Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 49-19 (2016) 525–530

Blind driving by means of auditory feedback

Pavlo Bazilinskyy, Lars van der Geest, Stefan van Leeuwen, Bart Numan, Joris Pijnacker, Joost de Winter

Department of BioMechanical Engineering, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Mekelweg 2, 2628 CD Delft, the Netherlands (Tel: +31152787891; e-mail: p.bazilinskyy@tudelft.nl)

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

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.10.612

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).

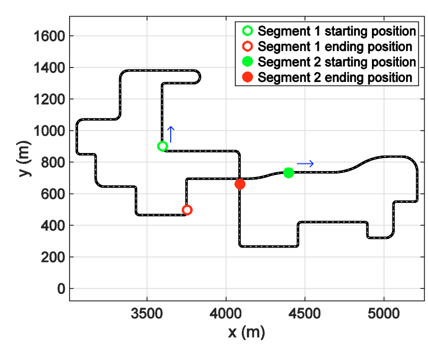

Fig. 2. Top view of Segment 1 and Segment 2 of the test track. x and y are Cartesian coordinates in meters.

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.