DO DRIVERS STEER TOWARD OR AWAY FROM LATERAL DIRECTIONAL VIBRATIONS AT THE STEERING WHEEL?

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ABSTRACT: A study was conducted to reveal whether drivers steer toward or away from vibro-tactile stimuli applied at either the left or the right half of the steering wheel. When instructed to react with a fixed mapping, steering toward the stimuli seems to be easier in an abstract environment with significantly faster reactions and fewer errors. However this effect is neutralized and tends to be inverted in a driving environment where steering away from the stimuli seems to be more logical. It is concluded that the additional driving context leads to a defensive behaviour where new and unacquainted stimuli cause avoiding reactions. The contralateral mapping is therefore recommended for in-vehicle applications of directional vibro-tactile stimuli at the steering wheel.

1 INTRODUCTION

While applications of visual and acoustic stimuli to inform or warn the driver in different situations are widely spread, synthetic haptic cues are just beginning to find their way into the vehicle. Promising results are achieved with lane departure warning systems, where an oscillation or vibration at the steering wheel signals an imminent deviation from the lane (see e.g. [1], [2]). However, a haptic signal based on symmetric oscillation or vibration lacks information on directionality, which is considered as the main fault of such a signal ([3]).

To date, most approaches to transfer directional information via the steering wheel are based on additional steering wheel torque applied in the appropriate direction (e.g. [2], [4], [5]). This may have a direct impact both on the vehicle (i.e. the driven trajectory) and the driver, sometimes causing reflexive steering reactions opposing the synthetic torque (e.g. [2], [6]). A haptic signal not reliant on additional torque to transfer information on directionality could be beneficial. In this paper, a concept is described where directional information is coded via the location of a vibro-tactile stimulation being either left or right on the steering wheel. As these stimuli are primarily sensed with mechanosensors in the glabrous skin of the palm, reflexive reactions can not occur. Furthermore and contrary to concepts based on steering torque, the steering wheel will not rotate without manual intervention by the driver.

Recent studies applying directional vibro-tactile stimuli at the steering wheel to inform the driver revealed conflicting results. The stimuli were deployed both providing navigational information in [7], thus necessitating reactions toward the vibration (i.e. ipsilateral reactions), and warnings of imminent lane departure events in [4], thus necessitating steering reactions opposing the vibration (i.e. contralateral reactions). Nevertheless, subjects easily and successfully adopted both the ipsilateral and the contralateral mapping when required to. Furthermore, the vibro-tactile excitation seemed to be very pleasant. Most subjects preferred the vibratory warning used in [4] compared to other concepts in a subjective rating ([5]).

So far, there seems to be no reasonable way to provoke either ipsilateral or contralateral reactions with one and the same vibratory excitation by simply adjusting the stimulus parameters (e.g. frequency, acceleration, duration). Thus a decision has to be made which mapping is to be implemented in an in-vehicle application. As subjects in the studies described above ([4], [7]) had no problems reacting either ipsi- or contralateraly when being instructed on how to react, the question now is which mapping, if any, is the natural one.

According to the principle of stimulus-response compatibility (SRC), reactions in two-choice tasks are faster and fewer errors occur when stimuli and responses correspond spatially (e.g. [8]). Thus reactions in the direction of a stimulus should be faster than reactions in the opposite direction. SR compatibility was demonstrated with directional acoustic stimuli and steering responses in [9], [10] and [11]. However, some additional factors may influence the reactions, e.g. the semantic load of the vibro-tactile stimulus and its affective character.

Adding semantic load to the stimuli influences reactions, as was shown in [10] and [12]. In [10] directional acoustic stimuli were either described as being simple tones (“steer toward/ away from the tone”) or warning signals indicating either the direction of a danger or the escape direction, thus facilitating contralateral and ipsilateral reactions, respectively. Subsuming all reactions, ipsilateral reactions were faster than contralateral ones as was expected with regard to the SRC effect. The addition of semantic load accelerated both contralateral and ipsilateral reactions (with the latter still being faster). A similar study was conducted in a driving simulator in [12], where stimuli were also described as being warning signals (direction of a danger or escape direction). In the driving simulator environment, the SRC effect was inverted leading to faster reactions in the contralateral direction.

It is hypothesized that the affective character of a vibro-tactile stimulus can also influence reactions. While attractive stimuli may abet ipsilateral reactions, drivers may wish to avoid aversive stimuli, thus reacting contralaterally.

As characteristic of the concept of directional steering wheel vibration, any stimulus clearly activates one single hand. It is assumed that the activated hand has a major contribution to the steering response. While turning the wheel to the left or the right with both hands requires actions of equivalent effort, this is not the case for single-handed pushing and pulling, as different muscles are associated with these actions (see e.g. [13])

A study was conducted in a driving simulator to reveal whether unidirectional steering wheel vibrations provoke ipsilateral or contralateral reactions. The study was designed so as to determine the existence of an SRC effect and the effect of additional semantic load. This study is briefly discussed in the next part, and main results are given and discussed in the third and fourth part of this paper (see also [14]). Finally, some conclusions and recommendations for in-vehicle applications of the concept are given in the last part.

2 METHOD

2.1 Participants

44 subjects (32 male, 12 female, aged 27 to 45) chosen from a database participated in the study. They all held a driving license and had normal or corrected to normal vision. None of them was familiar with lane departure warning systems.

Subjects were assigned to either the 'semantic group' or the 'non-semantic' group, below referred to as SG and NG, respectively. The groups were counterbalanced concerning subject's age, sex, handedness, basic reaction time and driving skills. A total of 41 valid datasets was collected (22 in group NG, 19 in group SG), as the data of three subjects had to be excluded from further analysis, mainly due to the occurrence of simulation sickness leading to interruption of the experiment.

2.2 Apparatus and Stimuli

The experiment took place in a static driving simulator. While most tasks were developed using Visual Basic V6.0, the driving scenarios were developed using the StiSim Drive 500 commercialized driving simulator software provided by Systems Technology Inc. [15].

A steering wheel was equipped with eight vibrating elements (motors with eccentric weights) on each side, each of which can be controlled independently. Thanks to mechanical adaptions, transmission of vibration from one side to the other was minimized. CAN signals processed by a microcontroller were used to excite each half of the steering wheel. The frequency was set to approximately 100Hz, which is within the range of greatest sensitivity of the human hand (e.g. [16]). Based on the results of a preliminary study, the acceleration of the stimuli was chosen so as produce a neutral sensation.

2.3 Procedure

2.3.1 Preliminary stage

Subjects were asked to fill out a questionnaire covering demographic data, driving skills, driving experience and handedness prior to the experiment. Upon arrival, subjects performed a computer-based reaction test to determine the basic reaction time (RT). Subjects were then asked to sit into the simulator mock-up and to adjust the seat so as to achieve a realistic and pleasant driving posture. They were asked to grip the steering wheel with both hands ("10-to-2"-position). This hand posture was to be kept throughout the complete experiment.

2.3.2 Free reaction

This part of the experiment examined whether an intuitive reaction on directional steering wheel vibration exists. Subjects were told that their steering wheel would all of a sudden vibrate while they were performing a secondary task. They were not aware of the unidirectionality of the stimulus and were instructed to react with a fast and instantaneous steering movement. The angular amount of the desired reaction was demonstrated. All instructions were presented on the simulator screen in written form, and the investigator was available for interposed question.

The secondary task throughout this part differed between groups. For subjects of group NG, white items (letters and numbers) were subsequently presented in the centre of the black simulator screen with a presentation time of 300ms and 100ms of blank screen between successive items. They were asked to ignore the letters and to name the numbers. This task was adopted from the RSVP task (rapid serial visual presentation) in [17] and is herein – despite the necessary adaptions made – also referred to as RSVP task. Subjects in group SG were asked to drive in a simple scenario consisting of a three-lane winding road without traffic at about 80-100 km/h. They were instructed to drive in the middle of the center lane.

In both groups the stimulus was applied only once and the experiment stopped immediately after stimulus presentation. Subjects were asked about their sensation and whether they perceived the directionality of the stimulus. They were then asked to verbally describe their reaction and to rate the stimulus in terms of valence, potency and arousal.

2.3.3 Instructed reaction

In the second part subjects were asked to react on directional vibro-tactile stimuli with a fixed mapping (ipsi- or contralateral). All subjects performed the task with both mappings, with the order counterbalanced throughout the cohort.

While subjects in group NG received only written and verbal instructions of the required mapping, subjects in group SG experienced the mapping in a driving scenario. A lane departure warning (LDW) function where the vibrating side indicated the direction of the imminent deviation was realized to account for the contralateral mapping. To memorize the ipsilateral mapping, subjects were asked to follow a white line on the lane center indicating the optimal trajectory (OT, see fig.1). In the ipsilateral condition, the vibrating side indicated the direction of the steering reaction necessary to stay on the trajectory. Enough time was given for the subjects to actively experience the mapping and to trigger vibrations by navigating the car to the lane borders and away from the lane center, respectively.

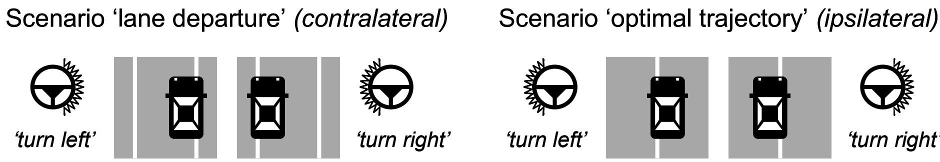

Fig.1. Scenarios used in group SG

When they were aware of the necessary reaction (ipsi- or contralateral), subjects performed two blocks of two minutes each with subsequent vibration stimuli on the steering wheel on which to react on (single task). Both left- and right-hand stimuli where uniformly distributed, and the order of appearance was randomized throughout each block. Subjects were left to close their eyes throughout these blocks.

The steering task and the RSVP task were then combined (dual task). It was assured that vibro-tactile stimuli on which to turn the steering wheel and visual stimuli on which to react on verbally were not presented simultaneously. Subjects were told to prioritize the steering task but all the same not to disregard the RSVP task. The dual task was performed two times in blocks of two minutes each. The experiment then continued with the same blocks (instruction, 2 x single task, 2 x dual task) using the other mapping. After each block, subjects were asked to rate their level of effort.

In a follow-up survey, subjects were asked to write down their strategy in performing the steering task and their sensation of the vibration. Subjects in group NG were also asked to write down any associations they had to real-world situations. Subjects were verbally assisted in answering, but strong care was taken not to influence them in expressing their own opinions.

Figure 2 visualizes the procedure of the study

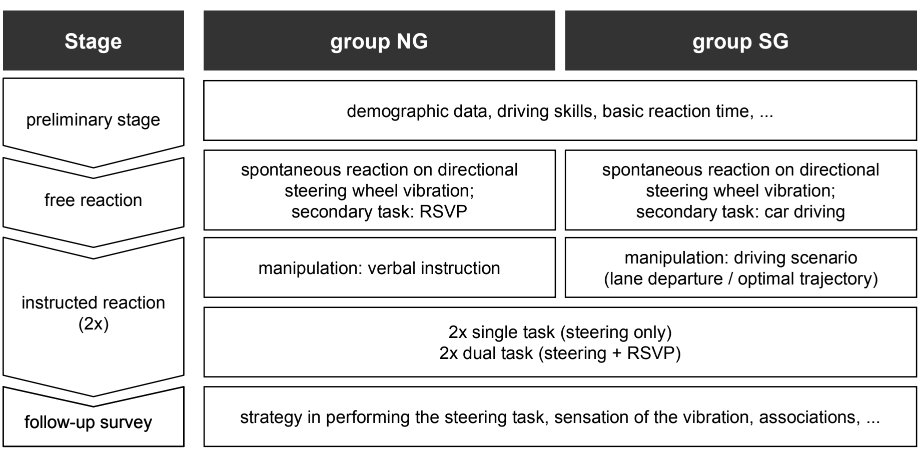

Fig.2. Procedure of the study (simplified illustration)

2.4 Data analysis

The direction of the steering reaction in the stage of free reaction was analyzed. In the stage of instructed reaction, RT was measured as being the time between stimulus onset and steering angle exceeding ±8° relative to the angle at stimulus onset. Errors made during the steering task (ERRSteer, steering reactions in the wrong direction) and errors made during the RSVP task (ERRRSVP, missed or falsely named numbers) were also analyzed. Besides these objective data, attention was directed on analyzing the subjective data stated throughout the experiment and in the follow-up survey.

3 RESULTS

3.1 Results of the free reaction

The steering reactions in the stage of free reaction do not show any regularity (see table 1). The direction of the reaction seems to be randomly decided. There is no systematic influence of subject's handedness nor does the course of the visible lane ahead (in group SG) have an influence. Some subjects in group SG stated that they were looking for any visible danger when the vibration occurred and – not able to find any correlation – did not react at all.

Table.1. Directions of the free reactions

	∑	ipsilateral	contralateral	no reaction
group NG	22	11	11	0
group SG	19	9	5	5

3.2 Results of the instructed reaction

Within this paper the focus is set on the results of the paired comparisons of RT and ERRSteer between both groups. Subsuming the single and dual task blocks, there is a small but significant ($p < .003$) difference in RT of 14ms between the ipsilateral and the contralateral mapping (see fig. 3a). The 17ms RT difference in the dual task blocks only is also significant ($p < .001$). While RT is apparently smaller in the single task condition, the difference in RT between the ipsi- and contralateral mapping is no longer significant ($p < .095$).

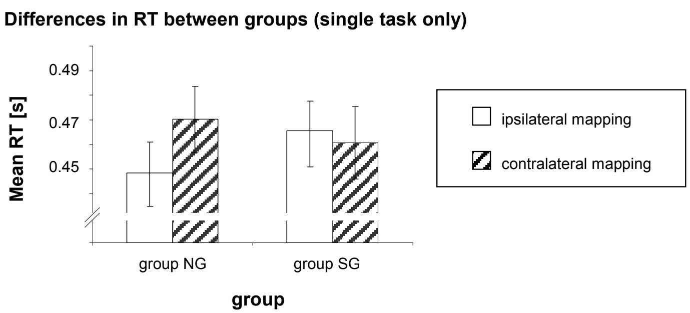

Fig.3. SRC effect in a) reaction time and b) erroneous steering reactions

Fig. 3b illustrates the absolute number of erroneous steering reactions made throughout the experiment. A significant ($p < .005$) difference between the two mappings can be observed with fewer errors made in the ipsilateral condition, which is mainly attributed to the significant ($p < .003$) differences in the single task blocks. The difference in ERRSteer in the dual task condition is not significant ($p < .075$). All in all only few errors were made, ranging from M = 0.65, SD = 1.67 in the single task condition using the ipsilateral mapping to M = 2.18, SD = 1.67 in the dual task condition using the contralateral mapping.

No overall effect of the additional semantic load could be observed when comparing the data of both groups altogether. However, a neutralizing effect of the semantic load was observed regarding RT in the single task only (see fig.4). While RT in the single task was faster using the ipsilateral mapping (448ms) compared to the contralateral mapping (469ms) in group NG, RT was almost the same for ipsi- (467ms) and contralateral (461ms) mapping in group SG, with the latter even being a little faster. This interaction effect of mapping and semantic load is significant ($p < .022$)

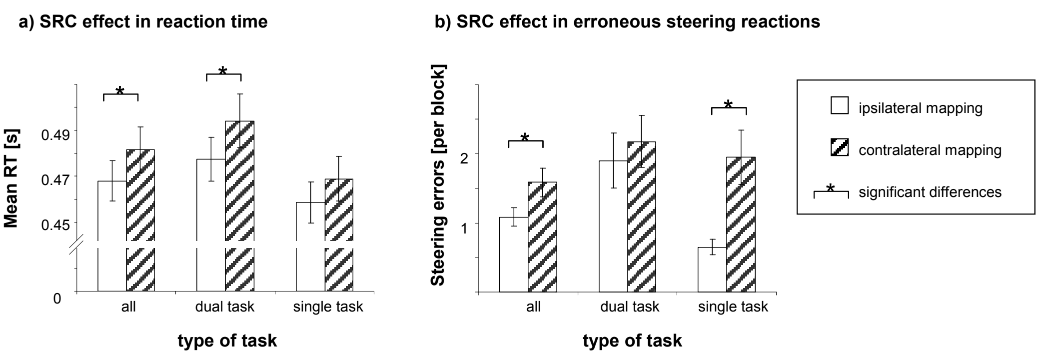

Fig.4. Neutralization of the SRC effect in group SG (single task only)

3.3 Other results

Subject's statements confirm the neutrality of the vibro-tactile stimulation. The stimuli were rated as being neutral or slightly convenient. Some subjects emphasized that the vibration on the steering wheel is nonintrusive and even ignorable. When asked about the strategy they had to accomplish the steering task, most subjects reported on motoric strategies. These were either to push or pull with the hand activated by the vibration or to pull with the active or the inactive hand. When applying the first strategy, all subjects stated that it was easier to pull on the steering wheel than to push it.

4 DISCUSSION

4.1 General discussion

Based on the results of the free reaction it is obvious that directional vibro-tactile stimuli do not trigger an instantaneous reaction to a specific direction. This is particularly evident considering subjects of group NG who equally reacted with ipsi- and contralateral rotations.

In general, SR compatibility was demonstrated for directional steering wheel vibrations and rotational responses. It is assumed that the single-hand activation abets the tendency towards ipsilateral reactions, as subjects stated that pulling on the wheel is easier than pushing on it. If there is an influence of the affective character of the vibration at all, it certainly does not abet contralateral reactions. However, an enhancement of the tendency towards contralateral reactions leading to a neutralization of the SRC effect occurred in the single task condition in group SG.

The RSVP task originally introduced to simulate the cognitive load while driving effectively restrained subjects of group SG from reactivating the scenarios they had experienced. However, while performing the single task and having their eyes closed, subjects stated that they were able to reactivate these scenarios. At the same time, subjects of group NG did not experience any driving context. It is concluded that the additional driving context in group SG leads to a defensive behaviour where new and unacquainted stimuli cause avoiding reactions. Thus the tendency towards contralateral reactions is enhanced.

The neutralization of the SRC effect in the single task condition in group SG can be attributed to a slight reduction of RT when using the contralateral mapping, but even more to a considerable increase of RT with the ipsilateral mapping. The OT scenario did, on the one hand, activate the association ‘deviation from the trajectory – steer toward the vibration’. But on the other hand, it introduced the driving context which activated the contrary association ‘signal – avoidance’. This leads to an additional conflict thus slowing down reactions. The LDW scenario provided an association consistent with the one introduced by the driving context, leading to slightly faster reactions.

The statements of the subjects of group NG support this conclusion. When asked about any associations to in-vehicle situations, only associations linking the stimuli to events necessitating contralateral steering reactions were stated by the subjects (e.g. passing profiled road markings or rumble strips, deviating into dirt road, hitting curbs). It seems that contralateral reactions are more logical in the driving context.

4.2 Discussion of methods

The driving context induced by the driving simulator used as the experimental environment is advantageous for subjects of group SG but rather disadvantageous for subjects of group NG as they were to experience an environment free of any driving context. Obviously the absence of context in group NG desired for methodical reasons can not be achieved in a driving simulator. For this reason, the driving context is to be considered as a relative measure. However the usage of the driving simulator offers numerous advantages, e.g. the existing structures for data acquisition. Furthermore it allows for comparability between groups with the only difference being the manipulation (written/verbal instruction vs. driving situations) prior to the blocks in the stage of instructed reactions.

Reactions can be accelerated when their effect is fed back visually to the subjects (see e.g. [11]). In the present study, a cursor on the simulator screen providing visual feedback of the reactions was originally planed. The movement of the cursor was quite jolting due to technical limitations, and the cursor was therefore removed from the screen. The little extent of the SRC effect in the present study can partly be attributed to the lack of visual feedback.

In both the LDW and the OT scenario, the vibration originates from passed road markings. While the first signals an imminent danger, the latter just informs about a comparatively harmless deviation from an optimal state. This may explain why the LDW scenario accelerated reactions, while the OT scenario did not. It is difficult to find a scenario for the ipsilateral mapping equivalent to the LDW scenario. This lack of equivalence is to be accepted as a methodical constraint, but it may also serve as remark for the predominance of the contralateral mapping in the driving context.

5 CONCLUSION

As was demonstrated in the present study, vibro-tactile directional stimuli at the steering wheel do not cause reflexive or instantaneous reactions to a specific direction. Thus a decision has to be made which mapping is to be implemented in an in-vehicle application.

An SRC effect was observed for directional vibratory stimulation and steering responses, leading to faster reactions toward the stimuli in an abstract environment. However a neutralization and tendency towards inversion of the effect was also observed and is concluded to originate from the addition of driving context to the task. As real-world driving obviously provides most driving context, the usage of the contralateral mapping is recommended in any in-vehicle application of the directional vibration at the steering wheel.

Further attention is now directed on the vibration itself with the intention to design stimuli that are neither neutral nor convenient (as in the present study) but rather feel threatening. It is hypothesized that this may further encourage the tendency toward contralateral reactions.

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