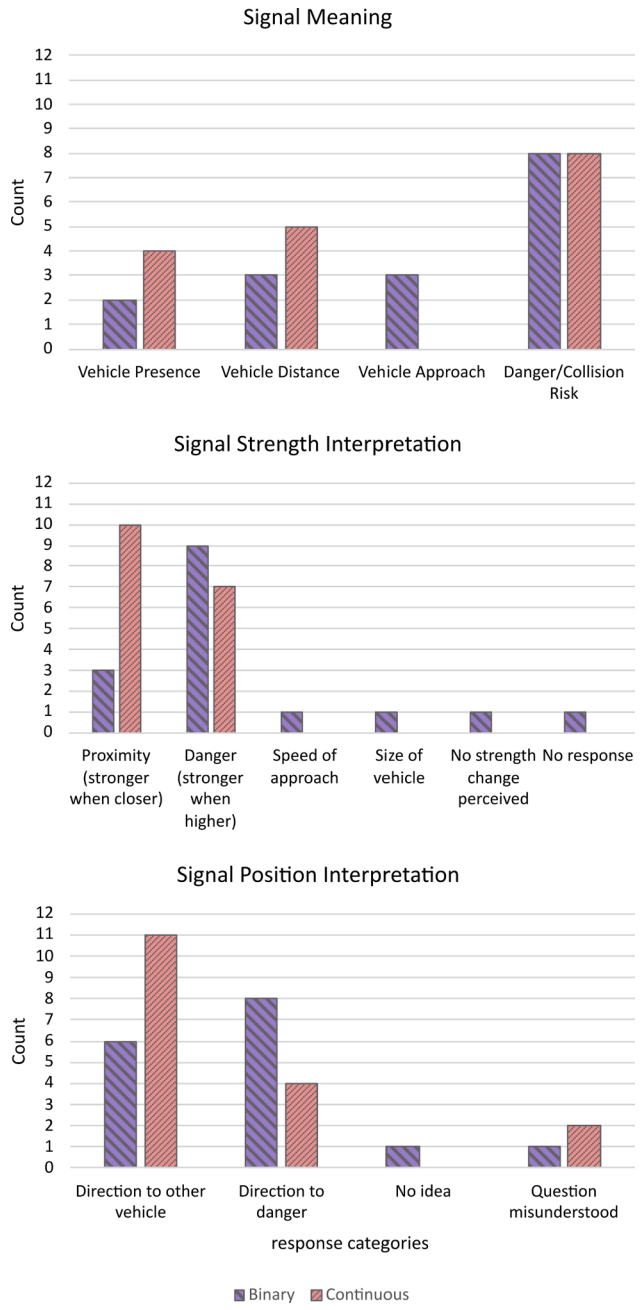


Fig. 4. Counts of categorized responses to three interview questions concerning a) Interpretation of signal meaning, b) Interpretation of signal strength, and c) Interpretation of signal position.

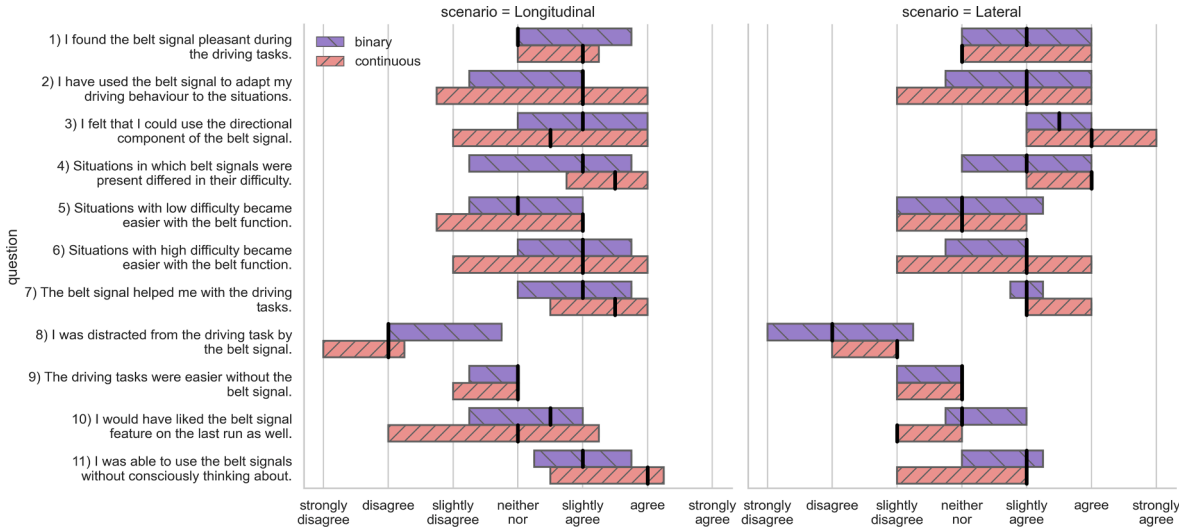


Fig. 5. Test drive questionnaire responses (median and interquartile ranges) for longitudinal (left) and lateral (right) scenarios and separated by stimulus mode (binary and continuous LLI).

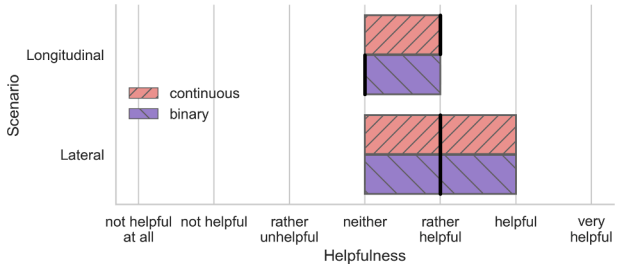


Fig. 6. Helpfulness ratings (median and interquartile ranges) for longitudinal and lateral trials with both binary and continuous LLI stimulus modes.

Fig. 7 shows mean usefulness and satisfaction scores. Neither usefulness ($w = 141.5, p = 0.6$) nor satisfaction scores ($w = 90.5, p = 0.9$) differed significantly between stimulus modes. Therefore our hypothesis H3 (advantage of time encoding) is not supported by acceptance scores. The acceptance ratings do not indicate that continuous signaling provides a larger subjective benefit than binary signaling. However, both usefulness ($v = 418.5, p < 0.001$) and satisfaction ($v = 328, p < 0.01$) are significantly above 0 (neutral) and thus positive. This supports our hypothesis H1 (subjective benefit). In terms of acceptance ratings, drivers benefited subjectively from direction and TTC-based urgency information encoded in tactile stimuli. A distinction between longitudinal and lateral trials is not possible because participants only received the acceptance questionnaire at the end of the experiment.

3.2. Driver Behavior

3.2.1. Minimal Time-To-Contact

Based on our hypotheses we would expect the mTTC to be higher in LLI than in baseline trials (H2 - objective benefit) and to be higher with the continuous LLI than with the binary LLI (H3 - advantage of time encoding). Fig. 8b shows the distributions of mTTC scores with and without an active LLI. In the longitudinal condition mTTC values were distributed near the 5 s LLI activation threshold and only rarely fell below 3.5 s with and without LLI activation (assistance on and off). For lateral trials the mTTC values were distributed around 3 s, regardless of whether a trial was assisted (on) or not (off = baseline).

Table 3 contains the output of the linear regression models of the mTTC for the longitudinal and lateral scenarios ($mTTC \sim stimulus\,mode$ and $mTTC \sim stimulus\,mode * scenario\,variant$, respectively). For both longitudinal and lateral trials there was no significant effect for assistance (LLI on, off). This stands in disagreement with our hypothesis H2 (objective benefit). The mTTC data does not indicate higher safety levels when assisted by the LLI for either a) highway scenarios or b) intersection scenarios. There was no effect for stimulus mode (binary, continuous) in longitudinal trials but a significant effect in lateral trials. In contrast to our hypothesis H3 (advantage of time encoding), according to which the continuous encoding should provide a larger benefit than binary signaling, mTTC values were on average 0.24 s lower with continuous than binary assistance. However, also in baseline trials this difference between groups was 0.26 s, suggesting the presence of an LLI-independent contribution. For lateral trials neither scenario variant nor the interaction between stimulus mode and scenario variant showed significant effects. The mTTC data therefore do not support hypothesis H3 (advantage of time encoding).

Table 2
Helpfulness rating regression coefficients with standard errors in parentheses. Asterisks indicate statistical significance.

	Dependent variable:	
	Helpfulness	
	(Longitudinal)	(Lateral)
Stimulus mode	−0.235	0.058
	(1.045)	(0.647)
Scenario variant		−0.197
		(0.617)
Interaction		0.490
		(0.922)
Observations	14	60

Note: *p<0.1; **p<0.05; ***p<0.01

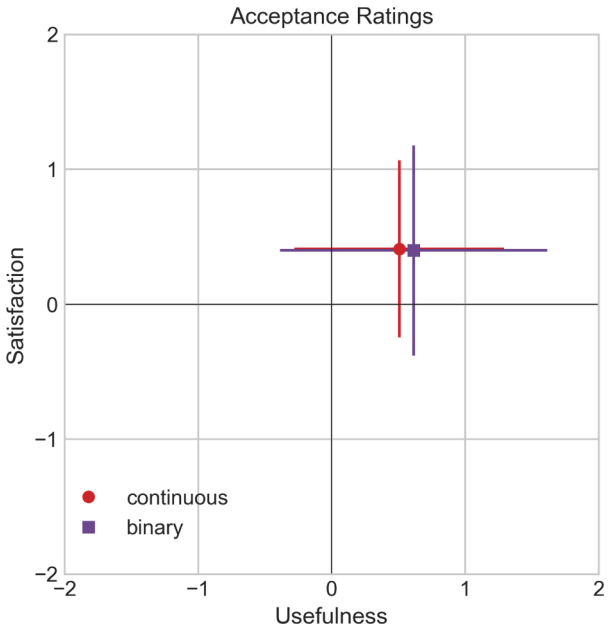
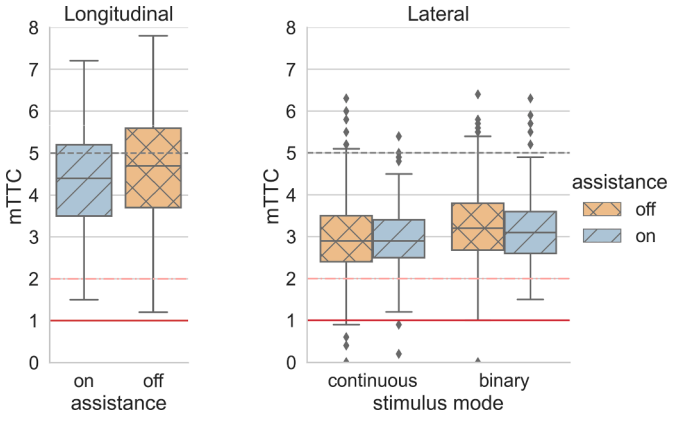


Fig. 7. Mean acceptance ratings (+ standard deviations) in terms of the dimensions *usefulness* and *satisfaction* for both LLI variants (continuous, binary).

3.2.2. Critical Situations

If any critical situations should occur, we would expect their rate to be lower in LLI trials than in baseline trials (H2 - objective benefit) and further to be lower with the continuous LLI than with the binary LLI (H3 - advantage of time encoding). Fig. 9 shows the percentage of critical situations for longitudinal and lateral scenarios with and without LLI assistance. Trials in longitudinal scenarios did not reach critical levels regardless of whether the LLI was active or not. In lateral scenarios critical situations were rare but nevertheless appear to have occurred more frequently without than with LLI assistance.

Table 4 shows the output of the logistic regression models for the occurrence of critical situations in the longitudinal and lateral scenarios (*critical* ∼ *assistance* + *stimulus mode* and *critical* ∼ *assistance* + *stimulus mode*scenario variant*, respectively). For trials in longitudinal scenarios there was no significant effect of assistance. However, in lateral trials there was a significant effect of assistance suggesting that the occurrence of critical situations was reduced in LLI assisted trials. This supports part b of hypothesis H2 (objective benefit). There were no significant effects of stimulus mode, lateral scenario variant (lateral) or the interaction between stimulus mode and scenario variant (lateral) and thus no support for hypothesis H3 (advantage of time encoding). Data on the occurrence of critical situations therefore suggest that drivers presented higher driving safety with LLI assistance in intersection scenarios with lateral traffic but do not indicate an advantage of continuous over binary tactile encoding.



(a) *Longitudinal trials* **(b)** *Lateral trials*

Fig. 8. Minimum Time-to-Contact measures from trials with (on) and without (off) enabled LLI assistance in longitudinal 8a and lateral 8b scenarios. For trials from lateral scenarios an additional distinction between different LLI variants (binary, continuous) is made.

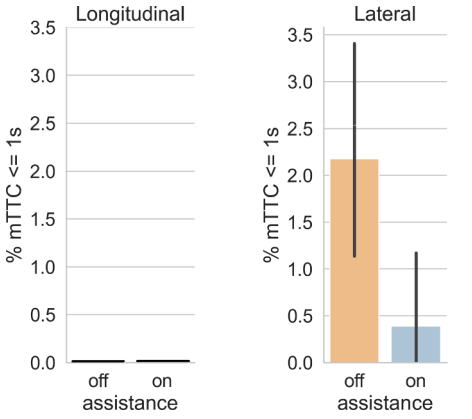
Table 3
mTTC regression coefficients with standard errors in parentheses. Asterisks indicate statistical significance.

	Dependent variable:	
	mTTC	
	(Longitudinal)	(Lateral)
Assistance	−0.279	0.002
	(0.169)	(0.061)
Stimulus mode	0.209	−0.183**
	(0.172)	(0.072)
Scenario variant		−0.066
		(0.084)
Interaction mode:variant		−0.185
		(0.118)
Intercept	4.572***	3.234***
	(0.137)	(0.054)
Observations	276	1,042

Note: *p < 0.1; **p < 0.05; ***p < 0.01

3.2.3. LLI Activation

Fig. 10 shows the percentage of trials which met the LLI activation criteria for longitudinal and lateral trials with and without LLI assistance. For longitudinal trials LLI activation criteria appear to have been met more frequently with the binary than the continuous LLI and further more frequently when the LLI was enabled (assistance on) than when it was disabled (assistance off). In lateral trials, LLI activation criteria where met much more often than in longitudinal trials, especially for scenarios with two approaching vehicles where almost all trials reached mTTC values below 5 s. For trials with vehicles approaching only from one side, LLI activation criteria appear to have been met less frequently in the continuous LLI group than for participants with the binary LLI. Table 5 contains the output of the logistic regression models for the occurrence of situations which would have triggered LLI activation in the longitudinal and lateral scenarios ($activation \sim assistance + stimulus\,mode$ and $activation \sim assistance + stimulus\,mode * scenario\,variant$, respectively). For longitudinal trials there were significant effects of assistance and stimulus mode. The percentage of trials which reached system activation thresholds was on average 10% higher with than without an active LLI. However, in the continuous LLI group the percentage of such trials was on average 10% lower than for drivers with a binary LLI. For lateral trials there was no significant effect of assistance. However, there were significant effects of stimulus mode, scenario variant and the interaction between the two on LLI activation. The percentage of trials which reached system activation thresholds was lower with continuous than with binary signaling and lower in scenarios with vehicles approaching from one side than from both sides.



(a) *Longitudinal scenarios* **(b)** *Lateral scenarios*

Fig. 9. Percentage of critical trials (mTTC <= 1 s) in longitudinal 9a and lateral 9b scenarios for trials with (on) and without (off) enabled. LLI assistance.

Table 4
Critical trial rate regression coefficients with standard errors in parentheses. Asterisks indicate statistical significance.

	Dependent variable:	
	Critical Situations	
	(Longitudinal)	(Lateral)
Assistance	18.374	−1.620**
	(2,418.685)	(0.745)
Stimulus mode	−0.621	0.728
	(1.233)	(0.500)
Scenario variant		−16.405
		(1,265.327)
Interaction mode:variant		15.609
		(1,265.327)
Intercept	−22.296	−3.822***
	(2,418.684)	(0.418)
Observations	591	1,176

Note: *p<0.1; **p<0.05; ***p<0.01

4. Discussion

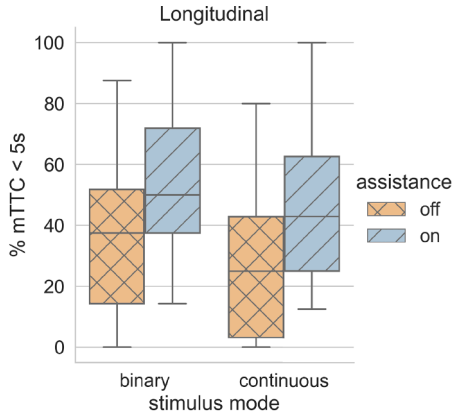
In this section we critically discuss and interpret the results of the presented driving simulator study in reference to existing literature. Based on this discussion, we outline proposals for potential follow-up research.

4.1. Subjective Effects

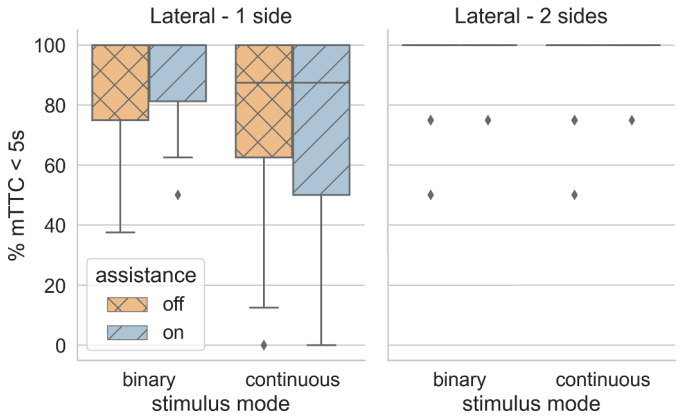
Participants were able to perceive intensity and direction components in stimuli and attribute them to nearby vehicles that may pose a collision risk. These findings agree with prior research on peoples' ability to attribute risk (De Rosario et al., 2010; Lylykangas et al., 2016), distance (Riener and Ferscha, 2008), and direction (Ho et al., 2005; Acik et al., 2005) information to properties of tactile stimuli.

This suggests that an employment of tactile stimuli with location- and intensity-based information encoding could be suitable for interfaces that should intuitively convey direction and danger information in the automotive context.

In terms of trial-level helpfulness ratings and post hoc usefulness and satisfaction scores, participants rated both LLI variants positively in longitudinal and lateral driving scenarios. Responses to custom questionnaire items further illustrate that participants felt supported by the LLI. These findings support our hypothesis H1 (subjective benefit) for both a) highway overtaking scenarios with low criticality and b) intersection scenarios with lateral traffic.



(a) *Longitudinal*



(b) *Lateral*

Fig. 10. Percentage of trials which met the LLI activation criteria (mTTC ⩽5 s) in longitudinal (10a) and lateral (10b) scenarios with (on) and without (off) LLI assistance for each LLI variant (binary, continuous). For lateral scenarios we further distinguish between two scenario variants (left: vehicles approach from one side, right: vehicles approach f.rom both sides).

Table 5
LLI activation regression coefficients with standard errors in parentheses. Asterisks indicate statistical significance.

	Dependent variable:	
	LLI Activation	
	(Longitudinal)	(Lateral)
Assistance	0.804***	−0.038
	(0.179)	(0.183)
Stimulus mode	−0.363**	−0.873***
	(0.173)	(0.193)
Scenario variant		1.168***
		(0.393)
Interaction mode:variant		0.958*
		(0.546)
Intercept	−0.590***	1.958***
	(0.135)	(0.167)
Observations	591	1,176

Note: *p<0.1; **p<0.05; ***p<0.01

4.2. Objective Effects

We measured objective safety effects in terms of the mTTC and the occurrence of critical events. In contrast to our hypothesis H2 (objective benefit), there was no significant difference in mTTC between trials in which the LLI was active and baseline trials without LLI activation for both longitudinal and lateral trials. Notably, in the longitudinal condition mTTC values were distributed around the 5 s LLI activation threshold and only rarely fell below 3.5 s. This stands in contrast to our previous experiments (Krüger, 2019; Krüger et al., 2020b) were mTTC values usually reached the range between 1 and 4 s, especially during baseline trials. Arguably this means that the trials in the present study were easy enough for participants to resolve them as well with their basic capabilities as with the additional assistance by the LLI.

For the lateral trials the situation is different: Here the mTTC values were mainly distributed around 3 s regardless of whether a trial was assisted (LLI) or not (baseline). This indicates that the scenario affected the mTTC but the LLI did not. The overall smaller and more narrowly distributed mTTC values can be explained largely by the nature of the scenario. While approaching an intersection, the time for reaching that intersection naturally drops. This time coincides with a TTC whenever one of the crossing vehicles would reach the intersection at the same time. Therefore, the mTTC is very likely to keep dropping as the driver approaches an intersection with crossing traffic until the point where the vehicle would come to a stop in front of it. Only few possibilities exist to avoid such a drop in mTTC: 1) maintaining a constant velocity while approaching the intersection once a non-colliding (= no feedback) trajectory has been determined, 2) approaching the intersection at a very low velocity and optionally stopping at an early point.

For this reason the direct mTTC is only of limited value for evaluating the safety in lateral trials. For our second safety measure, the proportion of critical trials, the applicability for longitudinal and lateral trials is reversed. Although classified by the TTC (Hayward, 1972; Van der Horst, 1991), an occurrence of a critical situation was not predetermined by design and may hence be attributed to driver capabilities. Our finding that the rate of critical situations was significantly higher without than with LLI assistance in lateral trials therefore suggests that the LLI helped drivers in avoiding critical situations. This supports part b) of our hypothesis H2 (objective benefit). For longitudinal trials where critical situations did not occur, a measure of their occurrence does not yield information about the LLI's impact on safety.

Besides the rate of critical situations we also investigated the occurrence of LLI-relevant situations, i.e., situations with a TTC below five seconds, as an additional indicator for how the LLI might affect driving behavior. We found that in the longitudinal condition the percentage of trials that met the LLI activation criterion was on average 10% higher with an activated LLI than in baseline trials. In terms of safety this may appear to be a contradiction to our hypothesis H2 (objective benefits). However, because mTTC values were distributed near the activation threshold and only rarely reached safety–critical levels, we argue that such an interpretation would be misguided. Instead we would like to discuss potential explanations that could be subject to future investigations.

A first explanation might lie in the novelty of the experience of the LLI. If the initial exploration drive should not have sufficed, the participants may have taken the trials with an active LLI as an additional opportunity to explore its functionality. Such a wish for exploration could have let them purposefully surpass the activation threshold also in cases where they could have avoided it. However, if the novelty should be the driving factor, one could argue to expect further exploratory behavior expressed through smaller mTTCs below the activation threshold as well. This does not appear to be the case.

Another explanation could be that participants may have utilized the LLI to sample information. A substantial portion of the signaling range, especially around the onset threshold, does not yet signify danger. In such a range it merely informs the driver about directions from which a dangerous situation could develop in the future if the present trajectory would be maintained and, in the case of the continuous LLI, also how imminent such a danger is. This informative value could serve as an incentive for using the LLI to sample safety-relevant information about the environment in order to improve one's situational awareness and driving competence. Such an explanation would be in line with an ecological approach to perception (Gibson, 1979) as well as related frameworks that emphasize the role of actions for sampling and understanding sensory input (Gibson, 1950; Lee, 1998; O'Regan and Noë, 2001; Friston, 2010). In Gibson's terms, the LLI may provide an *affordance* that can make some driving maneuvers more informative. When taking a more passive stance, the LLI could also enable drivers to rely on its input as a trigger for a needed correction. Such a reliance might in turn cause drivers to become less attentive outside the signaling range and accordingly increase their likelihood of entering the signaling range. While this third explanation may only find partial support in *active perception* frameworks, it would conform with the theory of risk homeostasis (Wilde, 1988).

Presently we cannot answer whether the increase in the percentage of trials that met the LLI activation criterion was due to novelty, active-, passive information sampling or another unspecified reason.

A study on long-term effects could aid in confirming or ruling out novelty as an explanation. Active and passive utilization could be contrasted by targeting their respective consequences, i.e., a participants awareness of relevant events that are not communicated by the LLI.

4.3. Binary and Continuous Stimuli

In addition to the extended investigation of the original LLI with a continuous encoding of the temporal proximity in the stimulus intensity, here we have introduced a binary LLI variant that is only capable of providing stimuli at a constant intensity whenever the TTC falls below a set threshold. By comparing effects of this binary LLI to the continuous LLI we aimed at learning about the subjective and practical value of the temporal information conveyed through a continuous encoding in the tested scenarios. In contrast to our third hypothesis H3 (advantage of time encoding), we found no significant differences between subjective ratings of helpfulness, usefulness and satisfaction. Both variants were regarded as equally positive. In terms of trial safety, quantified as the mTTC, we found

no difference between the LLI variants in longitudinal trials and lateral scenarios, even with traffic crossing from both sides. However, the average rate of trials in which participants entered a function-relevant TTC range was 10 percent higher with the binary LLI than with the continuous LLI both in longitudinal and lateral scenarios. This suggests that drivers behaved more cautiously when assisted by the continuous LLI than the binary LLI. One possible explanation for this difference could be that a binary signal is easier to interpret as a situation classification criterion than a continuously changing signal. Besides communicating that another object is in a TTC range between 5 and 0 s, the binary LLI expresses that a safety-relevant threshold has been crossed. Only the onset of the stimulus is thus informative with respect to the available time and can be learned to mean that any object in the signaled direction can develop into a risk within the foreseeable future. This warning property in turn may have led participants to reduce their caution above the signaling threshold and use any signal onset as a trigger to adapt their driving. In contrast, the gradual development of any continuous LLI stimulus essentially expresses a degree of danger attributed to the signal direction. It may thus be treated less as the crossing of a specific safety-relevant threshold and accordingly be less likely to reduce a driver's caution outside its activation range.

Taken together these subjective and objective results provide only partial support for our third hypothesis which predicted larger subjective and objective benefits of the continuous over the binary LLI.

A reason for the lack of subjective differences might have been that the situations were not challenging enough to reveal the informative advantage of the continuous LLI. Indeed, driving data show that in longitudinal trials with system activation the mTTC seldom dropped below 4 s for both stimulus variants, which means that only a narrow portion of the continuous signaling range was actually expressed. This makes the realized informative value of both variants more similar and could account for the similarities in the subjective evaluations. However, in the lateral condition mTTCs below 3 s were frequently reached which means that a larger range of continuous stimuli must have been expressed. Accordingly participants could have taken better advantage of continuous LLI properties, especially in trials where vehicles approached from two sides. Participant accounts on their perception of the stimuli may offer an explanation for why this was not the case: After the exploration drive, thirteen out of sixteen participants in the binary LLI condition stated that they have perceived signals of varying intensity. Additionally, when asked for their understanding of signal intensity only two of these participants mentioned that they either did not perceive a change in intensity or gave no response. The remaining participants linked the intensity to danger, proximity, speed of approach or vehicle size. This outcome surprised us. After all, the binary LLI utilized a single intensity level when active and therefore should not have caused a perception of varying intensity levels, let alone a coupling of a perceived intensity to events in the simulated environment. Also a thorough check of individual log-files confirmed that participants in the binary group have indeed only been exposed to the binary LLI.

This outcome challenges the assumption that tactile intensity perception is determined entirely by the physical stimulus intensity. Research on multimodal perception (McGurk and MacDonald, 1976; Fixmer and Hawkins, 1998; Botvinick et al., 1998) indeed provides grounds for doubting this assumption: McGurk and MacDonald (1976) demonstrated how the visual perception of a speaking person can modulate the perceived utterance to such an extend, that entire consonants are substituted when visual and auditory stimuli are in conflict. The *rubber hand illusion* (Botvinick et al., 1998) is another demonstration of the crossmodal influence between visual, tactile and proprioceptive perception. In this illusion, multimodal integration is exploited to generate a shift in the perception of one's own body parts and, in extension, has been found to be powerful enough for a self-association with non-corporeal forms (Ma and Hommel, 2015) or out-of-body illusions (Blanke et al., 2005).

Another link to our findings presents itself in research on *peripersonal space* (PpS), a representation of the space surrounding an agent's body that is thought to originate in the binding of information from proximal and distal sensory modalities such as vision and touch (Cardinali et al., 2009; Brozzoli et al., 2011). Studies on cross-modal extinction (di Pellegrino et al., 1997; Farnè et al., 2003) suggest the presence of PpS representations in humans which have been linked to the coordination of defensive behavior and also purposeful actions towards nearby objects (Graziano et al., 2004; Graziano and Cooke, 2006). Similar experimental paradigms have revealed a modulation of tactile perception by visual stimuli close to anticipated future hand positions (Belardinelli et al., 2018; Patané et al., 2019). A utilization of such crossmodal features while driving might offer an explanation for why participants reported perceiving varying stimulus intensities in the binary condition. If a contextual and distance-dependent modulation of tactile intensity perception should indeed be taking place, this would not only mean that a (perceptually) binary LLI would need to include a distance-dependent weakening of stimulus intensities to be perceived as constant but also that the slope of perceived intensity scaling for our continuous LLI could deviate from the linear relationship we were targeting to implement through our scaling function (see page 5). When we tested stimuli and system configurations prior to the experiment we did not notice any effects of this kind. However, our own prior knowledge about the system as well as an available comparison between binary and continuous stimulus variants may have masked such effects during pretests. Future work should investigate such multimodal and context-dependent effects on tactile intensity perception in the driving context more directly. Additionally it could be beneficial to investigate effects of the LLI on driving performance after longer exposure.

4.4. Long-Term Exposure

In the present study each participant only had about 40 min of LLI exposure. Considering the adaptive nature of human perception and sensory integration, any effects we observe may be dependent on the amount of experience participants had with the LLI. On the other hand, an adaptation in terms of an increase in perceptual thresholds or habituation effects (i.e., a loss of attention due to constant stimulation (van Erp, 2007)), may already be counteracted by the relative rarity, short-lived nature and attention relevance of individual stimuli. For studies on effects of prolonged LLI exposure, we propose to move from driving simulation to real vehicle implementation. This would not only increase scenario variability but also introduce factors not considered in controlled simulation such as vehicle vibrations, visibility- and road conditions, some of which may be difficult to observe.

When such unobserved factors have an influence on the response variables without being accounted for, this can lead to erroneous inferences. While this so called *unobserved heterogeneity* (Mannering et al., 2016) may already occur to a some extent in our driving simulator setting, it is likely to be amplified in real driving and should thus be addressed explicitly by appropriate statistical models (see e.g. Saeed et al., 2017; Waseem et al., 2019; Yamany et al., 2020).

Real-vehicle implementation would also entail a substantially expanded set of objects the assistance would need to be able to identify and model as potential hazards. For instance, in addition to vehicles also pedestrians can be at the risk of colliding but appropriate risk estimates for pedestrians in real-life may require more than a velocity-based trajectory extrapolation (see e.g. Guo et al., 2019). Expanding LLI functionality accordingly may be particularly valuable because, amongst others, pedestrians are much easier to miss by visual perception due to their relatively small size.

Real-vehicle employment could also face non-technical challenges which are presently not considered such as driver distraction. While the LLI has the potential to support distracted drivers to quickly focus on identified hazards, its availability as an additional safety-layer may also affect the drivers' susceptibility for distraction (Khan et al., 2020). If confirmed, such a property could reduce LLI applicability in manual driving. However, for the same reasons the LLI application scope could be shifted towards shared control and automated driving settings, in which driver distraction is to be expected. Here the LLI's contribution to scene understanding and system transparency might have a positive impact on user acceptance of vehicle automation (Saeed et al., 2020).

Another issue that relates to the proposed interface would be a defiance of seatbelt use that is still present in some regions and demographics (Farooq et al., 2021) and which would compromise any seatbelt-based communication. However, giving the seatbelt additional informative value through LLI functionality could also help in reducing such bad habits as it would provide one additional reason for seatbelt use.

4.5. LLI Function Expansion

Our method for deriving the TTC in two dimensions, as introduced on page 4, can also be understood as a deterministic heuristic for predicting the collision risk (see Eggert (2014) for a discussion on the link between risk and time-to-event estimates). Despite conveying information about a predicted future, the TTC-dependent signal maintains a direct causal link between current states and actions, and future event predictions: Steering into a collision trajectory activates a stimulus whereas steering away from a collision trajectory deactivates the stimulus. Maintaining or increasing a relative velocity that reduces the gap between vehicles increases stimulus intensity while actions that decrease it will trigger stimuli of stable or reduced intensity. A downside of such a direct correspondence between the future impact of current events and generated stimuli is that the potential impact of future situation-altering actions by other agents is not considered. Information about a collision-relevant action by another agent is only obtained and communicated at the time of the action, regardless of its prior probability. A system that would take the uncertainties associated with the future behavior of other drivers or other second order predictions into account (see e.g. Eggert and Puphal, 2017), could accordingly provide safety-relevant information for a larger set of situations and at an earlier point in time. However, such a system would carry the risk of making the causes of stimuli more difficult to infer for a driver.

It could also be necessary to find an appropriate way of encoding uncertainties in stimuli. We have previously successfully conveyed direction uncertainty on top of TTC-contingent urgency information through vibrotactile stimuli (Krüger et al., 2020a). Adding another dimension for collision uncertainty could nevertheless prove to be difficult to achieve when utilizing a channel that is already occupied with receiving time, direction, and direction uncertainty information. On the contrary, when interpreting the TTC as an inverse approximation to a collision probability (c.f. Sorkin et al., 1988), it might suffice to simply substitute a *TTC - intensity* encoding with a high level *probability - intensity* encoding. Even if such a shift should not have practical advantages, investigating it would help us to better understand on what level of abstraction sensory support should preferably be delivered to drivers to best interface with their processing capabilities and expectations. For instance, as the complexity of the model underlying the probability estimation increases, more effort may need to be put into highlighting explanatory features to have sufficient transparency for effective human–machine cooperation (Krüger et al., 2017; Sendhoff and Wersing, 2020; Gervasi et al., 2020) and trust calibration (Khastgir et al., 2018; Akash et al., 2020). Conversely, means of making driver intentions more transparent to the system (see e.g. Wang et al., 2020) could improve the quality of system predictions and the congruency between feedback and driver intentions.

4.6. Conclusion

We have introduced an approach for supporting the driver of a vehicle in perceiving safety-relevant objects by using directed tactile stimuli that are triggered by temporal proximity estimates in two spatial dimensions. After having previously observed that people were able to quickly understand and use the support provided by this *Lateral Line Interface* (LLI) for their benefit in situations of high criticality (Krüger et al., 2018; Krüger et al., 2020b), here we have investigated its subjective and objective impact in a new set of driving scenarios with reduced criticality and laterally crossing traffic. Our findings suggest that the LLI supports drivers in preventing critical situations in intersection scenarios but also that drivers are able to resolve evolving hazards with low initial criticality similarly well with and without LLI support. Nevertheless, participants consistently reported that the LLI was also helpful in these scenarios, indicating a utilization beyond the scope of a warning device. Future work will need to focus on the nature of this utilization and prolonged exposure in order to determine whether this form of assistance may be applied safely.

Declaration of Competing Interest

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