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Blind driving by means of auditory feedback

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Abstract: Driving is a safety-critical task that predominantly relies on vision. However, visual information from the environment is sometimes degraded or absent. In other cases, visual information is available, but the driver fails to use it due to distraction or impairment. Providing drivers with real-time auditory feedback about the state of the vehicle in relation to the environment may be an appropriate means of support when visual information is compromised. In this study, we explored whether driving can be performed solely by means of artificial auditory feedback. We focused on lane keeping, a task that is vital for safe driving. Three auditory parameter sets were tested: (1) predictor time, where the volume of a continuous tone was a linear function of the predicted lateral error from the lane centre 0 s, 1 s, 2 s, or 3 s into the future; (2) feedback mode (volume feedback vs. beep-frequency feedback) and mapping (linear vs. exponential relationship between predicted error and volume/beep frequency); and (3) corner support, in which in addition to volume feedback, a beep was offered upon entering/leaving a corner, or alternatively when crossing the lane centre while driving in a corner. A dead-zone was used, whereby the volume/beep-frequency feedback was provided only when the vehicle deviated more than 0.5 m from the centre of the lane. An experiment was conducted in which participants (N = 2) steered along a track with sharp 90-degree corners in a simulator with the visual projection shut down. Results showed that without predictor feedback (i.e., 0 s prediction), participants were more likely to depart the road compared to with predictor feedback. Moreover, volume feedback resulted in fewer road departures than beep-frequency feedback. The results of this study may be used in the design of in-vehicle auditory displays. Specifically, we recommend that feedback be based on anticipated error rather than current error.

Keywords: road safety, driver support, auditory display, human-machine interface, driving simulator

1. INTRODUCTION

Worldwide, billions of people engage in driving at some stage in their lives. Driving is crucial for economic success, but the corresponding cost is substantial. Over 1 million people die in road traffic crashes each year, and millions more become injured (World Health Organisation, 2015).

Driving is primarily a visual task (Groeger, 2000; Sivak, 1996). To be able to drive safely, drivers need to have a valid estimate of their position in relation to other road users and the road boundaries (Groeger, 2000; Macadam, 2003). However, sometimes, such as in case of fog, rain, or darkness, the visual information from the environment is degraded or absent (e.g., Edwards, 1999; Smith, 1982). Relevant visual information may also be unavailable because of occlusion by other road users or buildings, or when an object is in the blind spot (North, 1985; Staubach, 2009).

Even when visual information is available, the driver may fail to use it. In a naturalistic driving study, it was found that 78% of crashes involved a driver looking away from the forward road just prior to the crash (Klauer et al., 2006). This finding is consistent with a literature review of 50 years of driving safety research, which concluded that most crashes occur because "drivers fail to look at the right thing at the right time" (Lee, 2008, p. 525). Moreover, people tend to underestimate distance (Baumberger et al., 2005; Teghtsoonian and Teghtsoonian, 1970) and speed (Recarte and Nunes, 1996). In addition, there are large individual differences in visual ability. Contrast sensitivity, perceptual speed, and useful field of view decline substantially with age (Janke, 1994; Kline and Fuchs, 1993; Salthouse, 2009; Sekuler et al., 2000). Thus, there appears to be a need for assistive technology that supports the driver when visual information from the environment is degraded, or when the driver fails to process the available visual information.

The auditory modality is promising for warning or supporting human operators, because humans can receive auditory information from any direction, irrespective of the orientation of their head and eyes (Sanders and McCormick, 1987; Stanton and Edworthy, 1999). Furthermore, the ears can receive information at any moment, and humans have the ability to focus selectively on one sound in situations where multiple auditory signals are present (Hermann et al., 2011). Not surprisingly, various types of auditory displays (in the form of forward collision warning systems, parking assistance systems, and blind spot monitoring systems) are available on the market and have been found to improve road safety (e.g., Piccinini et al., 2012). Moreover, auditory feedback systems have been designed that support drivers in case visual information is unavailable (Colby, 2012; Hong et al., 2008; Verbist et al., 2009). As part of the Blind Driver Challenge, Hong et al. (2008) developed an auditory and vibrotactile feedback system that relays information to the driver about the car speed and movement direction. Verbist et al. (2009) proposed two continuous auditory displays based

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either on brown noise or a melody for supporting the lane-keeping task in the absence of visual information; both displays proved to be capable of supporting such a task.

Outside the domain of driving, the potential of auditory feedback has been studied as well. For example, auditory feedback was found to be effective for supporting blindfolded participants in steering a powered wheelchair (Vinod et al., 2010). In Simpson et al. (2008) the vision of pilots in actual flight was occluded by goggles, and an auditory artificial horizon was used for attitude identification and for recovering from displaced aircraft attitudes. The results showed that the pilots were able to manoeuver the aircraft within its flight envelope by means of auditory feedback only (and see De Florez, 1936, for a classic study on 'blind flight'; also Wickens, 1992, pp. 480–481). Vinje and Pitkin (1972) showed that participants performed a tracking task equally well when the tracking error information was provided via an auditory or a visual display.

Can driving be performed without any visual feedback? Without alternative feedback, this is impossible because drivers need to visually sample the road about every 4 s to keep the car on the road (Godthelp, Milgram, and Blaauw, 1984). Google put Steve Mahan, who lost 95% of his vision, behind the steering wheel of one of their prototypes of fully automated cars (Prince, 2012). Mahan was able to get to a restaurant and pick up his dry cleaning. However, substantial technological advances are required before self-driving cars can be put on the road (Shladover, 2015). Unless the driving task is wholly automated, humans have a crucial role in the driving task, and could benefit from real-time feedback

This study explored whether driving can be performed as an auditory task without any visual feedback. Specifically, we looked at lane keeping, a task that has to be conducted permanently and is crucial for safe driving (Brookhuis and De Waard, 1993). By means of this research, we aimed to generate knowledge that may be of value in the design of in-vehicle auditory displays. One example of such an application may be a situation where a driver falls asleep behind the wheel or is visually distracted, in which case appropriate (directional) auditory feedback could warn and support him/her in regaining control.

In the design of driver support systems and in the modelling of driver behaviour, a predictor time is often used (e.g., Donges, 1978; Hellström et al., 2009; Hingwe and Tomizuka, 1998; Petermeijer et al., 2015). This means that the driver responds to a predicted error rather than to the current error. It has also been advised to use graded (i.e., increasing with deviation from a target) instead of binary feedback (e.g., Lee et al., 2004; Wolf and Nees, 2015). Therefore, we tested the effectiveness of graded predictor feedback in our research.

2. METHOD

Apparatus. For this research, we used a fixed-base driving simulator (Fig. 1; Green Dino, the Netherlands). An interface was programmed in MATLAB/Simulink r2015a to retrieve data from the simulator and to generate audio output via Creative Sound Blaster Tactic 3D Alpha headphones. The participants were able to hear engine and tire sounds via loudspeakers mounted in the simulator. During the experiment, the LCD projectors of the simulator were turned off. The width of the car was 1.76 m and its length was 4.22 m.

Fig. 1. The driving simulator used in this research. In all trials, the visual projection was shut down.

Track. The track was a two-lane 7.5-km road without intersections and without other road users. It contained straight segments and sharp 90-degree corners, most of which had a radius of about 20 m (for research using the same track, see De Groot et al., 2012; Van Leeuwen et al., 2014, 2015). The lane width was 5 m. There were two starting points, yielding two different segments (Fig. 2). In each trial, the participant drove 3 km which took on average 4.80 min (*SD* = 0.72 min, *N* = 44).

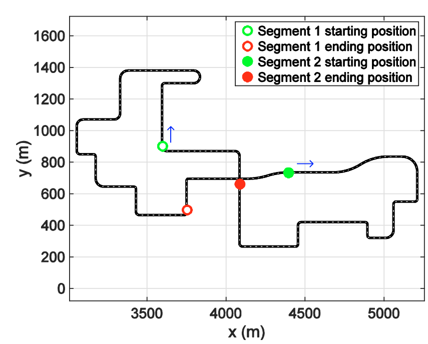

Fig. 2. Top view of Segment 1 and Segment 2 of the test track. x and y are Cartesian coordinates in meters.

Participants. The participants were two experienced drivers (two of the authors) with good knowledge of the auditory feedback concepts and the track.

Speed and gearbox settings. An automatic gearbox was used. The speed of the car was predetermined so that the participants did not use the pedals. Fig. 3 (top) illustrates the speed of the car in two left corners followed by a right corner.

Three parameter sets were tested in the following order per participant: 1) predictor time (consisting of 4 conditions), 2) feedback mode and mapping (consisting of 4 conditions), and 3) corner support (consisting of 3 conditions). Each participant tested each condition once on Segment 1 and once on Segment 2 (Fig. 2). The conditions and segments were randomized within each parameter set.

In all three parameter sets, a dead zone was used based on De Groot et al. (2011), see also Horiguchi et al. (2013) for the advantages of a dead zone in sonification for a manual control task. Thus, the volume and beep-frequency feedback were provided only when the predicted position of the car deviated from the centre of the right lane by more than 0.5 m.

Parameter set 1: Predictor time. The predicted lateral error was calculated by extrapolating the current position of the centre of the car (x, y), by t_{pred} seconds using the velocities in world coordinates (v_x, v_y). Volume feedback was used in this design. Specifically, the volume (on a scale from 0 to 1) of a 464 Hz tone became linearly louder with increasing predicted error with respect to the centre of the right lane (e) as follows: $0.1*|e-0.5|$ (Fig. 4, left). The participants had to steer away from the sound. That is, sound on the left was produced when the predicted lateral error was left of the centre of the right lane, whereas sound on the right was produced when the error was right of the lane centre.

Fig. 3 (middle & bottom) illustrates the working mechanism of the predictor. It can be seen that the larger the t_{pred}, the larger the difference between predicted and current error. For example, for t_{pred} = 3 s, at a travelled distance of 1700 m, the participant was left of the lane centre, while the predictor indicated that the car ends up to the right in 3 s time.

Parameter set 2: Feedback mode and mapping. We evaluated linearly graded volume feedback (VL), exponentially graded volume feedback (VE), linearly graded beep-frequency feedback (FL), and exponentially graded beep-frequency feedback (FE).

The linear volume was the same as in Parameter set 1, whereas the exponential volume was defined as $0.02*e^{|e-0.5|}$. In the beep feedback, the inter-beep time (IBT) was varied as a function of the predicted lateral error. In the FL condition, the reciprocal of the IBT was linearly related to the predicted error, whereas in the FE condition this was an exponential relationship. For both the FL and FE conditions, the beep duration was 0.14 s. Fig. 4 illustrates how the auditory feedback became louder, and the inter-beep interval became shorter, with predicted error.

As in parameter set 1, the sounds were directional: sound on the right was produced when deviating to the right, and vice versa. In all cases, a predictor time of 2 s was used, and the sound was a 464 Hz tone as in Parameter set 1.

Parameter set 3: Corner support. In this design, t_{pred} was 2 s, and linear graded volume feedback (VL) was used. An additional corner support was implemented, allowing drivers to infer when to make small corrections on straights and when to make large required steering angles in corners. Three concepts were tested. The first concept did not involve corner support. In the second concept, a beep was produced when the car entered and when the car left a corner. When entering a left corner, a beep on the right was produced, while when entering a right corner, a beep on the left was produced. When leaving a corner, a beep was produced both on the left and on the right. The third concept provided a beep on the left and right when crossing the lane centre in corners (i.e., when the sign of the predicted error changed).

In Parameter set 3, the linear graded volume feedback with t_{pred} = 2 s was used. A 565 ms long beep of 2165 Hz was used as corner support. The volume of this beep was constant.

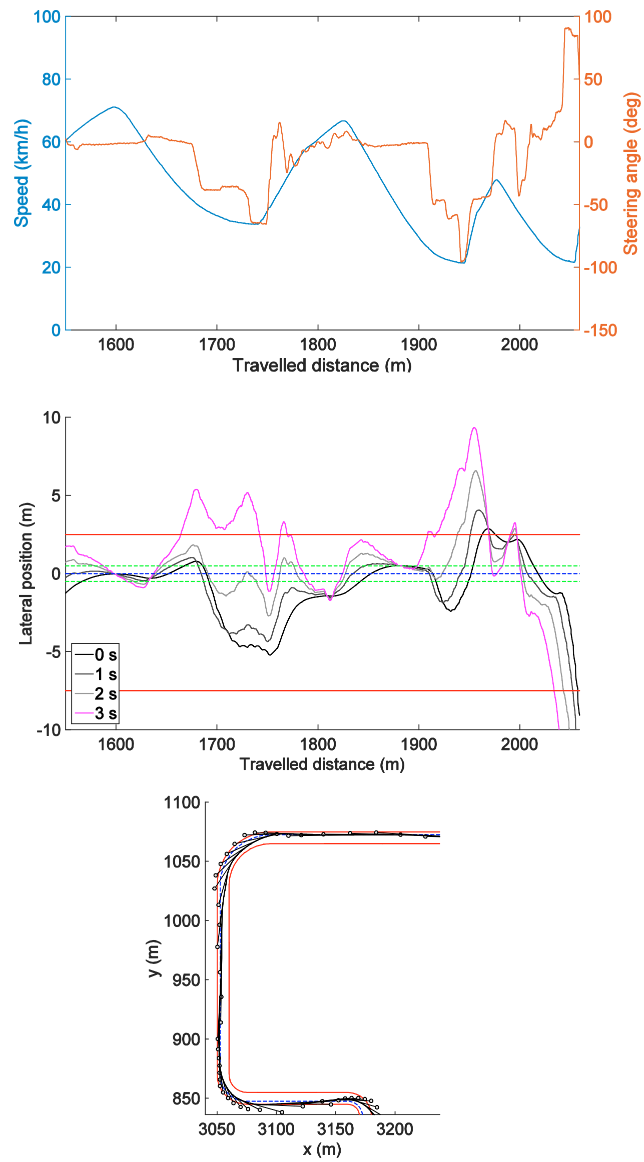

Fig. 3. Working mechanism of the predictor feedback. The three figures correspond to the same selected part of the route (participant 1, Segment 1, used predictor time = 3 s) consisting of two left corners followed by a right corner (radii of the centre of the right lane = 42.5 m, 22.5 m, & 12.5 m, respectively). The participant departed the road in the right corner. Top = Speed and steering angle versus travelled distance. Middle = Lateral error with respect to the centre of the right lane versus travelled distance, for t_{pred} = 0 s (i.e., the actual lateral error), 1 s, 2 s, and 3 s. The green lines at -0.5 m and 0.5 m represent the bandwidth of the feedback. Bottom = The path driven by the participant. The circular markers correspond to the predicted lateral error with t_{pred} = 3 s, calculated every 1 s. For the middle and bottom figures, the blue dashed line represents the right lane centre, and red lines represent the lane boundaries. For these figures, a low-pass filter was used, as signals were somewhat noisy.

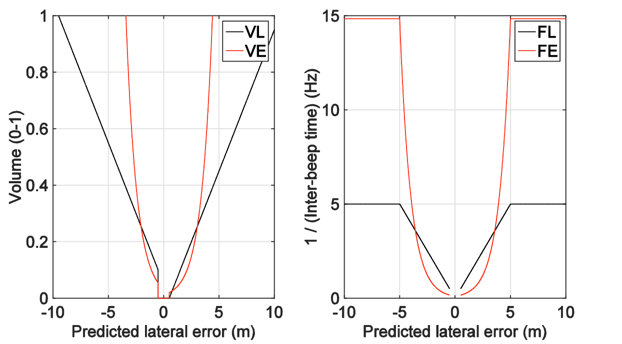

Fig. 4. Relationship between predicted lateral error and volume (left) / beep frequency (right)

Dependent measures. The participants' driving performance was evaluated using: 1) the on-target percentage (OTP), being the percentage of time the centre of the car was within 0.5 m of the centre of the right lane, and (2) the number of resets. A reset (i.e., road departure) occurred when all four edges of the car were outside the road boundaries. After each reset, the car was automatically placed back in the centre of the right lane with zero speed. For calculating OTP, data between 3 s prior to 10 s after each reset were removed to prevent a causal influence from resets on OTP. The predetermined speed was reached about 5 s after the reset.

3. RESULTS

Fig. 5 shows the effects of driving with different prediction times. It can be seen that the number of resets was highest when t_{pred} = 0 s. Specifically, there were about 30 resets per drive without prediction, and no more than 12 with prediction. There were no clear effects of predictor time on the OTP, with both participants driving within the 1-m wide dead-zone about 25 to 40 % of the time for all predictor times. Fig. 6 shows that the volume feedback was more effective than the beeping feedback in terms of the number of resets. There was no substantial effect of the feedback mode on OTP, with the participants driving within 0.5 m of the lane centre about 30 to 50% of the time. The differences between the linear and exponentially graded feedback were small as well. Fig. 7 shows that the corner support had no consistent effect on the number of resets and the OTP.

To elucidate why the lack of prediction yielded a high number of resets, we inspected the driven paths. Fig. 8 shows the paths of the two participants for the same road segment as depicted in Fig. 3. It can be seen that with t_{pred} = 0 s the participants often left the road, even on straight road segments. The participants veered off the road on the outside of the corner, indicating that they were too late with providing a steering input.

4. DISCUSSION

This research sonified the predicted lateral error of the car in a driving simulator experiment involving two experienced drivers with good knowledge of the auditory feedback and the test track. Moreover, we evaluated volume versus beep-frequency feedback, both with a linearly and exponentially graded dependency on the predicted lateral error. The 'blind' drivers were also given support in corners in the form of beeps issued upon entering and exiting corners, or when crossing the centre of the right lane in corners.

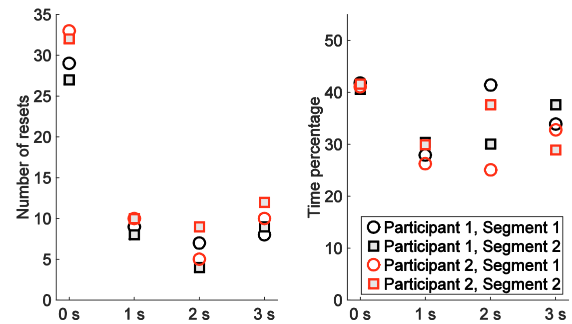

Fig. 5. Results for Parameter set 1 (Predictor time). Linear volume feedback was used.

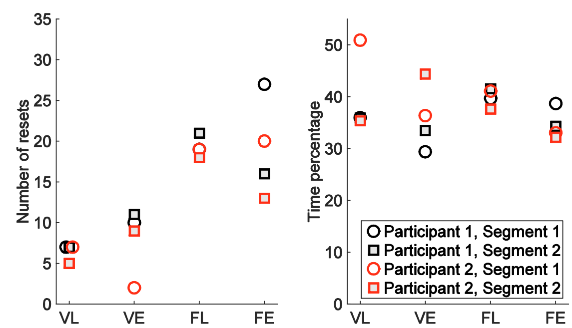

Fig. 6. Results for Parameter set 2 (Feedback mode & mapping). VL = linear graded volume feedback, VE = exponential volume feedback, FL = linear graded beep-frequency feedback, FE = exponential beep-frequency feedback. t_{pred} was 2 s.

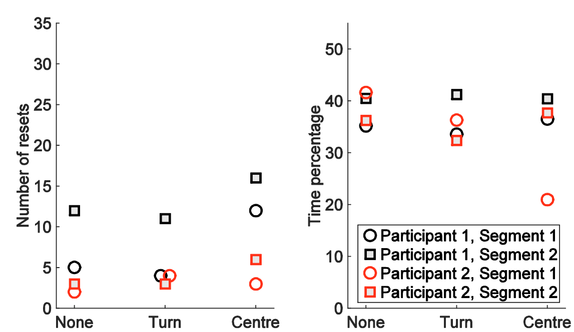

Fig. 7. Results for Parameter set 3 (Corner support). None = no corner support, Turn = beep when entering and leaving a corner, Centre = beep when crossing road centreline in a corner. t_{pred} was 2 s, and linear volume feedback was used.

The prediction time of 0 s resulted in a large number of road departures. With 0 s prediction, participants were often too late in compensating for errors from the lane centre (cf. Fig. 8). The auditory feedback linked to a predicted lateral error effectively supported the blinded participants in performing a lane-keeping task. One of the participants drove very well with the volume feedback combined with t_{pred} = 2 s, resulting in 'only' two resets in 3 km of driving (see Fig. 6: VE condition & Fig. 7: None condition). In summary, substantial improvements were obtained compared to driving with t_{pred} = 0 s, a condition that resulted in 30 resets per drive (Fig. 5).

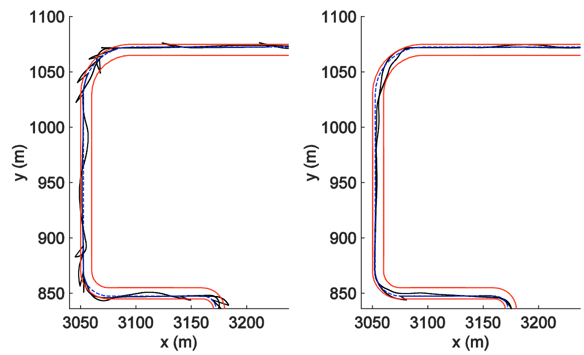

Fig. 8. Paths driven by the participants in Parameter set 1 when using t_{pred} = 0 s (left) and when using t_{pred} = 2 s (right).

Panëels et al. (2013) found that continuous guidance of visually impaired during a walking task was more effective than intermittent guidance. Similarly, we found that the volume feedback was more effective than the beep-frequency feedback, possibly because the former provided continual feedback. The intermittent nature of the low frequency beeps may have made it difficult for the participants to perceive when they were entering or leaving the 1-m wide dead-zone.

There were no substantial differences between systems with or without corner support. It is noted that when approaching a corner, the participants could hear the engine slowing down due to the automated speed control. In other words, the drivers could already infer that they were approaching a corner even without the corner support.

In conclusion, our results show that appropriate auditory support can be effective in conditions where visual information is absent. There were no reset-free runs, which indicates that under the given conditions driving cannot be a purely auditory task. One possible reason for the overall high number of road departures (other than obviously the lack of visual feedback) may be that the driving simulator did not offer tactile or vestibular motion feedback.

Future studies may build on the methods presented in this paper, and focus on the development of a 'blind driving' system by means of multimodal auditory/vibrotactile feedback. Improvement of the system may be achieved by taking into account that most of the road departures occurred in corners. The design of a corner support system that more accurately predicts the future path (e.g., based on steering angle) may prove to be fruitful.

The test track did not feature any stationary or moving obstacles. The speed was not controlled by the driver, which reduces the comparability with real-life driving. Furthermore, the participants were two experienced drivers, and so the results do not reflect the entire driving population. A single-subject experiment design (Sidman, 1960; Horner et al., 2005) was chosen to promote an iterative design approach. The results in this paper represent the first iteration in a series of planned studies on the topic of 'blind driving'.

5. ACKNOWLEDGEMENT

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