The Lateral Line: Augmenting Spatiotemporal Perception with a Tactile Interface

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ABSTRACT

In this paper we describe a concept for artificially supplementing peoples' spatiotemporal perception. Our target is to improve performance in tasks that rely on a fast and accurate understanding of movement dynamics in the environment.

To provide an exemplary research and application scenario, we implemented a prototype of the concept in a driving simulation environment and used an interface capable of providing vibrotactile stimuli around the waist to communicate spatiotemporal information. The tactile stimuli dynamically encode directions and temporal proximities towards approaching objects. Temporal proximity is defined as inversely proportional to the time-to-contact and can be interpreted as a measure of imminent collision risk and temporal urgency. Results of a user study demonstrate performance benefits in terms of enhanced driving safety. This indicates a potential for improving peoples' capabilities in assessing relevant properties of dynamic environments in order to purposefully adapt their actions.

CCS CONCEPTS

• **Human-centered computing → HCI design and evaluation methods**; **Interaction design theory, concepts and paradigms**; **Haptic devices**; **Interaction paradigms**; *Mixed / augmented reality*; *User interface design*; *Empirical studies in HCI*; *User studies*; *Interface design prototyping*.

KEYWORDS

Sensory Augmentation, Augmented Perception, Tactile Interface, TTC, Driver Assistance, Time Encoding

ACM Reference Format:

Matti Krüger, Christiane B. Wiebel-Herboth, and Heiko Wersing. 2020. The Lateral Line: Augmenting Spatiotemporal Perception with a Tactile Interface. In *Augmented Humans International Conference (AH 2020), March 16–17, 2020, Kaiserslautern, Germany*. ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/to-be-replaced

AH 2020, March 16–17, 2020, Kaiserslautern, Germany

ACM ISBN 1-2-3-4/to-be-replaced…$TBR
https://doi.org/10.1145/to-be-replaced

1 INTRODUCTION

Interactions that rely on an appropriate spatiotemporal coordination of operations such as avoiding moving obstacles or catching objects are usually limited by the sequential and directionally constrained nature of visual perception when multiple objects need to be tracked.

Many man-made scenarios, including participation in road- or maritime traffic, skiing and various team sports are examples for tasks in which this limitation becomes relevant and is arguably only mitigated by a strict set of constraints through (traffic) rules, substantial structural modifications in the environment or communication between involved individuals. In the automobile domain, attempts to further support a driver's situation understanding have for instance been made through visual [20, 24, 27, 70, 78], auditory [21, 23, 33, 39, 41, 48] and haptic [28, 30, 39, 40, 45, 53, 59] stimuli which alert the driver in specific safety critical situations (see further [1, 63]). Prominent and successful examples are the encoding of spatial distances in the frequency of sound stimuli for parking support [32, 79], lane departure warnings through steering wheel vibrations [4, 10, 31], and visible or audible warnings in cases of anticipated front collisions [67, 70]. However, usually the utility of such systems is limited to specific use cases, distances or velocity ranges and the created stimuli are mainly of alerting nature.

Here we introduce a concept aimed towards circumventing some of these limits by using tactile stimuli to supplement information rich enough for applications beyond alerting systems. In a survey on haptic driver assistance, Petermeijer et al. [51] identified a lack of investigations of dynamic temporal and spatial patterns which may offer means for expanding assistance. In line with this proposal, our concept builds on dynamically encoding relevant spatiotemporal information in tactile stimuli.

To facilitate an understanding of its novelty and potential utility we introduce the concept with an analogy:

While human senses may not have evolved for employment in the described kind of high velocity situations with multiple actors on intersecting trajectories, other members of the animal kingdom appear to have a stronger specialization in that niche:

Schooling, in the sense of a coordinated movement of a group in a common direction, is a remarkable ability of many aquatic vertebrates. Within a school, fish are able to adjust their position, acceleration and movement direction to that of multiple neighbors with such synchrony that they can appear to act as a common unit. In order to maintain the precise relative placement within a school during movement, its members need to be able to extract relevant information from their environment. One system of organs which is thought to play an important role in acquiring this information is known as the *lateral line*.

The lateral line describes a system of sensory organs that are sensitive to displacements of surrounding water and can thus be used to detect movements and vibrations. It converts local pressure changes into directional information and can be interpreted as a *remote sense of touch* or *sense of approach*. Fish appear to use the lateral line system for the formation of spatial awareness and for the ability to navigate. Predators have been found to employ their lateral line system to orient towards the source of vibrations such as those produced by fleeing prey [9]. Furthermore, fish with severed lateral lines seem unable to reintegrate themselves into a school [57]. Thus the use of the lateral line seems to be a crucial component for school formation.

In relation to the perception of approaching objects, roughly speaking, the lateral line provides two measures:
1. Direction of approach and 2. strength of approach which may be indicative of speed, size and proximity. Providing similar measures to humans could help to partially close the gaps left open by the existing sensory system and improve situation understanding and performance in complex dynamic situations. In the following section we introduce a concept which tries to transfer these properties.

2 CONCEPT

We propose to supplement a person's environment perception with two measures: The directions towards approaching objects which are on a collision trajectory with the user and the temporal proximities of each approaching object. The term *temporal proximity* is thereby to be taken as a variable that is (inversely) proportional to a time-to-contact (TTC)[1], which we here understand as a measure that depends on heading, distance, and momentary difference in velocity between two objects:

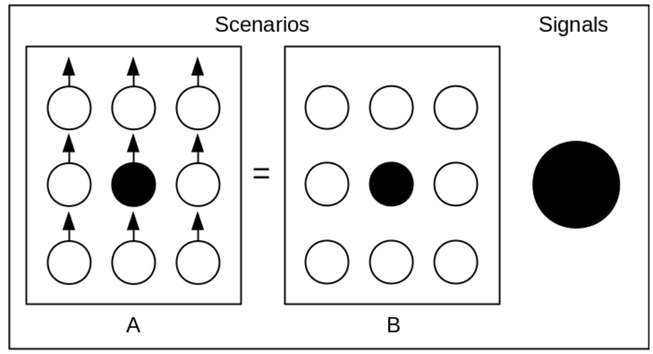
When assuming that an object b is moving behind an object a along the same path and trajectory with velocities V_a and V_b and a and b are distance D_{ab} apart, the TTC between a and b is given by:

$$TTC = \begin{cases} \frac{D_{ab}}{V_b - V_a}, & \text{if } V_b > V_a \\ \infty, & \text{otherwise} \end{cases} \quad (1)$$

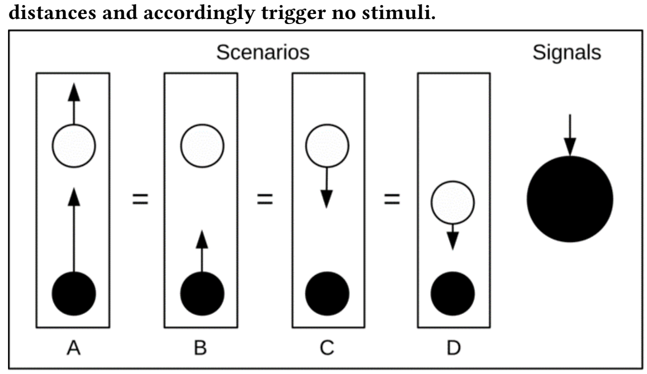
In contrast to a purely spatial proximity measure we argue that a measure of temporal proximity can serve as a suitable expression of approach: The temporal proximity between two objects usually increases when one object approaches the other or vice versa, unless one object evades the other with sufficient speed. The same holds for the spatial proximity, which however does not take into account how fast that proximity increases or even whether it increases (i.e. the object approaches) at all. In contrast, a time-to-event measure or prediction implies an increase in proximity over time if trajectories and velocities should not change significantly.

Importantly, short spatial distances (= high spatial proximity) further do not necessarily entail short temporal distances as long as the respective objects do not approach each other. The temporal distance between spatially close objects with non-intersecting trajectories may in fact be infinite (see Figure 1a for an illustration of this property).

[1]More generally one may also define a time-to-event where the event could for instance already encompass reaching a specific distance threshold that is assumed to be relevant for the application task.



(a) When objects do not move relative to each other [A, B], the temporal distances between them are infinite regardless of the spatial distances and accordingly trigger no stimuli.



(b) Due to the dependence on both distance and relative velocity, the four scenarios [A, B, C, D] are identical with respect to the corresponding directed temporal proximity signals relative to an object represented by the dark circle. A, B, and C have equal distances and relative velocities. D presents a smaller distance but also a reduced relative velocity resulting in the same TTC as in A, B, and C.

Figure 1: Temporal equivalents: Because of the relative nature of the time-to-contact, scenarios that differ in absolute terms may yield identical temporal proximity signals. Outgoing arrows: length=velocity, direction=movement direction; Incoming arrow: length=temporal proximity, direction=approach target.

Spatiotemporal measures or predictions therefore have a much wider applicability across different velocities and distances than purley spatial proximity measures (see Figure 1b for an illustration of this property) and yield higher relevance in informing about approaching objects and objects that are being approached.

We therefore assume that supplementing peoples' perception with the proposed spatiotemporal information allows them to develop a better understanding of the relevant dynamics in their surroundings and adapt their behavior accordingly. In addition to supporting the understanding of present situations, the predictive nature of the temporal proximity information provided to a user is further intended to facilitate the anticipation of future situations and the understanding of potential consequences of own action choices.

2.1 Application Scenario

In order to evaluate our approach for supplementing people's perception with directional and temporal information about approaching objects, we chose the task of driving a car on a highway as a plausible application scenario. This application domain has a number of advantages:

(1) It naturally contains a high variability in distances and relative velocities. Speed differences between and within lanes allow for testing of safety-relevant scenarios in which the understanding and utility of directionality in the signals can be evaluated.
(2) Simplicity: Lane-based navigation simplifies immediate trajectory- and thus TTC estimation as well as understanding of the same by drivers.
(3) Utility: The information content of signals can be useful to drivers. The TTC can be argued to be proportional to the safety of a situation. When the TTC is falling, the risk of an accident increases because there is less time and thus opportunity to prevent the accident.

In this application we communicate directions and temporal proximities towards other traffic participants on a collision trajectory with the user's vehicle. The proximities are thereby not defined relative to the body of the driver but relative to the outer boundaries of the vehicle which the driver controls. Figure 2 illustrates the implementation of the approach in a driving situation.

2.2 Interface

As an interface for information transmission we chose to use vibrotactile actuators. Thereby the direction towards approaching vehicles (relative to the driver's vehicle) is encoded in the location of vibration and the temporal proximity is encoded in the intensity of vibration (pulse width modulated) such that stimulus intensity is inversely proportional to the TTC in a defined temporal range (e.g. highest at 0 seconds, lowest at 8 seconds, no stimulus above 8 seconds).

The vibrotactile interface consists of a belt with equally spaced vibromotors spanning the length of the belt such that the locations of individual vibromotors can be aligned with directions relative to the wearer's body and the controlled vehicle (see Figure 3b). This allows for an approximate matching between direction encoding and stimulus position which should facilitate an intuitive understanding of the directional component in signals. Hereinafter we will refer to this interface as *Lateral Line Interface* or *LLI*.

Using vibrotactile stimuli has multiple benefits (see [37]): A driver's visual system is usually highly engaged and also auditory channels may be occupied by secondary tasks or other assistance functions. The tactile sense around the core of the body on the other hand is mainly idle while driving and thus likely available for novel input. Therefore no additional sensory load needs to be put on occupied modalities (see [25, 61, 77]). As tactile perception does not require active scanning [60] and is easily localizable [18] also the risk of creating stimuli that cannot be perceived is low. In contrast, visual stimuli need to be presented in the visual field with sufficient saliency to draw a driver's attention. Furthermore, in combination with the visual modality, multisensory facilitation

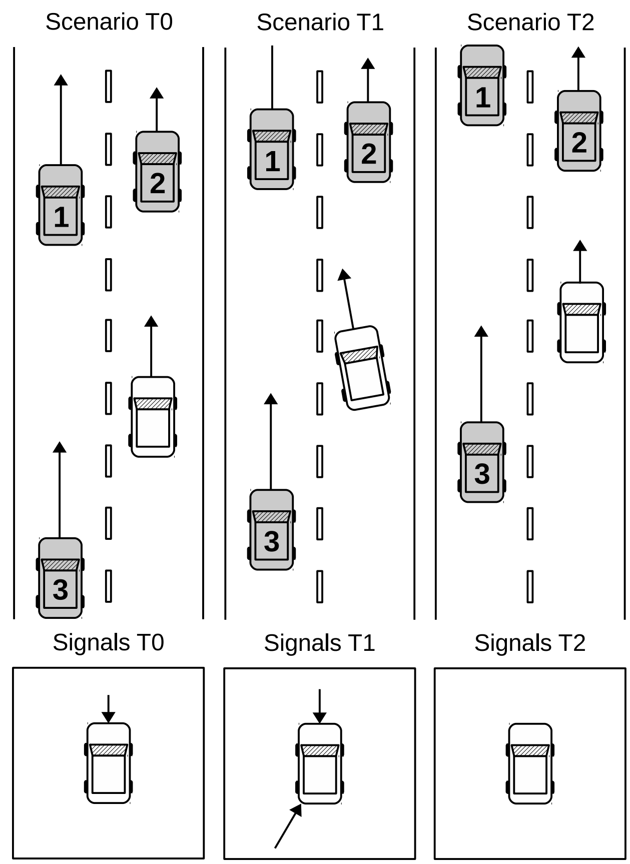


Figure 2: Traffic scenario and temporal proximity signals. Scenario: Outgoing arrows display the direction (heading) and velocity (length) of corresponding vehicles. Signals: Arrows represent the directions and associated temporal proximities or urgencies (length) encoded in the signals. At time T0 the ego-vehicle (white) is faster than vehicle 2 leading to a TTC reduction in the front direction. As a consequence the TTC is translated into a corresponding directed proximity signal. In response to the situation at T0, the driver decides to overtake vehicle 2 at T1 and initiates a lane change. This maneuver puts the ego vehicle on a second collision trajectory with vehicle 3, leading to a second directed temporal proximity signal. In the described implementation of the system, proximities are signaled relative to the current lane of the ego vehicle. Because the ego-vehicle is still on the same lane as vehicle 2 at T1, the front signal is still active and slightly stronger than before because the ego-vehicle has come closer to vehicle 2 compared to T0. The combination of the two proximity signals might prompt the driver to abort the overtaking maneuver until another gap becomes available (T2).

which is characterized by faster reaction times [3, 11, 26, 49, 72] and a reduced cognitive load [25, 77] may take place.

To our knowledge, the coupling of directional and temporal information encoding in tactile stimuli has not been investigated before.

Beyond vehicles, related approaches have mainly investigated spatial distance encodings for sensory support [2, 6, 7, 19, 59]. For example the "haptic radar" [7] introduced whisker-like properties which push the spatial range of touch perception beyond the boundaries of the body. In contrast, the LLI specifically targets dynamic situations by providing temporal information about approaching objects. The LLI can be "blind" to spatially nearby objects when they are not moving relative to the user (see figure 1a) but sensitive to even very distant objects that approach with sufficient speed. Thus systems like the "haptic radar" and the LLI can be seen as complementary. To evaluate the described approach and its effects on driver perception and performance we conducted a driving simulation study with a prototype of the system (see Figure 3a). Parts of this study were first introduced by Krüger et al. [37] focusing on subjective results. Here we evaluate effects of the approach on objective performance data.

3 METHODS

3.1 Participants

Data from 13 participants (12 male, mean age 33, [24-43]) were recorded. Participants were required to have a valid driving license and corrected-to-normal vision. All participants gave written informed consent before taking part in the study.

3.2 Experimental Setup

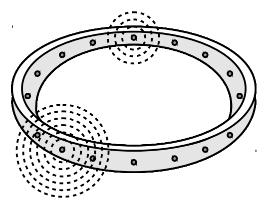
A static driving simulator running *SILAB 5.1* (WIVW GmbH) with real-vehicle controls for steering, braking and accelerating was used for the experiments. Three display panels (50 inch diagonal, Resolution: 3 x 1080p, updated at 60 Hz) were arranged to provide approximately 160° field of view and showed the front, side- and rear-view mirror views of the driving scene. A wearable 120 Hz monocular eye-tracker (Pupil Labs GmbH, see [34]) was used for gaze recording. Tactile stimuli were delivered via a belt which contains 16 equally spaced vibromotors (feelspace GmbH, see [47]) and a firmware customized for the purpose of the experiment.

The belt uses eccentric rotation mass motors with a maximum amplitude of 2.2 g and a frequency spectrum of 50-240 Hz (0.45 - 3.3 V) triggered with a 50 ms latency. Frequency and amplitude scale almost linearly with voltage. We used four different belt sizes to ensure a good fit for all participants as firm contact is critical for intensity perception and localization. In a pre-test we determined a joint smallest noticable intensity across 12 people as a lower bound for stimuli at the temporal stimulus threshold.

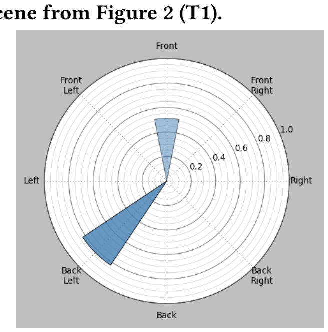
The perceived stimulus magnitude has been found to scale logarithmically with physical stimulus magnitude for various senses [16]. Expressed in a power law relation, exponent values can thereby differ between senses and stimulus sites [69]. Reference (Stephens's [69]) exponents for vibrations in the sub 240 Hz range on the body have been found to range from 0.75 to 0.97 [43] which approximates linear scaling. We tested mappings with exponents 0.75, 0.83 and 1.0 but found scaling with the smaller exponents to feel more irregular and thus decided to scale intensity with an exponent of 1.0.

Out of the 16 available vibromotors we only used 8, spaced 9.8 to 13 cm apart (depending on belt size) for the following reasons: Simultaneously signaling multiple directions requires sufficiently large distances between tactors to avoid interference by the funneling effect [35] or an illusion of apparent motion [74]. The eight directions map nicely to environment structures (three lanes, front, mid, back) and vibromotors partially align with anatomical reference points which may support intuitive direction mapping [8]. Note that Van Erp et al. [75] successfully used the same number and distribution of tactors for signaling directions in navigation tasks.

(a) Setup showing the driving simulator, eye-tracker (A), vibrotactile belt as LLI (B), and the driving scene from Figure 2 (T1).



(b) Sketch of the tactile interface with two active vibromotors (out of 16).



(c) Screenshot of a visualization of directional *temporal proximity* values which serve as LLI input.

Figure 3: Picture of the experimental setup (3a) containing the scenario illustrated in Figure 2 (T1). A sketch of the LLI (3b) and a live visualization (3c) show the associated vibromotor activations and directional urgency values respectively.

3.3 Procedure

The study was structured into three experimental blocks and one system exploration block. Table 1 lists the different experiment components. Before the start of the experiment, all participants had to complete a driving simulation familiarization procedure according to guidelines specified by Hoffmann and Buld [29]. By gradually increasing exposure to longitudinal and lateral accelerations and introducing a variety of driving tasks, this familiarization procedure simultaneously served the two objectives of reducing the probability of simulator sickness and introducing participants to virtual vehicle control and behavior.

Table 1: Experiment components and durations.

Description	Duration
Simulator familiarization	15 min
Block 1 (Baseline 1)	8 min
System exploration (LLI)	4 min
Questionnaire 1	4 min
Block 2 (LLI)	8 min
Block 3 (Baseline 2)	8 min
Questionnaire 2	4 min

3.4 Experimental Blocks and Trials

In the three experimental blocks participants were given the two tasks of a) driving accident-free and b) trying to maintain a velocity of 120 km/h when possible. The driving course was a straight two-lane highway with vehicles on the fast (left) lane driving noticeably above the 120 km/h target speed and vehicles on the right lane driving at exactly 120 km/h. Therefore the speed maintenance task could best be satisfied by staying on the right lane at most times. However, sometimes a vehicle on the right lane would slow down, forcing the driver to react. The braking of a front vehicle puts both tasks of accident-free driving and velocity maintenance at risk: slowing down to avoid crashing into the front vehicle violates the velocity task while staying on the lane at the target velocity would result in an accident. This made an overtaking maneuver the only sustainable solution. Doing so was however complicated by the traffic on the fast lane and thus additionally required the identification of feasible gaps (see Figure 2).

We regarded successful overtaking maneuvers in such situations as valid trials. Thereby the onset of a trial is marked by the time at which the front vehicle on the right lane starts to decelerate. The end of a trial is defined by the time at which the longitudinal coordinate of the ego-vehicle equals that of the slowing front vehicle, i.e. the time at which the slow vehicle is overtaken correctly. Due to this event-based definition, individual trial durations are dependent on driver behavior and situation difficulty and can therefore vary. Invalid trials were defined by a failure to respond appropriately to such events: breaking to an extent that overtaking became unfeasible and the target velocity was significantly reduced, overtaking on the emergency lane or creating an accident. Furthermore a trial was considered to be invalid if the spatial distance between front- and ego-vehicle at trial onset violated the realization of the respective trial difficulty setting defined by Equation 2. A total of 12 trials were realized in each experimental block for each participant. Between trials, periods of varying length without task-affecting events were inserted to reduce trial onset predictability. In Blocks 1 and 3 (Baseline) participants had to complete the task without the LLI. In Block 2, the LLI was active.

3.5 System Exploration Block

The system exploration block served the purpose of allowing the participants to familiarize themselves with the LLI. Here they could freely explore the functionality of the interface while driving through a prepared two-lane course with a variety of traffic situations. No information about the function or meaning of the LLI stimuli were given until after the free exploration phase. After finishing exploration, participants filled in a questionnaire and were interviewed about their perception and understanding of the LLI stimuli (see Krüger et al. [37]). The experimenter then introduced the participants to the concept of the LLI before continuing the experiment.

3.6 Independent Variables

Two independent variables were varied throughout the experiment: The availability of the assistance function (Block 1 and 3 vs. Block 2) and the task difficulty (*difficult* vs. *easy*).

We defined task difficulty in terms of the available time for a driver to react once a front vehicle started to decelerate assuming that this manipulation would also affect how demanding a situation would be experienced. This was realized by a) manipulating the available time-to-contact to the front vehicle and b) the number of feasible gaps available on the fast lane which would allow succesful overtaking. Thereby, the available time is computed as a time-to-contact which takes the deceleration of the front vehicle into account and assumes that the ego vehicle maintains its speed:

$$t = -\frac{\sqrt{(v_{\text{ego}} - v_{\text{front}})^2 - 2a_{\text{front}}d} - v_{\text{ego}} + v_{\text{front}}}{a_{\text{front}}} \quad \text{and} \quad a_{\text{front}} < 0 \tag{2}$$

Here t stands for the available time, v_{ego} and v_{front} for the start velocity of the ego- and the front vehicle respectively, a_{front} for the acceleration of the front vehicle and d for the initial distance between the two vehicles. We set t for trials labeled as *easy* to 7.4 seconds and for trials labeled as *difficult* to 5.4 seconds. In addition to the quantitative difference, *easy* and *difficult* trials also differed on a qualitative level: This difference consisted of the number of available gaps on the fast lane which the drivers could enter when assuming that they would keep the target velocity after trial onset. While in the difficult cases the first available gap would need to be taken, in easy cases also entering the second gap was still possible without causing an accident[2].

3.7 Dependent Measures

In correspondence to the two primary tasks for the participants, we evaluated performance in terms of the two dependent measures driving safety and velocity as functions of two independent variables: LLI availability and task difficulty (*difficult* vs. *easy*).

We operationalized safety at any point in time as the smallest time-to-contact (TTC) across all directions at that moment. For each trial we use the minimum of all TTCs (mTTC) measured in that trial[3] as a summary statistic. The mTTC measure therefore expresses how dangerous a trial got overall (smaller value = higher danger) rather than how dangerous it was on average. To assess

[2]Besides the time-to-contact, in the experimental scenario the time available for a driver to react is additionally constrained by the availability of feasible gaps on the passing lane. The size and frequency of these time windows depend on the velocity difference between the ego vehicle and passing vehicles as well as on the distance between individual vehicles on the passing lane. For the experiment we kept these two variables roughly constant which allowed us to vary difficulty only with the time variable described by Equation 2.

[3]See e.g. Eggert [13] for an account on the link between risk and time-to-event measures and Eggert and Puphal [14] for a proposed probabilistic extension of time-to-event based risk estimates that may be well suited for potential future real-world scenario evaluations of our concept.

driving velocity we use the arithmetic mean over a trial as our dependent measure.

In mobile systems a tradeoff between velocity and safety may be seen as an inherent property. Such a tradeoff between safety and velocity is not by itself problematic but it could be argued that any measurable safety benefit in terms of mTTC may be fully accounted for by a corresponding decrease in driving velocity[4]. We were therefore not only interested in whether the LLI condition would yield higher safety but also whether a potential safety improvement would be accompanied by a corresponding change in average velocity or whether safety could be improved independently of the average velocity.

3.8 Hypotheses

If people should be able to purposefully integrate the spatiotemporal information provided by the LLI into their environment perception, we hypothesize that they should also be able to carry out driving tasks more safely without affecting average velocity compared to driving without an LLI. Furthermore, for particularly demanding situation we would assume such a benefit to be even more pronounced due to the alleged sensory support and circumvention of visual limitations. This results in the following hypotheses:

- H1: Participants adapt their driving behavior in LLI trials such that safety is improved compared to the baseline conditions.
- H2: If present, such an improvement in safety would not be explained by a lower average velocity.
- H3: Task difficulty affects driving behavior such that safety and average velocity decrease in difficult trials compared to easy trials.
- H4: If present, effects of LLI usage on the driving behavior are moderated by task difficulty such that positive safety effects are more pronounced in difficult trials compared to easy trials.

4 RESULTS

4.1 Trial Validity

Prior to investigating performance, we evaluated the number of valid trials for each condition. Trial validity was defined as a filter criterion to ensure that all data entering further analysis would be comparable and to exclude trials in which the task was not achieved.

In the first baseline condition, 21% of all trials across participants were classified as invalid. In the LLI condition, the percentage of invalid trials was reduced to 7.7%. In the second baseline block 7.1% of all trials across participants were excluded as invalid trials. These results show that overall the driving task was feasible but not trivial. However, the increasing success rate suggests that a substantial improvement took place between the first experimental block (baseline) and the second experimental block (LLI). No difference in failure count was observed between the second and the third experimental block. However, the results on trial validity do not convey information about the quality of task performance in each trial. This will be further analyzed in the following.

[4]Note that this effect is partially prevented by experimental design. Vehicles on the passing lane are driving at a velocity slightly above target velocity. The slower the ego-vehicle is, the more difficult a lane change becomes. Therefore participants should additionally be motivated not to slow down too much in order to still be able to do a successful (safe) lane change.

4.2 Safety

To analyze the effects on driving safety in each valid trial (see figure 4), we first conducted a two-way repeated measures ANOVA to compare the main effects of condition and trial difficulty and their interaction on the minimum time-to-contact (mTTC). *Condition* included three levels (Baseline 1, LLI, Baseline 2) and trial difficulty consisted of two levels (easy and difficult). The effects of condition and trial difficulty were statistically significant at the 0.05 significance level. The main effect for condition yielded an F ratio of $F(2.0, 16.72) = 5.917$, $p < 0.01$. A post-hoc Tukey test showed that the mTTC differed significantly at $p<.05$ between Baseline 1 (M = 2.64 s, SD = 1.319) and LLI condition (M = 3.127 s, SD = 1.265) and between the LLI condition and Baseline 2 (M = 2.767 s, SD = 1.219). There was no significant difference in mTTC between Baseline 1 and Baseline 2. This safety benefit observed in the LLI condition compared to the baseline condition suggests that a purposeful use of the information provided has taken place. Because a safety benefit of the LLI usage compared to the baseline condition persisted also for trials in the second baseline condition (after the introduction of the LLI), we can exclude the possibility that the described benefit can be solely explained by learning effects. These results support our first hypothesis.

The main effect for trial difficulty yielded an F ratio of $F(1.0, 80.297) = 56.577$, $p < 0.001$, indicating a significant difference in mTTC between easy (M = 3.313 s, SD = 1.303) and difficult (M = 2.432 s, SD = 1.101) trials. With an average temporal *safety difference* of 0.88 seconds which approximately equals a distance of 29 meters when driving at 120 km/h, the difficulty manipulation thus appears to have been successful which supports our hypothesis 3. There was no significant interaction between condition and trial difficulty, $F(2.0, 0.293) = 0.103$, $p = 0.901$. Therefore, contrary to hypothesis 4, no evidence for a modulation of LLI effects by task difficulty was found.

Figure 5 additionally shows the average temporal development of minimum TTCs across conditions. Upon trial onset, the safety initially decreased in all conditions due to the deceleration of the front vehicle. In easy trials this decrease continued for 4.5 seconds and 3.8 seconds in Baseline 1 and 2 respectively. In the LLI condition recovery appeared already around 2 seconds and the resulting safety advantage remained for most of the trial. In *difficult* trials the overall initial safety was by definition much lower in all conditions. Also here the recovery in the LLI condition was much faster than in the baseline conditions. Later during trials the condition differences diminished while *safety* reached non-critical levels.

4.3 Velocity

As a second performance measure we inspected driving velocity in the different experimental conditions (see figure 6). To test whether a difference between driving velocities exists when driving with the LLI compared to driving without the LLI, we conducted a two-way repeated measures ANOVA, comparing the main effects of condition and trial difficulty and the interaction effect between the two on the average velocity during a valid trial.

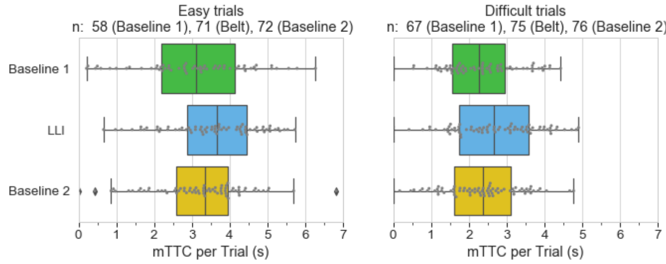


Figure 4: Distributions of mTTC values for all trials as an indicator for *trial safety*, ordered by conditions. Boxplots show minimum and maximum values (whiskers), and the first, second (=median) and third quartiles (box). Overlayed grey dots show mTTC values of individual trials.

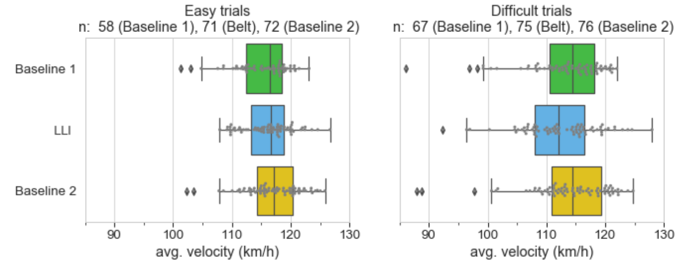
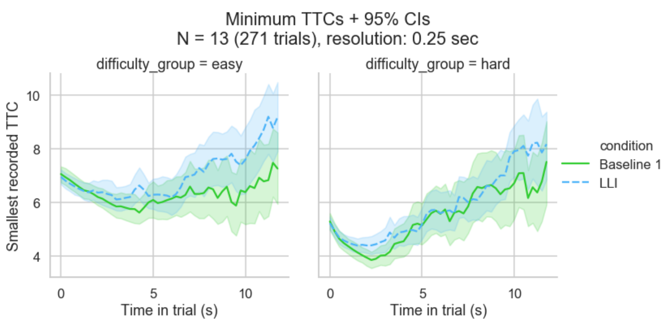
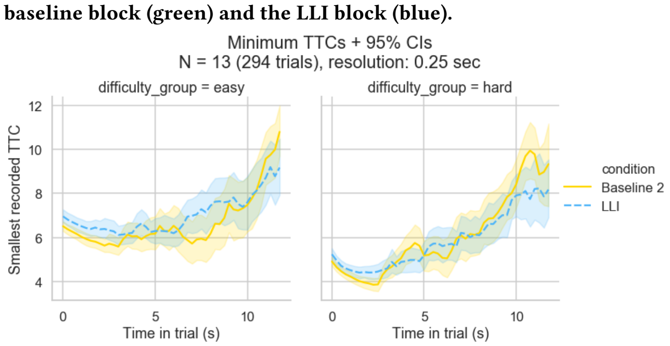


Figure 6: Distributions of average velocity measures for all trials, ordered by conditions. Boxplots show minimum and maximum values (whiskers), and the first, second (=median) and third quartiles (box). Overlayed grey dots show average velocity values of individual trials.



(a) Average minimum TTC over time as an indicator for temporal safety development + 95% confidence intervals (CIs) for trials from the first baseline block (green) and the LLI block (blue).



(b) Average minimum TTC over time + 95% CIs for trials from the second baseline block (yellow) and the LLI block (blue).

Figure 5: Average minimum TTC over time as an indicator for temporal safety development.

Condition included three levels (Baseline 1, LLI, Baseline 2) and trial difficulty consisted of the two levels (easy and difficult). There was no significant main effect of condition, $F(2.0, 136.73) = 2.004$, $p = 0.136$. This result indicates that on average participants did not differ in their driving velocities depending on the LLI availability. Furthermore, in support of hypothesis 2, it excludes the possibility that the temporal safety benefit reported for the LLI condition compared to the baseline conditions can be accounted for by a velocity-reduction alone. The effect for trial difficulty was statistically significant, yielding an F ratio of $F(1, 946.95) = 27.762$, $p < 0.001$ and indicating a significant difference in average velocity between easy ($M = 116.18$ km/h, $SD = 4.53$) and difficult ($M = 113.16$ km/h, $SD = 6.84$) trials. As observed for the mTTC measure, this result further supports the claim of a successful difficulty manipulation (hypothesis 3) which appears to have caused participants to slow down more in trials classified as difficult. There was no significant interaction between condition and trial difficulty, $F(2.0, 47.93) = 0.701$, $p = 0.496$.

5 DISCUSSION

We introduced a concept for supplementing people's spatiotemporal perception using tactile stimuli which are informative of directions and temporal proximities towards approaching objects. Inspired by sensory capabilities of many aquatic vertebrates that enable coordinated movements in dynamic multi-agent environments, we applied this concept in a driving simulation scenario as a first approach to evaluate whether the signal content can be understood and used to improve performance in mobile situations.

In the automotive [17, 28, 42, 52, 65] and navigation domains [12, 47, 58, 62, 64, 66, 68, 75, 80], vibrotactile displays have previously been proposed as promising interfaces for various functions. Related work thereby focused on the encoding of directions (e.g. [5, 46, 54–56, 71, 73, 75]) and spatial distances (e.g. [2, 6, 7, 19, 44, 59]) in signal components. However, the use of spatial encodings limits the utility of such systems to specific movement velocities. At a velocity of 100 km/h, a distance of 20 meters in the movement direction is usually much more critical than the same distance would be at a velocity of 30 km/h. Nevertheless, a spatial distance encoding would signal both cases in the same manner. In contrast, a spatiotemporal encoding as introduced here is a function of both relative velocity and distance and thus naturally applicable across a wide range of velocities and distances. Spatiotemporal information, in this case a directed time-to-contact, can also be seen as more relevant and less disturbing than a simple distance metric because only objects that signal a potential collision danger induce a stimulus. By making the stimulus-saliency inversely proportional to the time-to-contact, the spatiotemporal encoding has the additional advantageous property of naturally facilitating prioritization in

cases of multiple simultaneously communicated items.
To our knowledge a simultaneous encoding of directions and a TTC-contingent measure for one or more events has not been described or investigated before.

We conducted a user study with a prototype that implements the proposed concept in a driving simulator and found that driving safety, quantified as mTTC, was significantly higher with the supplementary spatiotemporal information provided via the *Lateral Line Interface* (LLI) than without it. This safety benefit compared to baseline conditions suggests that participants were able to understand and utilize the provided information and that the purposeful use of this information was beneficial for task performance. For the second performance measure of average velocity there was no evidence for a difference between baseline and LLI conditions. The independence between trial safety and average velocity is particularly interesting because it means that the safety benefit in LLI trials cannot be accounted for by an average velocity reduction alone. This suggests that LLI usage does not simply shift participants to a different portion of a safety-velocity Pareto front but that it may in fact elevate it and therefore improve overall driving performance.

As illustrated in section *Application Scenario*, both stimulus direction and saliency, i.e. directional and temporal information, can play a role in supporting safety maintenance. Due to the dynamic encoding of these information we argue that the suggested concept is not just a warning device but constitutes an example for sensory enhancement that for instance allows a user to plan and prioritize actions according to the saliencies of individual stimuli. However, the reported improvements in safety might also be explained by less information. Using e.g. only the tactile stimulus onset as an alerting signal might be sufficient to achieve similar safety benefits by shortening reaction times to potential dangers. Questionnaire and interview responses reported by Krüger et al. [37] indicated an understanding and subjective utility of both stimulus direction and time-contingent stimulus saliency, suggesting a use of the full information provided by the system. In the future this question should be explicitly addressed by testing and comparing a variant of the system without (continuous) time encoding. Conversely, investigating possible extensions such as a LLI-based system with adaptive or cooperative assistance [38], by e.g. considering a user's current situational awareness, might provide insights about peoples' ability to utilize more complex and adaptive sensory support systems.

Besides addressing the above points, future studies could target a better understanding of the role of longterm system exposure. In the present study the exposure to the LLI was rather short and may not yet have reached its full potential in terms of the emergence of new perceptual and behavioral qualities. Long term exposure may lead to a manifestation of systematic relations between actions and associated sensory changes, so called sensorimotor contingencies [50], which have been hypothesized as the basis for sensory modality formation [15, 50, 76].

Some subjective accounts from interviews and questionnaires reported by Krüger et al. [37] already described stimuli as being perceived in terms of the communicated information rather than the tactile stimulation. Studies on long term usage could help to identify whether such qualitative shifts develop universally and what amount of exposure would be required.

One factor which may have substantially facilitated stimulus understanding and utility is a potential cross-modal facilitation [22] through the relationship between the TTC and optical flow: Optical flow describes the pattern of directions and velocities of visible features across a scene relative to an observer. When moving through space, optical flow appears to radiate from the movement direction. This radiating center which does not present flow in any direction is known as an expansion point. Similarly, an approaching object creates an optical expansion area that has a stable center but grows as the object approaches. Importantly, the rate of such an expansion encodes the TTC for the respective object and thus yields a visual feature that correlates with the stimuli provided by the LLI and may boost understanding. Once such a link is established, stimuli by the LLI may conversely guide eye-movements in order to benefit from the higher spatial resolution of visual perception. An expansion of measures to include more direct physiological correlates of sensory integration and potential perceptual alterations (see e.g. [36]) should be a valuable addition. This might also help to identify the underlying cognitive mechanisms that mediate the effects of the proposed system.

To conclude, we proposed a novel approach for supplementing peoples' spatiotemporal perception in dynamic situations using tactile stimuli. We implemented a first prototype - the *Lateral Line Interface* (LLI) - and evaluated it in the context of a driving simulation study. Results show that particpants could understand and use the provided information by adapting their driving behavior to improve safety. We suggest that the LLI denotes a system with applicability beyond that of basic warning systems.

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