Ears Outside the Car: Evaluation of Binaural Vehicular Sounds and Visual Animations as Driver's Blind Spot Indicators

Jani Lylykangas
Faculty of Information Technology and Communication Sciences, TAUCHI Research Center, Tampere University, Tampere, Finland
jani.lylykangas@tuni.fi

Ahmed Farooq
Faculty of Information Technology and Communication Sciences, TAUCHI Research Center, Tampere University, Tampere, Finland
ahmed.farooq@tuni.fi

Hanna Venesvirta
Faculty of Information Technology and Communication Sciences, TAUCHI Research Center, Tampere University, Tampere, Finland
hanna.venesvirta@tuni.fi

Roope Raisamo
Faculty of Information Technology and Communication Sciences, TAUCHI Research Center, Tampere University, Tampere, Finland
roope.raisamo@tuni.fi

Veikko Surakka
Faculty of Information Technology and Communication Sciences, TAUCHI Research Center, Tampere University, Tampere, Finland
veikko.surakka@tuni.fi

ABSTRACT

Driving demands a significant amount of visual attention, which may impair drivers' ability to detect and react to visual information such as blind spot warnings. This online pilot study ($N = 242$) evaluated the perception of binaural auditory cues and concurrent visual animations about overtaking vehicles designed to improve drivers' situational awareness. The results showed that the spatial direction of the sounds was perceived in a high degree of precision, and they were rated as pleasant and natural sounding. Spatial congruency between the two information modalities was accurately perceived with visualizations rated as significantly more reliable blind spot indicators than sounds. The results suggest that spatial direction of binaural sounds can be consistently interpreted both alone and in tandem with visualizations in the given driving scenario. Binaural sounds could enhance drivers' situational awareness in an eyes-free way to anticipate overtaking vehicles already before they trigger visual blind spot warnings.

CCS CONCEPTS

• **Human-centered computing**; • **Interaction design**; • **Empirical studies in interaction design**;

KEYWORDS

Blind spot warning, Lane change, Binaural stimulation, Augmented reality, Situational awareness

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1 INTRODUCTION

Lane changes require high visual attention and pose risks of collisions with vehicles in adjacent lanes. Blind spot and closing vehicle warning systems help detect and alert drivers about vehicles in blind spots, reducing lane-change crash rates [7]. These systems typically use a visual alert in or near side-view mirrors [1, 7], or visualization in the instrument panel. Although, intelligent safety technologies can help in preventing accidents, there is a potential downside where human situational awareness and performance declines due to excessive reliance on technology [21] or engagement to non-driving related tasks [22]. A drawback of the visual blind spot indicators is that driving requires a high level of visual attention. This may lead to a visual overload state in which a driver is overwhelmed with information, resulting in difficulty in identifying important information and making quick and accurate decisions. Consequently, there is room for improvement by taking advantage of additional information modalities and more intuitive interaction models.

Data from onboard sensors can enhance drivers' traffic awareness using various sensory modalities, for example, by human augmentation and extended reality solutions. Human augmentation utilizes multimodal interaction to enhance human sensing, action, and cognitive abilities [20]. Augmented reality (AR), as defined by Mallem [13], enables spatial and temporal virtual and real worlds to co-exist and aims to enhance human perception in the real environment, for example, to improve users' situational awareness. The term situation/situational awareness (SA), defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and a projection of their status in the near future" [8], was established in aerospace research and it has been studied extensively in land transportation along with the increased vehicular intelligence and automation [19].

AR applications designed to enhance drivers' SA are already available. A recent example is an AR head-up display (e.g., Volkswagen ID. Series AR-HUD) projecting navigation information with dynamic 3D graphics on a windscreen. An example of a haptic AR application is a lane departure warning, which vibrates a seat (e.g., Cadillac XTS Safety Seat Alert) or steering wheel (e.g., Nissan Lane Departure Warning), imitating the feel of tires hitting a rumble strip. Auditory AR applications include, for example, synthetic engine sounds played through in-cabin or exterior speakers (e.g., BMW Engine Sound Enhancement system). Safety-wise, however, auditory AR applications have greater potential for improving SA than realized so far. Especially the human spatial hearing could be utilized to improve the drivers' awareness for critical traffic events beyond the driver's vision or hearing capability.

Spatial hearing is crucial for SA regarding unseeable events. For example, pedestrians can deduce the distance and direction of approaching vehicles behind based on binaural disparities from the sound source(s) (e.g., interaural time and level differences) reaching their ears [10]. Unfortunately, these important directional cues are inaudible for a car driver until they are too close to prevent dangerous lane changes. This in turn can have a negative impact on SA and driving safety. Spatial audio technologies create a three-dimensional sound experience, imitating the way in which humans perceive environmental sounds [11]. The immersive and realistic experience of digital audio can enhance different applications including vehicular sound systems (e.g., [5, 12]). Research demonstrates improved human SA with the help of spatial audio in various use contexts [4]. Spatially presented abstract, non-speech auditory icons (i.e., earcons) using multichannel surround sound systems have been used to represent the movement of different road users, including cars, trucks, motorbikes, pedestrians, and bicyclists [6]. The results show that spatial earcons can benefit drivers in high-risk traffic scenarios [6, 9, 24, 25]. Binaural auditory signals are a type of spatial audio. They can be recorded with microphones in the ear canals or synthesized digitally [15]. Reproducing binaural signals through headphones or speakers allows for sound localization especially in the horizontal plane, aiding in detecting events behind the listener. Recent audio signal processing advancements enable dynamic adaptation of binaural sounds to environmental factors, including compensating for head movements in real-time [14, 17].

Before implementing a synthesized and adaptive spatial audio system for driving simulator experiments, we conducted the current online pilot study with a relatively large sample of participants. The aim was to preliminary investigate the basic concept of using natural-sounding AR stimuli as closing vehicle/blind spot warnings. We used authentic binaural sounds of overtaking cars to validate their perception and subjective ratings both alone and when combined with animations illustrating different overtaking situations on a multi-lane roadway with regard to future studies to be conducted in more applied settings.

2 METHOD

2.1 Participants

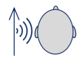
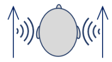
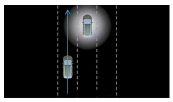
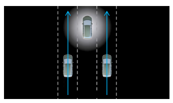
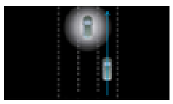
A total of 251 participants from the United States were recruited via Prolific participant pool for an online experiment [18] based on the following inclusion criteria: age 18–50 years; U.S. citizenship; first language English; no hearing loss or hearing difficulties; normal or corrected-to-normal vision; minimum Prolific approval rate of 99% for past studies for which the participant had attended. They were required to use a stereo headset for participation. The study was approved by a local research ethics committee. All participants provided an online informed consent prior to their participation and received a monetary compensation of ~2,80 USD (2,5 GBP) for completing the experiment. Nine participants were excluded from the analysis based on the following criteria: two (0.8%) with premature (i.e., shorter than the duration of the experimental stimulus) response times in ≥50% of the trials; one (0.4%) reported not having normal hearing; six (2,5%) whose environmental disturbance rating scores were 3–5 on a scale of 1 = not at all; 2 = slightly; 3 = moderately; 4 = very; 5 = extremely disturbing. Demographics and background of the remaining 242 participants were as follows: Mean age (±SD) = 35 (8.14) years; Gender – female = 109 (45%), male = 131 (54.1%), other = 2 (0.8%); Headset type – headphones = 127 (52.5%), earphones = 115 (47.5%); Headset connection – cable = 170 (70.2%), wireless 72 (29.8%); Active noise cancellation technology – in use = 124 (51.2%), no = 90 (37.2%), not known = 28 (11.6%).

2.2 Stimuli

2.2.1 Auditory stimuli. Binaural sounds were recorded with Soundman OKM – II Classic in-ear stereo microphones and Olympus DM-720 recorder on the verge of the highway section with a 100 km/h speed limit about 10 meters from the roadside. From these recordings four 10-second-long sound stimuli were created using Audacity software (MacOS version 2.42) as follows. A 10-second clip of a car approaching from behind and bypassing the recordist from the right was excerpted to create a right-overtaking (R) audio track. This sound was also used to create a left-overtaking (L) audio track using the Swap Stereo Channels function. A mix of R and L audio tracks was used to create sounds of cars overtaking from both sides. To avoid canceling out the binaural spatial effect caused by the identical-mirrored R and L audio tracks, a slight onset asynchrony was introduced in their mixing. Two audio tracks, LR and RL, were created by using a 250-ms onset delay for R and L audio tracks, respectively, in the mixes. The two versions, LR and RL, were needed to balance the side of the delayed sound onset (i.e., in LR track the left-overtaking car appeared approaching slightly ahead of the right-overtaking car, and in RL track it was the opposite).

The L, R, LR, and RL audio tracks were supplemented with a background sound layer to simulate authentic listening situations while driving in a car. Background road noise was recorded with inbuilt microphones of Olympus DM-720 with a low-cut filter in a passenger car cabin driving at 100 km/h on a highway. This was mixed with 50 Hz sinewave and Brownian noise to add sound frequencies that were omitted due to the low-cut filtered in-car recording. After mixing the produced background noise track with all audio tracks, a 500 ms fade-in and fade-out were applied to each audio track's beginning and end, respectively. The produced stimuli were exported from AUP to WAV format using Signed 16-bit PCM encoding.

Table 1: Three visualizations of cars overtaking the highlighted ego vehicle, four binaural sounds, and their bimodal combinations to create four spatially congruent, six partially spatially congruent and two spatially incongruent auditory-visual stimuli. Arrows in the visualizations and binaural sound symbols illustrate the motion path of the overtaking vehicles and the spatial direction of the binaural sounds, respectively.

	4 × Auditory stimulus			
				
3 × Visualization	LEFT (L)	LEFT-RIGHT (LR)	RIGHT-LEFT (RL)	RIGHT (R)
 Overtake from the left	Congruent	Partially Congruent	Partially Congruent	Incongruent
 Overtake from both sides	Partially Congruent	Congruent	Congruent	Partially Congruent
 Overtake from the right	Incongruent	Partially Congruent	Partially Congruent	Congruent

2.2.2 Auditory-visual stimuli. Visualizations of the blind-spot indicators were implemented using Microsoft®PowerPoint®animations. During the 10-second-long videos, a highlighted ego vehicle driving in the middle of a three-lane roadway was approached and overtaken from the rear by a vehicle driving on the adjacent lane on the left, right, or both sides (see Table 1).

The three visualizations produced were combined with the L, R, LR, and RL auditory stimuli using Windows®10 Video Editor. Table 1 shows the resulted 12 different auditory-visual stimuli, including four congruent and eight more or less incongruent stimuli in terms of their spatial consistency.

2.3 Procedure

On the online questionnaire, the participants were informed that the purpose of the study was to collect subjective experiences about different visualizations and vehicular sounds in presenting car sensor data measured from the driver's blind spot. After agreeing to participate, they filled in a background questionnaire and environmental disturbance rating scale explained in Participants section. This was followed by audio setting videos for checking the direction of left and right audio channels and adjusting the sound volume of the background road noise track to match the participant's own estimation of road noise heard inside a car driving on a highway. The experimental trials were divided into two blocks. Block 1 included evaluations of the auditory stimuli, and in a subsequent Block 2, the auditory-visual stimuli were evaluated. In both blocks the participants were instructed to 1) imagine being in a car driving on a highway, 2) play the sound/video and listen/watch carefully, and 3) provide their ratings for the questions. They were noted for the possibility to repeat the stimuli for each question.

In each trial of Block 1, the participants were asked to identify from which side they heard the car(s) overtaking in a forced-choice discrimination task including four choices: three for each possible sound stimulus direction (on the left, on both sides, on the right) and an option to indicate uncertainty (unsure). In addition, they were asked to rate the sound with respect to its pleasantness and naturalness in two separate seven-point rating scales where '-3' was 'unpleasant' and 'unnatural', and '+3' was 'pleasant' and 'natural', respectively. In both scales, '0' was a neutral option. The four different sound stimuli were evaluated in a similar procedure twice, resulting in a total of eight trials that were presented in a randomized order. In each trial of Block 2, the participants were asked to rate a video stimulus with respect to the spatial consistency between the auditory and visual information (i.e., accordance between the direction/location of the sound and the visualization of the passing car(s)) using a seven-point rating scale where '1' was 'not at all consistent' and '7' was 'very much consistent'. In addition, the participants were asked how much they would rely on the sound and the visualization as a blind spot indicator by rating the two modalities separately in seven-point rating scales where '1' was 'not at all' and '7' was 'very much'. The different auditory-visual blind-spot indicator stimuli were evaluated in a similar procedure resulting in a total of 12 trials that were presented in a randomized order. Finally, the participants rerated the environmental disturbance experienced during the experiment and submitted the questionnaire.

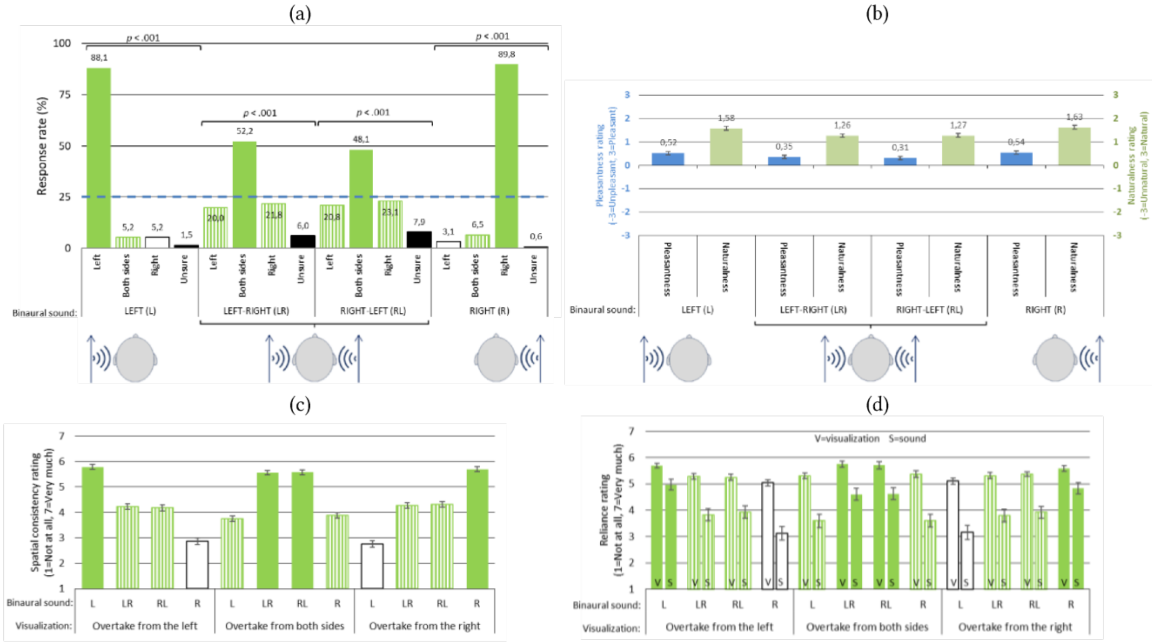


Figure 1: (a) The observed direction evaluations of the auditory stimuli. Dashed line shows the expected chance-level evaluation rate. (b) Average pleasantness and naturalness ratings (± *SEMs*) of the auditory stimuli. (c) Average ratings (± *SEMs*) of spatial consistency for the auditory-visual stimuli. (d) Average reliance ratings (± *SEMs*) for sounds and visualizations of the auditory-visual stimuli.

2.4 Data Analysis

Sound direction evaluations of the auditory stimuli were analyzed with one-way Chi-square tests. One-way repeated-measures (RM) analysis of variance (ANOVA) was used for subjective ratings of pleasantness and naturalness of the auditory stimuli and for spatial consistency of the auditory-visual stimuli. Reliance ratings of the auditory-visual stimuli were analyzed with two-way RM ANOVA. Both ANOVAs were followed by Bonferroni-corrected post hoc pairwise comparisons using paired t-tests. Greenhouse-Geisser correction for degrees of freedom was applied when needed. Thirty-four (0.7%) experimental trials in which the response time was shorter than the duration of the experimental stimulus were considered premature and excluded from the analysis regarding the sound direction evaluation data. Subjective ratings of pleasantness, naturalness, spatial consistency, and reliance of the excluded trials were replaced with series means.

3 RESULTS

Figure 1(a) shows the direction evaluations of the auditory stimuli. All the Chi-square tests conducted separately for each stimulus ratings were statistically significant at the level of $p < .001$. Figure 1(a) clearly shows that the significant findings result from the fact that direction evaluations were well in congruence with the intended direction cue of the binaural sounds (indicated by solid bars). The response rates of the partially congruent, incongruent, and unsure responses (indicated by vertical stripes, framed white, and black bars, respectively) were noticeably lower and below the expected chance-level response rate of 25%.

Figure 1(b) shows subjective ratings of the auditory stimuli. One-way ANOVAs showed a significant effect of the stimulus for the ratings of pleasantness, $F(2.86, 690.02) = 13.14$, $p < .001$ and naturalness, $F(2.72, 656.48) = 26.28$, $p < .001$. Post hoc pairwise comparisons showed that L and R stimuli were rated as more pleasant than LR (MD = 0.17, $p = .007$, MD = 0.19, $p < .001$, respectively) and RL (MD = 0.21, $p < .001$, MD = 0.23, $p < .001$, respectively) stimuli. In addition, L and R stimuli were rated as more natural sounding than LR (MD = 0.31, $p < .001$, MD = 0.36, $p < .001$, respectively) and RL (MD = 0.31 , $p < .001$, MD = 0.36, $p < .001$, respectively) stimuli. The other pairwise comparisons were nonsignificant.

Figure 1(c) shows ratings of spatial consistency of the auditory-visual stimuli. One-way RM ANOVA with auditory-visual stimulus as a factor showed a significant effect, $F(5.90, 1421.62) = 123.85$, $p < .001$. Post hoc pairwise comparisons showed that all congruent stimuli (solid bars) were rated as significantly more spatially consistent than partially congruent stimuli (vertical stripes bars), and incongruent stimuli (framed white bars) at the level of $p < .001$. In addition, all partially congruent stimuli were rated as significantly more spatially consistent than incongruent stimuli at the level of $p < .001$. One partially congruent stimulus, overtake from both sides visualization combined with L sound, was rated as less spatially consistent than three other partially congruent stimuli, that is, overtake from the left visualization combined with LR sound, $p = .022$, and overtake from the right visualization combined with LR and

RL sounds, p = .007 and p = .002, respectively. The other pairwise comparisons were nonsignificant.

Figure 1(d) shows reliance ratings of the auditory-visual stimuli. Two-way 2 × 12 (modality × stimulus) RM ANOVA showed significant main effects of modality, $F(1, 241) = 105.84$, $p < .001$ and stimulus, $F(6.08, 1465.12) = 57.54$, $p < .001$, and a significant interaction of the main effects, $F(5.88, 1417.41) = 14.72$, $p < .001$. The primary reason for the significant main effect of modality was that visualizations were generally rated as more reliable blind spot indicators than sounds (MD = 1.40). However, visual inspection of Figure 1(d) suggest that reliance ratings of sounds and visualizations appeared to be closer to each other in spatially congruent auditory-visual stimuli (solid bars) regarding overtake from the left and overtake from the right visualizations (MD = 0.73 and 0.76, respectively) than in the other auditory-visual stimuli (MDs = 1.08–1.94), which explains the significant interaction effect.

4 DISCUSSION AND CONCLUSIONS

In this study, we aimed to investigate the potential of binaural auditory stimuli as a means of conveying AR spatial information to drivers to enhance their awareness about vehicles approaching from behind. The results of the study showed that the participants were able to evaluate the spatial direction of the auditory stimuli about overtaking cars in a coherent manner. This happened although the participants used different kinds of headset configurations, showing that binaural sounds delivered the intended spatial information robustly. An important finding regarding the potential acceptance of the sounds as a novel interaction method in a driving context was that they were in general experienced as fairly pleasant and natural sounding. Additionally, the results showed that spatial congruency and incongruency between the sounds and visualizations of the overtakes was accurately perceived.

We note however, that although the direction evaluations of LR and RL stimuli (i.e., sounds of cars overtaking form both sides) were well above the chance level, they were lower compared to L and R stimuli (i.e., sounds of one car overtaking from left or right). This could be partly due to different headsets and listening conditions that could not be fully controlled in the online setup. Additionally, a limitation of the LR and RL stimulus designs was that they presented a similar car sound from the left and right, which is unlikely to happen in real life. This artificiality could impede their perception as two separate vehicles, and it may also explain their lower pleasantness and naturalness ratings compared to L and R stimuli. This has implications for designing binaural auditory warnings to convey information about multiple objects or events simultaneously. The results suggest that binaural sounds could be used to convey complex spatial information that may be difficult to perceive through conventional visual or auditory warnings. For example, warning drivers about two vehicles overtaking simultaneously from the left and right is difficult to perceive in one glance from warning lights located in the corresponding side-view mirrors. However, receiving this information in one chunk could be possible with the help of binaural LR and/or RL stimuli.

As headphones may not be recommended or practical wearables in daily driving [16], the next step would include testing of the optimal performance of the sounds with a stereo-speaker configuration [15]. This would help to determine whether the spatial information conveyed by binaural sounds is still robust and consistent when presented in free-field listening conditions inside a car cabin. It is also necessary to examine drivers' capacity to differentiate auditory blind spot stimuli from other audio sources, such as talk and music, while driving. This would provide insight into the effectiveness of binaural sounds compared to the conventional visual and non-spatial auditory warnings in real-world driving scenarios.

Further investigation is necessary for assessing drivers SA and to determine their trust and acceptance of binaural sounds as a supplemental method to visual information, which is crucial for successful implementation in future vehicles [23]. In this study, visual information was preferred over binaural sounds especially in ambiguous (i.e., incongruent) auditory-visual stimuli where conflicting information was present. This can be taken as a natural finding which shows that in the case of ambiguous information from one sense, other senses are used to confirm what is going on, showing that auditory information does not override or interfere the use of other senses. Establishing intuitive and natural communication methods, like using spatial audio to guide visual search [2, 3] toward important information outside the driver's direct field of view, is essential for reorienting drivers and facilitating appropriate interventions during manual/autonomous driving control transitions and in unexpected situations, such as automation failures.

In conclusion, this study provided evidence that binaural sounds can deliver spatial information robustly and consistently in a natural sounding and pleasant way, supporting the idea of improving and completing the driver's SA. These findings have important implications for the design of auditory warnings in vehicles and suggest that binaural sounds could be used to convey complex spatial information that may be difficult to perceive through conventional visual or auditory warnings.

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