ABSTRACT
Existing car navigation systems require visual or auditory attention. Providing the driver with directional cues could potentially increase safety. We conducted an experiment comparing directional haptic and non-speech audio cues to visual cueing in a navigation task. Participants (N=16) drove the Lane Change Test simulator with different navigational cues. The participants were to recognize the directional cue (left or right) by responding as fast as possible using a tablet. Reaction times and errors were measured. The participants were also interviewed about the different cues and filled up the NASA-TLX questionnaire. The results showed that in comparison to visual cues all the other cues were reacted to significantly faster. Haptic only cueing resulted in the most errors, but it was evaluated as the most pleasant and the least physically demanding. The results suggest that non-visual cueing could improve safety.

INTRODUCTION
Car navigation systems are widely used nowadays. These systems generally rely on giving visual and auditory instructions. This can have some disadvantages for the driver because they recruit senses and attentional resources that are central for the driving task itself. Visual in-vehicle navigation information displays have been shown to have negative effects on traffic safety (e.g. [7, 10]). A major problem is visual distraction caused by gazing at the navigator. Processing the symbols on 2D maps requires some cognitive effort. Auditory channel on the other hand suffers from noisy environments (e.g. music and conversations), which can reduce its usability as the only modality. Tactile feedback is seldom used in car navigation and it could bypass some of the limitations that visual-audio systems have. Jacob et al. [6] listed four reasons to integrate haptics into mobile navigation. The reasons are: freeing the eyes for other purposes, enabling faster decision-making, reducing cognitive load and avoiding language barriers with global audiences. They also apply in car navigation context.

So how can the importance of visual channel be reduced in navigation situations? Navigation cues should be intuitive to minimize cognitive load, but previous studies have given mixed results on the subject [15]. Many studies in haptic navigation have been focused on tactile icons, such as Tactons [5] and Haptic Icons [11]. Although these studies show that high recognition rates can be achieved with tactile icons, these icons still cause higher cognitive load. They take time to interpret and require learning. One reason for this might be that the tactile stimulations use one channel to provide messages. So splitting this single channel information in two channels could facilitate cognitive processing in certain situations like navigating to the left and right. Thus, directional cues in the present context are defined as audio or tactile stimuli given to one side of the body to alert of an event occurring on the same side. Simple directional cues could direct attention like a tap on the shoulder without increasing cognitive requirements in already demanding situations [15].

Attentional cueing using haptics has been shown to decrease reaction times [14] compared to visual cues. In another study [9] using audio cues, conflicting message semantics and sound-source location led to an increased error rate. This resembles the dominant approach in current navigation systems as all messages come from the same direction. For example, a navigator on the right side of the driver may instruct him to turn left. To prevent any extra cognitive load the use of simple directional cues (left and right) could be beneficial. As these cues cannot provide the
same amount of information as more complex tactile icons, they could be combined with conventional visual cues.

Current car navigation research has focused mainly on three forms of tactile displays: tactile seats (e.g. [4]), tactile belts (e.g. [1]) and tactile steering wheels (e.g. [8]). We chose the seat approach: stimuli were provided on the driver’s thighs. Using the seat has several advantages: stimulus can be precisely located in one side of the body; the stimulus device can also be an integral part of the car and have constant contact with the driver. Communicating complex messages without direct contact with the skin could be challenging but simple directional cues should be more easily recognizable. In a previous study with a tactile seat recognition rates of over 90 % have been achieved [4].

Directionally congruent haptic and audio cues can increase performance [14, 9] but the results dealing with display modality and cognitive load are mixed [15]. One study [8] found that speech-based audio-haptic cues reduced driver distraction compared to single modality cues. They also reported that haptic cues decreased performance compared to audio cues. Another study [1] found that haptic cues did not increase performance compared to a conventional car navigation system.

We applied two kinds of directional cues: haptic cues on the driver’s thighs and audio cues provided by headphones. Our goal was to have easily distinguishable cues that could reduce driver distraction in a cognitively demanding driving situation. To our knowledge, directional haptic-audio cues have not been studied together with visual cues before. Our research question was the following: are directional audio, haptic, or haptic-audio cues less distractive than visual cues and what is the preferred modality for the users in a cognitively demanding driving situation?

**METHOD**

**Participants**

Sixteen participants (14 male, 2 female, mean age 35, range 18-52 years) took part in the experiment. All were right-handed and had a normal vision, hearing and sense of touch by their own report. All had a driving license and drove 1000-35000 kilometers per year (in average 14000).

**Apparatus**

We built a haptic seat prototype for the experiment. This prototype consisted of a car seat with integrated actuators to provide haptic cues. In addition, we used a desktop PC, gaming steering wheel and pedals for the driving task and a tablet for the navigation. Headphones were used to provide audio cues. We acknowledge that this does not correspond to a real driving environment [8]. We chose headphones to make audio and haptic cues more comparable: reducing the effect of background noise and distance to the body. The whole setup is shown in Figure 1a. We used the Lane Change Test simulator [12] and a self-implemented navigation task software with data logging.

**Stimuli**

Cues were used to express two directions: left and right. Separate attentional cues were not used as the actual cues were designed to both capture attention and to guide the driver. Baseline visual condition consisted of blue boxes (11.5 x 5.5 cm) indicating the direction (left or right) in white letters. They were presented in the center of the right side of the screen without time limit (Figure 1b). We did not use arrows as they were employed as choice buttons (Figure 1b) and that would have provided an advantage for the visual cues. Directional audio condition provided audio cues for the navigation task via headphones with sine waves (time of stimulation 120 ms) sounds to left or right ear. Directional haptics condition utilized cues of the same length (120 ms) provided by the haptic seat prototype, a sine wave type vibration on the driver’s left or right thigh indicating a turn. For audio signal frequency and time period were 2050 Hz and 490 ms, for vibration 12.5 Hz and 80 ms. Design guidelines [2] suggest that duration of a signal burst should be between 100-150 ms. Synchronicity of the cues was verified in internal tests; testers reported that the cues were experienced simultaneously. In every condition, participants had to choose the direction by pressing arrow buttons on the tablet screen (Figure 1b). The arrows were arranged vertically so that it would be practical to reverse their positions, thus standardizing button location between trials. Had they been arranged horizontally, right-left condition would have been clearly non-congruent.

**Experimental Design**

Three tasks were performed simultaneously in the study: driving a Lane Change Test simulator, counting numbers and performing a navigation task. We wanted to have multiple measures of cognitive load to see if cues have different effects on these measures. We compared a visual navigation condition (baseline) to three other conditions: directional audio, directional haptics and directional haptics-audio; the within-subjects independent variable was display modality. As objective dependent variables we measured reaction time to the navigation messages, error rate in navigation, lane deviation (mean distance from the ideal driving line), driving errors (choosing the wrong lane), and the amount of numbers counted (with counting errors subtracted). The participants filled in NASA-TLX questionnaires [3] for each stimulus condition. The participants were also shortly interviewed after the tests. Cognitive load was increased by asking the participants to
count numbers, which has been shown to significantly affect reaction times in a driving task [13]. Wickens’ [16] multiple resource theory predicts that high cognitive load and multiple tasks are needed to observe performance differences between conditions.

**Procedure**

The study was conducted in a laboratory where participants were driving the Lane Change Test simulator. This consisted of driving a straight road and performing lane changes to left or right according to the instructions given by the simulator. Six different tracks were driven, one with each display modality and also one for practice and another one after the modality conditions to rule out learning effects. There were 18 lane changes (9 lefts, 9 rights) in each track. Time between lane changes was around nine seconds. Participants were also doing the counting task which consisted of counting forward seven numbers at a time (7, 14, 21…). In addition, participants had a navigation task in the experimental conditions, choosing between left and right arrows on the tablet screen based on the stimulus received. This happened every 6-10 seconds, 17 times (8-9 lefts, 8-9 rights) in total. Half of the participants had the arrow positions reversed. Each participant completed every route but the display modality order was counterbalanced.

In the beginning the participants were briefly familiarized with the experiment and they had a chance to practice recognizing the cues and driving with the counting task. They were also allowed to adjust headphones to a comfortable volume and seat distance to the steering wheel and pedals. The actual driving tasks for the four modality conditions were then carried out. Reaction times, navigation errors and mean lane deviation were measured. Counting errors and numbers counted correctly were also measured during the tasks. After each task, a NASA-TLX questionnaire was answered. An interview of the different methods was made after the experiment. Each condition lasted for 5-10 minutes, the experiment in total 45 minutes.

**RESULTS**

**Interviews and NASA-TLX**

Participants were asked to name the most pleasant stimulus method and tell why they chose it (see Figure 2). In addition, participants were asked if they would use directional audio or directional haptic cues for navigation and why. Six participants (37 %) preferred the haptic-only method. It was described as clear (4 participants), comfortable (2 participants) and less distractive than the other methods (2 participants). Two participants said that it felt unpleasant and another two said that visual cues would support haptic cues. Four participants (25 %) preferred the visual method. Visual cues were described as easier (2) and as less demanding than the other methods (2). Haptic-audio and audio methods were both preferred by three participants (19 %). Haptic-audio method was especially liked for its multimodality (3) which was said to be helpful. Audio cues were described as clear (3) but it was also said that other sources of noise in the traffic disturb them (3). Five participants said that visual cues would support audio cues.

**Figure 2. The most pleasant navigation method.**

NASA-TLX questionnaire data was analyzed using Friedman tests. We found a statistically significant difference in physical demand (p < 0.041). Other items were not statistically significant. Pairwise comparisons for physical demand were made with Wilcoxon tests. We found a statistically significant difference between conditions: haptic condition was less demanding than visual (p < 0.022) or audio (p < 0.027) condition (Figure 3).

**Reaction times and navigation errors**

The reaction times in the navigation task were analyzed using one-way repeated measures ANOVA and Bonferroni-corrected post-hoc pairwise comparisons. ANOVA revealed statistically significant differences between conditions (p < 0.001). The results showed that participants reacted 465-603 ms faster in haptic (p < 0.001), haptic-audio (p < 0.001) and audio (p < 0.002) conditions compared to the visual condition (Figure 4). Navigation errors were analyzed using Friedman tests. A statistically significant difference between conditions was found (p < 0.011). After this pairwise comparisons were made with Wilcoxon tests. Total amount of errors was fairly low in all conditions (0.7-5.1% of turns), but there were significantly more navigation errors in haptic than in audio (p < 0.012) or haptic-audio (p < 0.033) conditions (Figure 5). There were no statistically significant differences in lane deviations, numbers counted correctly, or in driving errors.

**Figure 3. Physical demand in NASA-TLX.**

**Figure 4. Reaction times in the navigation task.**

**Figure 5. Error percentages in the navigation task.**
DISCUSSION AND CONCLUSIONS

We presented an experiment which shows that haptic, audio and haptic-audio cues were processed faster than visual cues. This may indicate a lower cognitive demand when using haptic, audio and haptic-audio directional cues. Multimodal cues (haptic-audio) did not lead to faster processing than unimodal cues (haptic or audio). This suggests that using haptic and audio cues together might not give extra benefits in performance.

Haptic cues required less physical effort than visual or audio cues but led to significantly more errors than audio and haptic-audio cues. These results may reflect driver characteristics and the driving environment, as people have different sensitivities to touch and sound and respond differently to stressful situations, which may lead to missing cues. Directional cues were widely preferred subjectively: 75% of participants preferred haptic-, audio- or haptic-audio cues to visual cues. In addition, 94% of participants would use directional haptic or audio cues alone or combined to other modalities.

Some issues should be considered when interpreting the results. Headphones are not a feasible option for a real car context. In addition, navigating the environment includes more than just left-right turns. Generalizing the results should be done with caution. Acknowledging these limitations, the findings support the idea of using directional cueing in navigation. Directional cues could be used to increase driving safety in situations that are demanding on the visual and auditory senses. There are some design implications to existing navigation devices; tactile, audio and visual cues could be located on the same side as the turns are. It is likely that directional cueing would function well for other purposes than just navigation (e.g., collision warning or notification of a blind area). More research is needed to see how directional cues would function in a real car context.

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