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BLIND DRIVING BY MEANS OF THE TRACK ANGLE ERROR

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This study is the third iteration in a series of studies aimed to develop a system that allows driving blindfolded. We used a sonification approach, where the predicted angular error of the car 2 seconds into the future was translated into spatialized beeping sounds. In a driving simulator experiment, we tested with 20 participants whether a surround-sound feedback system that uses four speakers yields better lane-keeping performance than binary directional feedback produced by two speakers. We also examined whether adding a corner support system to the binary system improves lane-keeping performance. Compared to the two previous iterations, this study presents a more realistic experimental setting, as participants were unfamiliar with the feedback system and received the feedback without headphones. The results show that participants had poor lane-keeping performance. Furthermore, the driving task was perceived as demanding, especially in the case of the additional corner support. Our findings from the blind driving projects suggest that drivers benefit from simple auditory feedback; additional auditory stimuli (e.g., corner support) add workload without improving performance.
Keywords: blind driving, auditory feedback, lane keeping, driving simulator experiment

1. Introduction

Driving is a visual task [1]. However, visual information from the environment is often compromised, for example in the case of darkness, fog, or rain [2,3]. Studies have shown that the loss of visual field is a predictor of crash involvement [4]. Moreover, even if visual information is present, drivers may not use it properly: about 6% of fatal accidents are caused by distraction [5].

Shladover argued that fully automated cars (i.e., SAE level 5 automation) will not be available before 2075, and that lower levels of automation will be released first [6]. In automation levels 3 and 4, the driver does not have to pay attention to the road, but has to take back control when the performance envelope of the automation system is exceeded. When taking back control, the driver needs to establish awareness of the vehicle's position on the road. The use of sound could help in this process.

Auditory displays are effective for warning or supporting human operators because sounds can be perceived regardless of the orientation of the eyes [7]. Belz et al. [8] found that auditory collision warnings reduced brake response times in case of an imminent rear-end collision as compared to a dash-mounted visual display and no display. In a driving simulator study where participants used an advanced traveller information display, it was found that an auditory-only or audio-visual display yielded faster response times, more correct turns, and lower subjective workload than a visual-only display [9].

Sound can also aid in the perception of speed and distance. A study using videos of traffic scenarios found that participants who received a lower level of auditory feedback of the internal car noise chose a higher speed and were less accurate in estimating their speed [10]. In Bazilinskyy et al. [11], participants were able to estimate the distance to an object by means of artificial sounds; the mapping of distance to sounds is a process called 'sonification'.

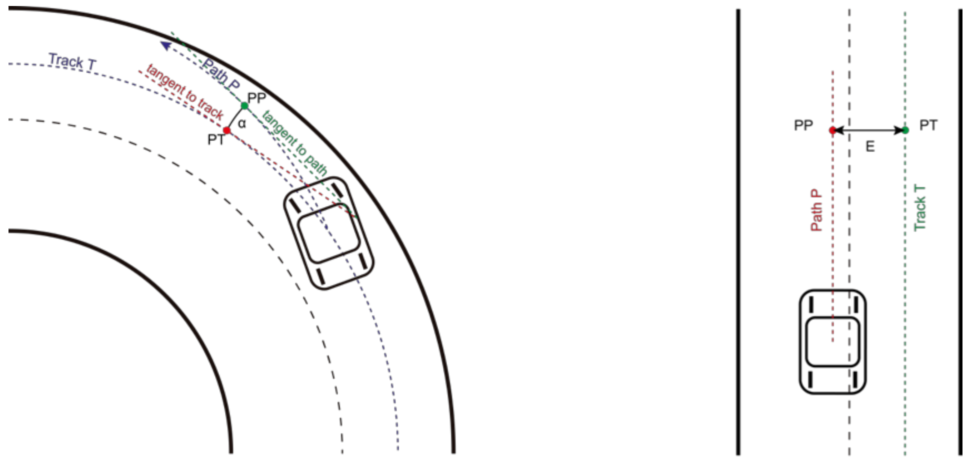
Auditory feedback can also be applied to assist blind persons. One example is the racing auditory display (RAD) by Smith and Nayar [12], which allows blind players to play the same racing game as sighted players. The RAD uses a spatialized soundscape to represent the driver's relative risk of hitting either edge of the track. Furthermore, a turn indicator system was used, which alerted drivers about the type of upcoming turn by means of spatialized sound. The results showed that participants appreciated the RAD concept and that they were able to drive competitive lap times. A real-world example of the use of auditory feedback for assisting blind individuals is a device used for para-biathlon, where blind athletes are guided where to shoot in a two-dimensional space by sound [13].

Summarizing, auditory systems may be promising in supporting drivers when visual information is unavailable. To test the feasibility of such a system, the extreme case is evaluated here, by eliminating all visual input. The paper presents follow-up research aiming to improve the auditory feedback systems designed in Blind Driving 1 (BD1; [14]) and Blind Driving 2 (BD2; [15]). Specifically:

1. In BD1, the authors found that a preview time of 2 seconds yielded the best lane keeping performance as compared to preview times of 0, 1, and 3 seconds; this finding corresponds to literature about preview in normal (i.e., non-blinded) driving and other tracking tasks [16,17]. A preview time of 2 seconds was adopted in the present study.
2. In BD1, the feedback was tested by two of the authors, with deep knowledge of the system and the track. In BD2, the feedback was tested by four authors/developers of the system and an expert racing driver. That is, six of the seven participants were well acquainted with the rationale of the tested feedback systems. In the present study, novice participants were used, as a more realistic user sample.
3. In BD1 and BD2, headphones were used. Herein, the feedback was provided without headphones. Accordingly, compared to BD1 and BD2, this study presents a more realistic experimental setting.
4. In BD1, the future lateral position was based on the velocity vector, whereas in BD2, the predictor algorithm of BD1 was improved by including the steering angle in the prediction. Here, we propose directional feedback based on the angular error of the vehicle with respect to the target track (i.e., the center of the driving lane). We hypothesize that such feedback is intuitively understood.
5. In BD1 and BD2, sound was produced from the left of the headphones when the predicted lateral error was left of the lane center, and vice versa. Here, we tested whether a surround-sound feedback system that uses four speakers ('beacon') yields better lane-keeping performance than directional feedback presented with two speakers ('binary'). With binary feedback, the sound came from speakers at either the right or the left of the participant, which resembles the feedback provided in BD1 and BD2. The beacon feedback depicts the direction and the magnitude of the steering angle that must be applied to correct the position of the car.
6. In BD1, the added value of two types of corner support (a beep when entering and leaving a corner vs. a beep when crossing the road centerline in a corner) was tested. In BD1, corner support resulted in equivalent driving performance as compared to without corner support. In BD3, we re-examined whether adding corner support to the binary feedback (similar to the corner support tested in BD1) improves lane-keeping performance compared to the binary feedback system without corner support.

2. Method

A fixed-base driving simulator (Fig. 1, Green Dino, The Netherlands) was used (the same as in BD1 and BD2). An interface was programmed in MATLAB/Simulink r2016b to retrieve data from the simulator and to generate sounds from the 4.0 speaker system (Creative Inspire 4.1 4400 without the subwoofer) mounted in the driving simulator. The distance between the left and right speakers was about 1 m. The rear speakers were positioned at about the height of the ears of the participant. The front speakers were positioned somewhat higher than the rear speakers.



(a) Situation where alpha is defined (b) Situation where alpha is undefined, and E is used instead

Figure 1: Working principle of the error prediction algorithm. α = angle alpha, E = lateral error, PP = predicted point of the path, PT = prediction point on the track.

The same track was used as in BD1 and BD2. This track was a two-lane 7.5-km road without intersections and without other road users. It contained straights, 180-degree corners, and 90-degree corners, most with a radius of about 20 m. For an example of research using the same track, see [18]. The lane width was 5 m. Participants started at different points along the track. In each trial, the participant drove for 3 minutes. The speed of the car was controlled automatically. The speed in curves was 20 to 30 km/h, depending on the curve radius, and the speed on straights was about 70 km/h. Information about the current speed was not provided to the participants.

A representation of the error-prediction algorithm is given in Fig. 1a. Using the steering angle and velocity, a prediction point (PP), representing the position of the car if it continues with the current constant steering input, is calculated 2 seconds into the future (as in BD2 [15]). A representation of the distance between the car and PP on the track (i.e., lane center) determines a predicted point on the track (PT), the position of the car 2 seconds into the future if it remains on the track (i.e., the center of the right line). Angle alpha is the angle between the tangent lines to PT and PP. The magnitude and sign of alpha are translated to auditory feedback.

A limitation of the proposed error prediction is the case shown in Fig. 1b, where angle alpha is undefined while the vehicle is not on the desired track. Accordingly, when alpha is between 3 degrees to the left and 3 degrees to the right of the track, the expected lateral error (E; i.e., the distance from PP to T) is used instead of the angle alpha. That is, when the angle is small, the algorithm switches from the sonification of angle information to the sonification of lateral position.

Figure 2 illustrates the principle of the prediction algorithm based on actual vehicle data from the trajectory of the vehicle in a 180-degree turn. The magenta lines represent the predicted paths of the vehicle; these are identical to what would be generated by the predictor algorithm in BD2.

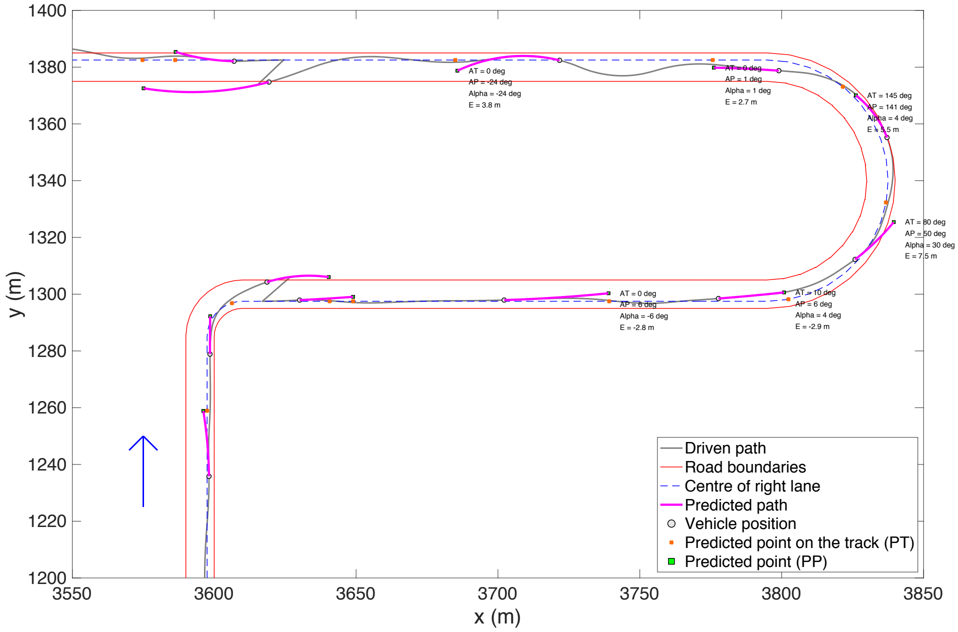


Figure 2: Working principle of the prediction algorithm in a 180-degree left turn. AT = angle of the tangent line along the predicted point on the track (PT); AP = angle of the tangent line along the predicted point of the path (PP); alpha = AT−AP. E = lateral error between PP and PT. The position of the vehicle is shown every 5 s.

The vehicle dynamics model represented a passenger car including realistic tire modelling. However, because the speed of the car was controlled automatically at a moderate speed, the nonlinear regions of the tires were never reached, so slip was never experienced.

We presented three types of auditory feedback (binary, beacon, and corner support). The auditory feedback was audible over engine sounds that were outputted by the driving simulator software.

1) With the **binary** feedback, the sound came from either the right rear speaker (if alpha was positive, i.e., greater than 3 degrees to the right of the track) or the left rear speaker (if alpha was negative, i.e., greater than 3 degrees to the left of the track). Feedback was also provided from the right or left rear speakers if alpha was smaller than 3 degrees while the lateral error E was larger than 0.5 m. The volume increased with increasing alpha, and the aim was to steer away from the sound to minimize the sound volume. No auditory feedback was provided when the participant was within an angle bandwidth of 3 degrees and a lateral position bandwidth of 0.5 m. The sound was beeps with a frequency of 464 Hz; the duration of each beep was 0.2 seconds, with an inter-beep time of 0.2 seconds.

2) With the **beacon** feedback, the predicted error was mapped to the four speakers using a division of volume between the speakers to mimic a shifting sound location in front of the driver. When angle alpha was between −20 and 20 degrees, the sound was linearly divided between the two front speakers. An alpha between 20 and 40 degrees was mapped between the two right speakers, and an alpha between −20 and −40 degrees was mapped between the two left speakers. An angle exceeding this bandwidth was represented by either the right rear speaker or the left rear speaker. As with the binary condition, the volume increased with increasing alpha. No feedback was provided if the participant was within an angular bandwidth of 3 degrees and a lateral position bandwidth of 0.5 m.

3) To clarify when a corner starts or ends, **corner support** was used *in addition* to binary feedback. At the start of a corner, loud beeps were generated from either the left rear speakers (for right curves) or the right rear speaker (for left curves). The beep was played once, twice, or three times, depending on the sharpness of the corner. For a wide curve, with a required steering angle between 0 and 90 deg, the sound played three times. The tone played twice for a required steering wheel angle between 90 and 180 deg, and once for a required steering wheel angle between 180 and 270 deg. The beeps had a fre-

quency of 928 Hz, a duration of 0.1 seconds, and inter-beep time of 0.2 seconds. When exiting the corner, the participant heard the same sound from both speakers for 0.9 seconds.

Twenty persons (15 males; 5 females), aged 19 to 26 with a mean age of 22.9 years, participated in the experiment. All participants possessed a driver's license; the average amount of driving experience was 4.5 years. All participants provided written informed consent, and the research was approved by the Human Research Ethics Committee of the university.

Each participant drove three trials with a blindfold, receiving one type of auditory feedback per trial. Before each trial, a brief description was given about the particular system, and participants drove 1 minute without blindfold to familiarise with the system. Half of the participants started with the binary feedback system, followed by the binary feedback system with corner support, and lastly the beacon feedback system (i.e., 1. binary, 2. binary+corner, 3. beacon). The other half tested the systems in the following order: 1. beacon, 2. binary, 3. binary+corner. After each trial, participants completed the NASA Task Load Index (TLX) questionnaire [19] and a technology acceptance scale [20]. The latter was a five-point semantic-differential scale where participants were asked: "*I find the auditory feedback in the last trial…*" Participants had to select their response between two adjectives for 7 items (1. useful–useless, 2. pleasant–unpleasant. 3. effective–superfluous, 4. irritating–likeable, 5. assisting–worthless, 6. undesirable–desirable, and 7. raising alertness–sleep-inducing). Note that two items (bad–good, nice–annoying) from the original scale were not used, due to an error in the questionnaire.

The number of resets and the on-target percentage (OTP) were used as performance measures. A reset occurred when the car was entirely off the road, resulting in a restart in the middle of the lane. The on-target percentage was defined as the percentage of time the center of the vehicle was within 0.5 m from the lane center. Intervals from 3 seconds before and 10 seconds after each reset were removed from the calculation of OTP. We used a repeated measures analysis of variance (ANOVA) and paired-samples t test to investigate whether the means of conditions significantly differed from each other.

3. Results

The results for the number of resets and the on-target percentage are shown in Figure 3. A repeated-measures ANOVA showed differences in the number of resets between the three conditions, $F(2, 38) = 4.27$, $p = 0.021$, $\eta_p = 0.18$. Post-hoc paired t tests showed that there was a statistically significant difference in the number of resets between the binary condition and the binary+corner condition ($t(19) = 3.37$, $p = 0.003$) and between the beacon condition and the binary+corner condition ($t(19) = 2.50$, $p = 0.022$). There were no significant differences between the OTPs of the three conditions, $F(2, 38) = 0.85$, $p = 0.435$, $\eta_p = 0.04$. The number of resets was high, considering that there were only 3 minutes of driving per participant per condition. Because 3 seconds before and 10 seconds after each reset were removed from the analysis, the OTP was calculated based on 40%, 42%, and 30% of the driving time for the binary, beacon, and binary+corner conditions, respectively.

The scores on the NASA-TLX were overall high (60 to 80%), with the exception of physical demand (20 to 30%) (Fig. 4). Repeated measures ANOVAs indicated significant effects for mental demand ($F(2, 36) = 5.40$, $p = 0.009$, $\eta_p = 0.23$), physical demand ($F(2, 36) = 3.86$, $p = 0.030$, $\eta_p = 0.18$), performance ($F(2, 36) = 8.12$, $p = 0.001$, $\eta_p = 0.31$), effort ($F(2, 36) = 4.20$, $p = 0.023$, $\eta_p = 0.19$), and frustration ($F(2, 36) = 5.96$, $p = 0.006$, $\eta_p = 0.25$), but not for temporal demand ($F(2, 36) = 1.68$, $p = 0.200$, $\eta_p = 0.09$).

The highest workload ratings were observed for the binary+corner condition. For example, the performance item yielded higher ratings (i.e., more towards the 'failure' end) for the binary+corner condition than for both the binary condition ($t(19) = 3.36$, $p = 0.003$) and the beacon condition ($t(18) = 2.47$, $p = 0.024$). Similarly, the binary+corner condition yielded significantly higher ratings for the frustration item (i.e., more towards the 'very high' end) than both the binary condition ($t(19) = 3.21$, $p = 0.005$) and the beacon condition ($t(18) = 2.22$, $p = 0.039$).

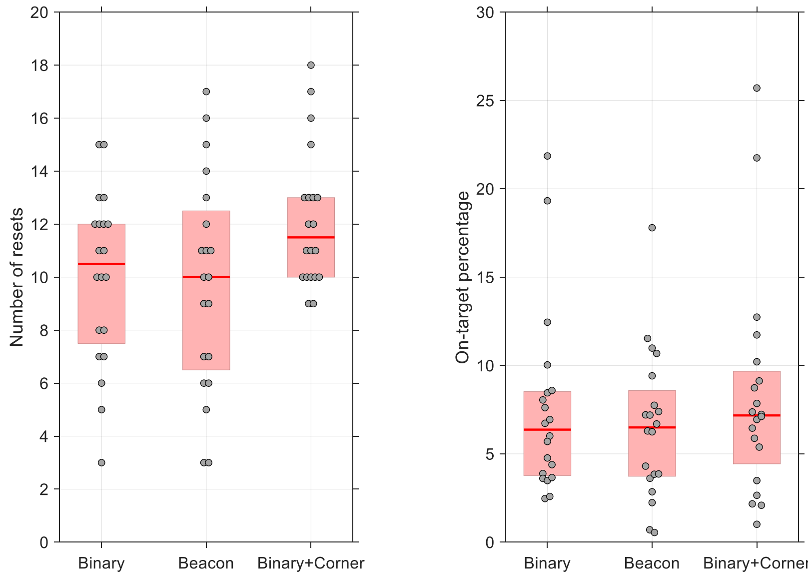


Figure 3: Boxplots of the performance measures. Each marker represents one participant.

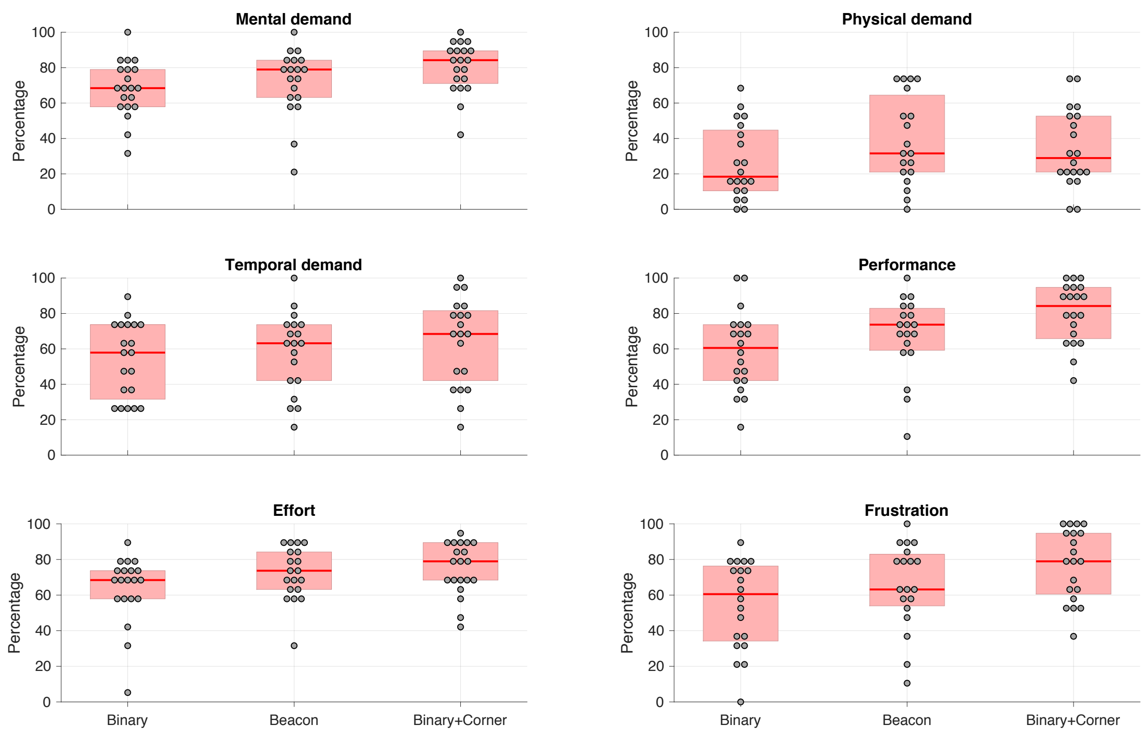


Figure 4: Boxplots of the NASA Task Load Index (TLX) scores. Items are rated from very low (0%) to very high (100%), except for performance which was rated from perfect (0%) to failure (100%). One participant did not complete the TLX for the beacon condition (i.e., $n = 19$ instead of $n = 20$).

The results of the acceptance scale (Fig. 5) showed that the binary and beacon systems were seen as useful and effective, whereas the binary+corner system was relatively unpleasant and superfluous. The binary+corner system scored highly on ‘raising alertness’, which is probably because of the loud beeps provided upon entering and leaving each corner. All three systems were perceived as irritating.

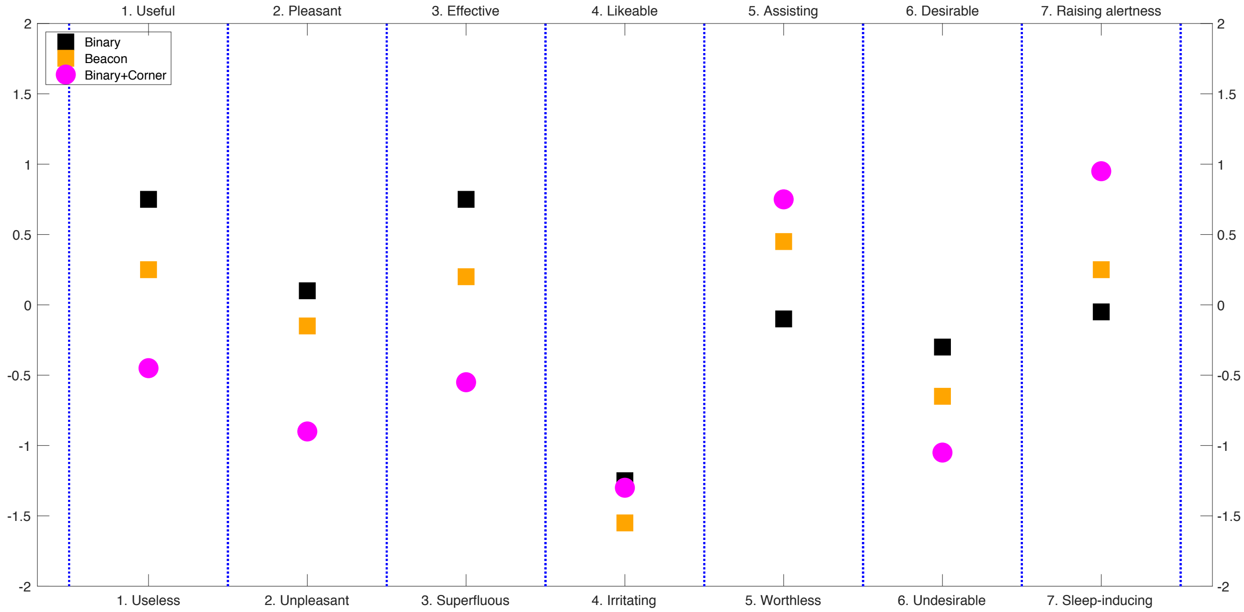


Figure 5. Mean scores on the acceptance scale.

4. Discussion

This study aimed to use auditory feedback to assist a driver when visual information is unavailable. We used sonification where the predicted angular error was translated into spatialized beeping sounds.

The participants showed an overall poor driving performance (i.e., high number of resets) and high self-reported workload. The high workload might have been caused by a lack of training: the participants in the present experiment were exposed to each feedback system only once.

The number of resets and workload were higher for the binary+corner condition compared to the other two conditions, indicating that augmenting the binary feedback system with corner support is confusing and distracting, and that drivers benefit from a simple system, such as the binary support.

The feedback in BD3 was implemented in such a way that when the angle was below 3 degrees, the lateral error determined the magnitude of the feedback. As soon as the driver corrected this lateral error, the angle between the predicted path and track often became greater than 3 degrees, and the participant was informed to steer in the opposite direction. This switching of feedback direction may have been confusing. An algorithm that combines the lateral error prediction with the angle between the predicted curve and track therefore deserves to be investigated.

In our study, the volume was distributed across four speakers. Further research could examine whether the use of a head-related transfer function (HRTF) improves driving performance, as it provides a more realistic representation of the sound source. Donges [21] developed a manual control model of driving, consisting of an open-loop component (anticipating upcoming curves) and a compensatory component (correcting lateral and heading errors). Developing a similar model of driving behaviour for auditory rather than visual feedback may be an interesting direction for future research.

5. Supplementary materials

MATLAB and Simulink code and video examples of the three conditions (the visuals were turned on for illustrative purposes) are available at https://doi.org/10.4121/uuid:6c02218f-cd2c-4eb2-8c93-1eeac44690ed. This repository also contains MATLAB and Simulink code for BD1 and BD2.

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