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ARTICLE

Superior side sound localisation performance in a full-chassis driving simulator

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ABSTRACT

Alerts presented through the auditory modality improve drivers' crash avoidance performance in driving simulations, but drivers' ability to accurately localise the source of the auditory alerts is understudied. Because the results of driving simulation studies may hinge on assumptions that sound locations are accurately perceived by drivers, this study used a sound localisation task in a full-chassis driving simulator. Twenty-nine participants engaged in a sound localisation task while seated in the driving simulator. Performance was assessed by sound localisation accuracy, relative directional error, and participant confidence across seven sound sources surrounding the simulator. Performance was best when sounds were presented in left and right cardinal regions, and poorest when presented from the front and rear. Participants were less confident in their localisation judgments when sounds were presented from the rear.

Practitioner summary: Drivers' ability to accurately localise auditory alerts is understudied. Participants performed an auditory localisation task with external sounds while seated in a full-chassis driving simulator. Participants were better detecting sounds from the sides instead of the front and rear. This has implications for external auditory alarms during driving.

Abbreviations: ANOVA: analysis of variance; dB: decibel; f: frequency; Hz: hertz; LHD: left hand drive; ms: milliseconds; RTI: realtime technologies; s: seconds; SPL: sound pressure level

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Perception; ergonomics tools and methods; driving; hearing; transport; ergonomics

Approximately 1.35 million fatalities occur worldwide per year due to traffic crashes (WHO 2018). The use of car horns and both visual and auditory alarms in collision-warning systems are intended to alert drivers to the threat of an immediate crash, and warning systems have been designed with an emphasis on rear-end collisions (Parasuraman, Hancock, and Olofinboba 1997). However, while the effectiveness of visual alerts (e.g. high brake lights) for reducing the rate of rear-end collisions is a human factors success story (Malone 1987), designing effective visual alerts for crashes from other directions is more challenging. Alarms for non-frontal threats to the driver are more reliant on auditory localisation, as hearing is an omnidirectional sense. However, testing auditory alerts requires both safe and generalisable research methodologies, and it is difficult to achieve both in laboratory tests and field tests.

Sound localisation

Prior research in sound localisation has observed relevant characteristics in terms of localisation accuracy and speed. For instance, there appears to be minimal differences in accuracy between continuous and pulsed auditory beacons in a navigation task (Tran, Letowski, and Abouchacra 2000), and compound or complex auditory stimuli appear to be more advantageous for localisation accuracy and speed than purely tonal auditory stimuli (Catchpole, McKeown, and Withington 2004). Furthermore, when considering auditory alerts alone compared to only vibrotactile stimuli, auditory alerts are more effective at facilitating localisation (Ho, Tan, and Spence 2006). For an overview of the theoretical basis behind sound localisation, see Spence and Ho (2008a).

Driving simulation

Driving simulators afford generalisable research results in transportation research through increased experimental control, ease of repeated measures study designs, budgeting, and safety of participants. State of the art simulators allow for virtually infinitely customisable driving scenarios using advanced video projection

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and surround sound technologies, which allows researchers to investigate complex research designs that may be otherwise too costly, introduce undue risk to study participants, or prove unfeasible to perform in naturalistic or field observational tests.

Stoner, Fisher, and Mollenhauer (2011) state that assessing the validity of a simulated driving experience is a 'prerequisite to generalizing the results found in research'. Extensive studies have been conducted to examine the extent that driving simulations match real-world conditions through the many facets of validity (Reimer and Meler 2011). However, Kaptein, Theeuwes, and Van der Horst (1996) highlighted the lack of examinations of sound studies in their review of the considerations of driving simulator validity. The paucity of sound cueing validation research was echoed by later reviews on sensory perception in driving simulation (Pinto, Cavallo, and Ohlmann 2008). Regardless, matching simulated sounds to real-world conditions of a vehicle on the road would require a considerable amount of fidelity, including a fully enclosed vehicle and multiple sound sources (e.g. motor, exterior sounds, and road vibrations) surrounding the vehicle (Riener 2010), to achieve uniform driver responses to stimuli.

Auditory modalities are effective in localisation but merging multiple modalities may be even more effective at alerting and capturing attention (Spence and Ho 2008b). Therefore, transportation safety studies examining collision warning systems by using multi-sensory modality alerts have become increasingly popular, in both driving simulation and field studies (Baldwin and Lewis 2014; Meng and Spence 2015). In these studies, experimental collision warning alarms are typically presented through auditory, visual, tactile, and haptic sensory modalities, with most research designs assessing multiple modalities' effectiveness in alerting drivers (Jones and Sarter 2008; Meng and Spence 2015). Incorporating an alert through the auditory modality combined with visual or haptic modalities increases the alert's effectiveness and betters task outcomes relevant to the alert (Fitch, Kiefer, Hankey, and Kleiner 2007). Other work in sound localisation has shown that observers seated in a test vehicle with auditory alerts presented through interior car speakers are relatively poor in their abilities to accurately localise sound sources within the vehicle (Fitch et al. 2007). Similar work using driving simulators remains relatively understudied, however. While many full-chassis driving simulators have speakers in factory locations, the primary means of presenting the driving scenario's environmental noise (i.e. road, wind, engine sound) is from speakers mounted around the periphery of the simulator vehicle. These speakers afford the presentation of experimental sounds, in addition to the scenario or environmental sounds.

Given the moderate prevalence of non-frontal crashes (e.g. Geedipally, Patil, and Lord 2010), advances in collision detection systems (Mukhtar, Xia, and Tang 2015), and the benefits of driving simulation testing over basic laboratory tests and field tests, this study investigates the characteristics of auditory localisation from external sources within the context of a driving simulator vehicle chassis.

The present study

This study examined driving simulation participants' abilities to localise sound in a conventional full-chassis driving simulator with an arc screen featuring a 7.1 surround sound system. This provides validation of human sound localisation capability in a driving simulator environment with high equipment fidelity and can also confirm whether sound localisation as observed in basic psychophysical studies translates over to these environments, specifically that sound localisation performance is best for sounds directly in front of the listener (Middlebrooks and Green 1991). The auditory cues chosen for this task were a prototypical car horn sound and an experimental sound that was designed using alarm literature guidelines (Hellier, Edworthy, and Dennis 1993; Lewis, Eisert, and Baldwin 2018; Patterson 1990). The experimental alarm sound was introduced here to compare against a typical car horn sound as the car horn has significant socio-cultural associations that may influence behaviour in an experimental context, particularly for experienced drivers. The alarm sound was intended to be both a prototypical alerting sound that should signal to individuals that an event needed immediate attention and a candidate auditory alarm for collision warning systems. To examine the validity of auditory cue presentations, specifically for research assessing external-vehicle alerts, a sound localisation task consisting of these two sounds was conducted in the driving simulator using seven sound presentation locations (five physical and two surround sound blended locations).

Methods

Participants

In total, 29 participants (17 men and 12 women) with a mean age of 26.8 years engaged in the sound localisation task following an experimental task to test the impact of external alerts. During a previous experimental task, the same participants drove through a simulated urban environment, evading intruding cars and bicycles from front, side, and rear/blind spot locations around the vehicle which emitted either the car horn or experimental sound. This would have allowed for prior exposure to the sounds tested in the sound localisation task. Participants reported having normal hearing abilities that did not impair conversation. The sound localisation task duration was 20 min, immediately following completion of the previous 60-min experimental task, and participants were compensated $75 (US dollars) in total for the two tasks.

Apparatus and materials

An immersive, full-chassis Real Time Technologies, Inc. 2015 Ford Fusion driving simulator equipped with a 7.1 surround sound stereo system was used to facilitate the sound localisation task. Approximately, 2 ft. of the front end of the chassis is removed to reduce its length (see Figure 1) and a vertical metal plate is attached to block view of its interior hood. A static image of a sound test booth appeared on the forward arc screen, rear view mirrors, and rear projection screen during the presentation of stimuli. The participant's centreline facing forward, in this case the left-hand drive (LHD) seating position, was chosen as the 0° azimuth for this study as this location is a commonly placed speaker location by simulator fabricators and offers generalised guidance for future studies seeking to present auditory alarms to humans in simulators. Sound sources were organised into seven locations: three cardinal positions as Forward (0°), Left (−90°), and Right (90°) positions, and four positions located at the Forward-Left (−45°), Rearward-Left (−135°), Forward-Right (45°), and Rearward-Right (135°). The Left (−90°) and Right (90°) sound sources were created using the stereophonic presentation method of summing localisation using physical speakers located at the non-cardinal positions. Speaker placement was such that no physical objects besides the vehicle chassis were in the sound projection pathway from speaker source to participant head-level. The car horn sound was live recorded (available at www.grsites.com, the Sound Effects archive). The sound file (1.75 s) comprised three distinct horn sounds, the first approximately 300 ms long, and the last two approximately 500 ms long with about 50 ms of silence between the horn sounds. Frequency analysis indicated the horn sounds had multiple spectral peaks, with the highest at 400 and 2500 Hz. The experimental sound featured waveform characteristics, such as recommended inter-burst intervals throughout the alarm duration, guided by previous work in the ergonomics auditory alarms literature (Lewis, Eisert, and Baldwin 2018; Patterson 1990). Specifically, the experimental sound (2.45 s) was constructed in Audacity (version 2.2.1) with a base frequency at 1000 Hz, with a 0 ms interburst interval, with three harmonics (2f, 3f, 4f), and a pulse duration of 250 ms, with 10 pulses in total. Both sounds were presented at a mean of 75 dB SPL, with the simulation room having a mean ambient noise level of 54 dB SPL. The ambient, background noise was composed of simulated idling sounds presented from below the driving simulator's chassis and facilities noises (e.g. force air heating/cooling). Sound level measurements were collected in dB SPL via a professional-grade decibel metre located at the driver's eye-level sitting in the driver's seat (LHD vehicle). Samples were recorded three times for 30 s and averaged to determine mean sound level intensity during the study.

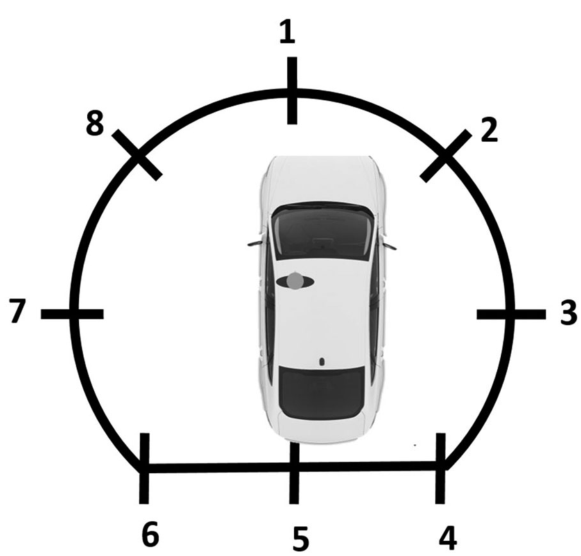

Figure 1. Sound localisation participant response diagram.

Experimental design

Participants experienced a series of 84 sounds blocked across two levels, the experimental sound and the 'car horn', each presented at the seven speaker locations six times via RTI driving simulator software. Sound presentation order was blocked, and trial locations were randomised using RTI simulator software. Responses were recorded using Qualtrics surveys on a Windows tablet in the vehicle. Sound localisation accuracy was recorded by selecting a directional location represented by a figure of the simulator environment and possible speaker locations in the survey (Figure 1) was the primary response. Participants also provided their confidence in their location choice for each trial, which was recorded using a slider bar in the survey to indicate 0–100% confidence.

Responses were scored by their deviation from the source location in terms of absolute degrees of spatial error, which were measured at 45° increments. An error score of 0° indicated a correct response, while 180° represented maximum error after responses were scaled. Previous in-vehicle sound localisation analyses have included a categorical conversion of error degrees to 'off by 1' coding examples, which was also used in this study (Fitch, Kiefer, Hankey, and Kleiner 2007).

Results

A total of 2345 trials were used in the analysis, including 1218 experiment sound and 1217 car horn trials. Only one data point was excluded from statistical analysis, as it was missing in the Qualtrics data record. Overall accuracy for all trials was 25.3%; aggregate experimental trials accuracy was 26.7% (326/1218); and car horn accuracy was 23.9% (291/1217) (see Table 1).

Table 1. Percentage response correct by presentation location and sound type.

	Presentation location				
Sound type	Left (%)	Right (%)	Front (%)	Rear (%)	Overall (%)
All	61.4	69.0	37.3	40.3	25.3
Experimental	60.2	68.0	38.5	45.1	26.8
Car horn	62.6	70.1	36.0	35.4	23.9

Descriptive analysis

Responses for the eight locations were first analysed by degree of error and converted into 'off by' bins from 0 (correct response) to 3+ (3 or more 45° incremental errors). Figure 2 shows the distribution of accurate responses per location, in addition to the percentage of error by increments of 'off by x' participants made in their judgments. In aggregate, participants fared better when sounds were presented in the Left, Front Left, Front Right, and Right locations, while performance suffered in regions that were to the immediate forward and 135° rearwards locations. Interestingly, the simulated physical speaker locations at the Left and Right performed better than true speakers, a promising result in support of surround-sound technology in simulator environments (see Figure 3).

Responses were then merged into bins representing cardinal locations relative to the driver to simplify analyses and generalise findings to methodology applications. Results by cardinal locations in Experimental sound accuracies were 38.5% at Front, 60.2% Left, 68% Right, and 45.1% for Rear locations; Car Horn sound accuracies were 36.0% at Front, 62.6% Left, 70.1% Right, and 35.4% for Rear locations. Participants performed better on average when sounds were presented from the Left and Right cardinal positions.

Inferential statistics on degree of error and confidence

For clarity and simplicity, the following inferential statistics analysis similarly merges the averages for the

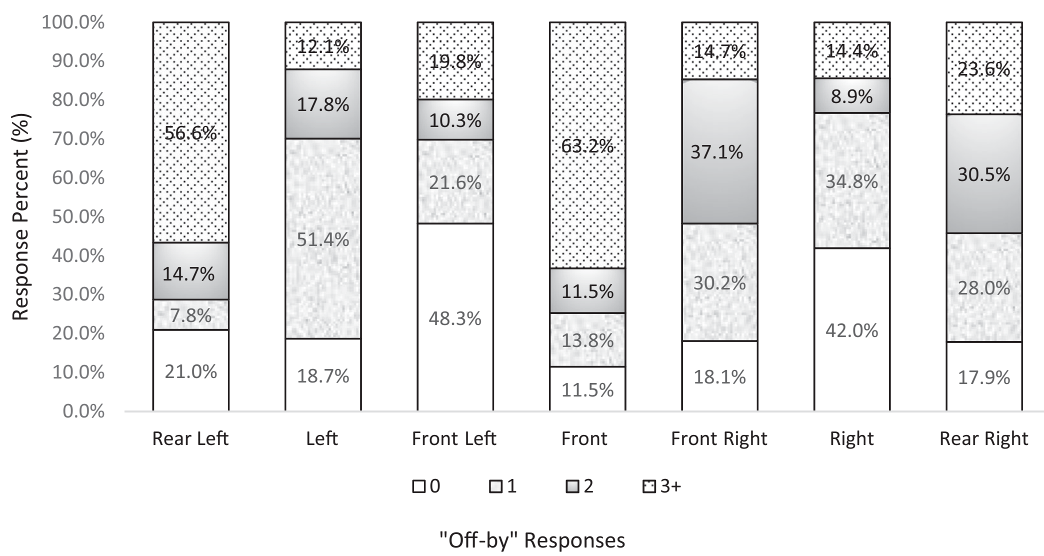

Figure 2. Response error distributions as a result of participant 'off-by' speaker location choices.

Figure 3. Aggregate response distributions by binned regions for both sounds.

diagonal directions onto the four cardinal directions (front, rear, left right). Sounds from the rear-right and rear-left speakers would have to be merged to provide an assessment of the Rear cardinal direction given equipment limitations. For consistency, sounds from the front, front-left, and front-right were then merged to provide an assessment of the Front cardinal direction. The left and right directions were unmodified for this analysis. A 2 (sound type) × 4 (direction) within-subjects repeated measures ANOVA was conducted using JASP statistical software (version 0.9.2, http://www.jasp-stats.org) (JASP Team 2018) built on the R language (https://www.R-project.org) (R Core Team 2018) to examine the effect of sound type and cardinal sound direction on correct localisation responses with degree of error (0–180°, with 0° representing a correct response) as the dependent variable. Results showed a significant main effect of cardinal direction on response accuracy, $F(3, 84) = 17.454$, $p < .001$, $\eta^2 = 0.384$; however, no significant main effect for sound type on response accuracy was found, $F\ (1, 28) = 1.262$, $p = .271$, $\eta^2 = 0.043$, and no significant sound type was found by direction interaction, Greenhouse-Geisser corrected, $F\ (2.292, 64.169) = 0.843$, $p = .474$, $\eta^2 = 0.029$. A Bonferroni-corrected *post hoc* analysis of direction found that sounds from the left ($M = 57.41°$, $SD = 30.12°$) and the right ($M = 44.61°$, $SD = 36.91°$) were significantly different from each

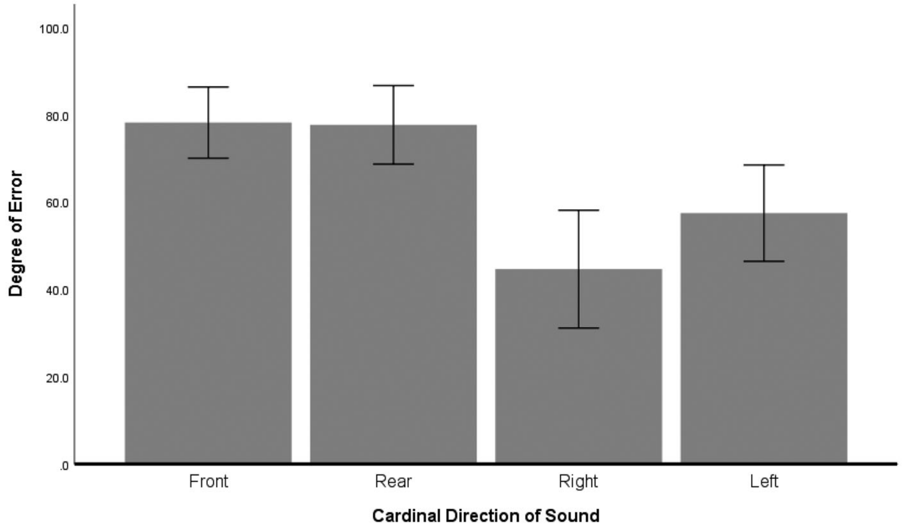

Figure 4. Degree of error by cardinal direction of sound. Error bars represent 95% confidence intervals.

other, t (28) = 3.248, $p = .018$, $d = -0.603$, and the front ($M = 78.15°$, SD = 22.78°) and rear ($M = 77.62°$, SD = 26.57°) were not significantly different from each other, t (28) = 0.088, $p > .05$, $d = 0.016$. Sounds from the left direction had significantly lower degrees of error than sounds from the front, t (28) = 4.023, $p = .002$, $d = 0.747$, and the rear, t (28) = 3.80, $p = .004$, $d = 0.705$, and sounds from the right direction had significantly lower degrees of error than sounds from the front, t (28)=5.576, $p < .001$, $d = 1.035$, and the rear, t (28)=5.066, $p < .001$, $d = 0.941$ (see Figure 4).

A second 2 (sound type) × 4 (direction) within-subjects repeated measures ANOVA was conducted on reported confidence in the location judgement on a scale of 0–100%. One participant was excluded from this analysis due to responding with the same confidence level for all trials. No significant effect of sound type was found, F (1,28) = 0.086, $p = .771$, $\eta^2 = 0.003$, and no sound type by direction interaction, Greenhouse–Geisser corrected, F (2.32, 64.954) = 1.679, $p = .19$, $\eta^2 = 0.057$. There was a significant main effect of direction on confidence, F (3, 84)=7.147, $p < .001$, η^2=0.203. A Bonferroni-corrected *post hoc* analysis of direction found that percent confidence in localisation judgement for sounds from the rear ($M = 59.37$, SD = 15.94) was significantly different than percent confidence for sounds from the front ($M = 63.89$, SD = 15.05), t (27)=3.378, p=.013, $d = 0.627$, right ($M = 65.24$, SD = 16.99), t (27)= −3.447, p=.011, d= −0.64, and left ($M = 65.32$, SD = 17.88), t (27)= −4.234, $p < .001$, d= −0.786. No significant differences were observed in percent confidence for right, left, and front sound locations (all $p > .05$) (see Figure 5).

Discussion

This study showed the difficulty and inaccuracy of drivers' sound localisation abilities in the context of a driving simulator environment featuring a full-chassis vehicle that is identical to conventional passenger cars. Performance was best when sounds were presented in left and right cardinal regions, and poorest when presented from the front and rear. Participants were less confident in their localisation judgments when sounds were presented from the rear. These findings suggest that experimental task-relevant sounds in conventional layouts in full-chassis driving simulators present significant challenges localising sounds that vary along the azimuth.

Implications for theory

Individuals can detect interaural differences on the order of microseconds in basic psychophysical experiments, reflecting sensitivity to a key source of information for detecting the location of sounds in the azimuth (Durlach and Colburn 1978). Participants in sound localisation studies appear to be effective at localising sounds in front of them on the azimuth with some allowable range on the altitude of the sound source (Makous and Middlebrooks 1990), with occasional incidence of front/back errors (for a review, see Middlebrooks and Green 1991).

However, the pattern of better localisation accuracy for sounds presented at the front was not replicated here. This may be because (1) the sound path was impeded by windshields and other components of the simulator chassis, and (2) the participants were seated

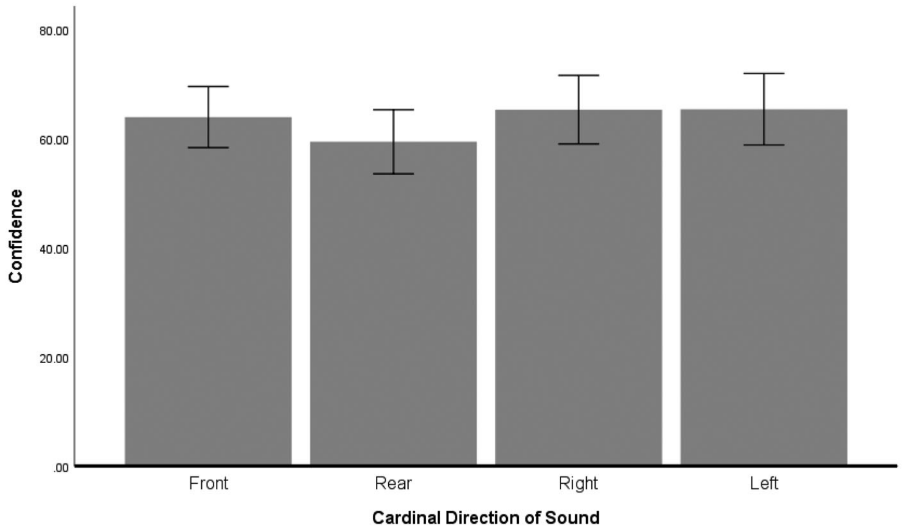

Figure 5. Participant confidence in their accuracy (scale of 100) by cardinal direction of sound. Error bars represent 95% confidence intervals.

in the left front seat with differing distances from the sides of the car, which may affect the characteristics needed to detect just-noticeable interaural time differences. Good and Gilkey (1996) observed similar losses for sound localisation accuracy along the frontal (i.e. front/back dimension), but maintained better accuracy along the median plane (i.e. left/right dimension) when sounds were presented with a broadband masking noise. Furthermore, Treeby, Paurobally, and Pan (2007) showed that sound impedances may interfere with interaural time and level differences, particularly for sounds near the interaural axis and for high-frequency sounds. The authors of this study hypothesised the chassis may impede the higher frequencies of the experimental alarm sound more than the lower frequencies (i.e. < 500 Hz) of the prototypical car horn sound, resulting in differences in interaural cues between the two sounds. However, any such differences between the two sounds were not found to be significant within the localisation accuracy results, nor were any significant differences observed within localisation confidence. Overall, these results imply that basic sound localisation assumptions must be carefully applied in the context of external sounds coming into the vehicle.

Implications for auditory alerts

Results replicate previous work focussed on internally presented auditory warnings (Baldwin and Lewis 2014; Fitch et al. 2007; Lewis, Eisert, and Baldwin 2018). This study illuminates confounds and challenges in the experimental design process when conducting driving simulation studies that feature auditory stimuli beyond road and engine noise. For example, studies that examine driver ability to locate the source of an auditory alert in a collision avoidance context may be presenting sounds inside the vehicle from a location that participants have a fundamental difficulty localising if it is ultimately intended to be presented outside of the vehicle. Fitch et al. (2007) observed better performance at the front and rear for sounds presented within the vehicle cabin, while this study observes better performance at the left and right for sounds presented outside of the vehicle chassis.

The results also emphasise the researcher's need to carefully consider how auditory stimuli are presented in experiments. An additional design consideration to amplify the effectiveness in an externally presented auditory warning system is the coupling of another sensory modality, such as haptic feedback in the driver's seat pan or a visual display on an integrated infotainment screen, which would maximise alert impacts through multisensory integration. Multi-modal warning systems have been shown to improve message-relevant driver corrective actions (Craig, Achtemeier, Morris, Tian, and Patzer 2017; Fitch, Bowman, and Llaneras 2014) and collision warning systems (Fitch, Kiefer, Hankey, and Kleiner 2007; Ho and Spence 2005).

Limitations and future directions

Constraints imposed by the hardware setup of a driving simulator include the necessity for the driver's vision point, or their physical orientation and positioning relative to the video projection screens, requires the simulator cab to be placed in an offset position, rather than centred within the acoustical space. As a result, speakers are not equidistant from the driver's ears, and some sounds receive unequal distortion (e.g. reverberation rate) due to differences in the vehicle's surfaces in the sound travel paths. Also, performance for the surround sound blended presentation locations may have been different if otherwise presented as a physical speaker.

The concern for participant well-being and the mitigation of simulator sickness required the windows to be lowered in this experiment, which keeps the temperature cool within the chassis. Sound localisation accuracy may vary with differing openness of vehicle windows, prompting further research into sound localisation ability with external sound sources. The prior experimental task also may have introduced learning effects or bias based on the direction of the alert, although the prior experimental scenario attempted to provide equal balance in the location of threat vehicles and bicycles and their corresponding auditory alerts around the vehicle. In addition, the sound presentation accuracy and participants' localisation abilities may significantly differ across simulator cab design (i.e. full-chassis, half-chassis, desktop PC) and audio-visual system feature type (i.e. arc, flat pane, monitor screens; multi-speaker surround, stereo sound setups). Furthermore, more research is needed in assessing the performance of an external auditory warning in conjunction with an in-vehicle alert using an additional sensory modality, specifically one featuring spatial cues, such as haptics, to bolster situational awareness and alert localisation while driving (Ho, Tan, and Spence 2005).

Interestingly, a significant difference was observed between left and right localisation accuracy, although not to the degree observed between left/right and front/rear directions. As shown in Figures 2 and 3, participants were frequently 'off by 1' on sounds coming from the left and often indicated that left direction sounds were coming from the front-left (45°). Future research should explore the robustness of this difference and its underpinnings.

The primary focus of this research was on localisation accuracy instead of response speed, the latter of which would perhaps reflect some degree of localisation discrimination efficiency. Those data were not collected here, but future research could investigate how different locations affect speed of response when presented outside of a simulator vehicle chassis. Besides this, considering different types of chassis such as truck cabins could potentially yield different results due to their layout. Furthermore, adding more speakers, and correspondingly a more detailed statistical appraisal, would allow for more fine-tuned assessment of localisation of sounds from different directions.

Practical applications

Notably, there appears to be a dissociation between actual accuracy as measured by degree of error response and the participants' confidence in their judgments. While accuracy was better for external sounds presented from the left and right than front and rear, participants specifically had less confidence in judgments for sounds coming from the rear instead of both the front and rear. This implies that participants may be biased towards higher confidence in judgments for localisation within easy access of their visual field and periphery, and less confident in the less visually accessible rear location, which is likely an effect of operating in audio-visual environments but may negatively impact self-assessment in environments of low-to-no vision.

Besides the implications for sound orientation in the context of simulator research, this provides validation for the spatial distributions of orientation accuracy within a passenger vehicle for external auditory alerts, which is relevant for traffic safety engineers. Knowing the effectiveness of auditory alerts in terms of whether drivers will accurately detect the source of the alert, should orientation be critical to the warning, would be helpful for those designing integrated intelligent traffic systems (e.g. vehicle to vehicle and vehicle to infrastructure systems). This has relevancy to the deployment of connected vehicles (i.e. V2V and V2I) warning systems that may present localised imminent collision event information within or exterior to a vehicle. This may also improve electronic human-machine interfaces when dealing with pedestrians and other vulnerable road users. Further, this may help to guide our understanding and expectations of the timeliness and accuracy of drivers' responses to emergency vehicles when 'move over' laws or behaviours are required for efficient passage of emergency responders.

Conclusion

Alerts improve drivers' crash avoidance in driving, but the capability to accurately localise auditory alerts remains understudied. Driving simulation studies on alerts may hinge on the faulty notion that sound sources are accurately localised. Therefore, this study investigated sound localisation with a high fidelity full-chassis driving simulator. It was observed that performance was better for sounds presented in right and left regions, and worse from the front and rear. The findings have implications for experimental design when using auditory stimuli in driving simulators, as well as for designing environmental alarms intended to be heard from within a vehicle.

Disclosure statement

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References

Baldwin, C. L., and B. A. Lewis. 2014. "Perceived Urgency Mapping across Modalities Within a Driving Context." *Applied Ergonomics* 45 (5): 1270–1277. doi:10.1016/j.apergo.2013.05.002.

Catchpole, K. R., J. D. McKeown, and D. J. Withington. 2004. "Localizable Auditory Warning Pulses." *Ergonomics* 47 (7): 748–771. doi:10.1080/00140130310001629739.

Craig, C. M., J. Achtemeier, N.L. Morris, D. Tian, and B. Patzer. 2017. *In-Vehicle Work Zone Messages* (MnDOT 2017-19). Saint Paul, MN: Minnesota Department of Transportation, University of Minnesota Digital Conservancy. http://hdl.handle.net/11299/189538.

Durlach, N. I., and H. S. Colburn. 1978. "Binaural Phenomena." In *Handbook of Perception Volume IV: Hearing*, edited by E. C. Carterette and M. P. Friedman, 365–466. New York, NY: Academic Press.

Fitch, G. M., D. S. Bowman, and R. E. Llaneras. 2014. "Distracted Driver Performance to Multiple Alerts in a Multiple-Conflict Scenario." *Human Factors: The Journal of the Human Factors and Ergonomics Society* 56 (8): 1497–1505. doi:10.1177/0018720814531785.

Fitch, G. M., R. J. Kiefer, J. M. Hankey, and B. M. Kleiner. 2007. "Toward Developing an Approach for Alerting Drivers to the Direction of a Crash Threat." *Human Factors: The Journal of the Human Factors and Ergonomics Society* 49 (4): 710–720. doi:10.1518/001872007X215782.

Geedipally, S., S. Patil, and D. Lord. 2010. "Examination of Methods to Estimate Crash Counts by Collision Type." *Transportation Research Record: Journal of the Transportation Research Board* 2165 (1): 12–20. doi:10.3141/2165-02.

Good, M. D., and R. H. Gilkey. 1996. "Sound Localization in Noise: The Effect of Signal-to-Noise Ratio." *The Journal of the Acoustical Society of America* 99 (2): 1108–1117. doi:10.1121/1.415233.

Hellier, E., J. Edworthy, and I. Dennis. 1993. "Improving Auditory Warning Design: Quantifying and Predicting the Effects of Different Warning Parameters on Perceived Urgency." *Human Factors: The Journal of the Human Factors and Ergonomics Society* 35 (4): 693–706. doi:10.1177/001872089303500408.

Ho, C., and C. Spence. 2005. "Assessing the Effectiveness of Various Auditory Cues in Capturing a Driver's Visual Attention." *Journal of Experimental Psychology: Applied* 11: 157–174. doi:10.1037/1076-898X.11.3.157.

Ho, C., H. Z. Tan, and C. Spence. 2005. "Using Spatial Vibrotactile Cues to Direct Visual Attention in Driving Scenes." *Transportation Research Part F: Traffic Psychology and Behaviour* 8 (6): 397–412. doi:10.1016/j.trf.2005.05.002.

Ho, C., H. Z. Tan, and C. Spence. 2006. "The Differential Effect of Vibrotactile and Auditory Cues on Visual Spatial Attention." *Ergonomics* 49 (7): 724–738. doi:10.1080/00140130600589887.

JASP Team. 2018. JASP (version 0.9.2) [computer software]. https://jasp-stats.org/faq/how-do-i-cite-jasp/.

Jones, L. A., and N. B. Sarter. 2008. "Tactile Displays: Guidance for Their Design and Application." *Human Factors: The Journal of the Human Factors and Ergonomics Society* 50 (1): 90–111. doi:10.1518/001872008X250638.

Kaptein, N. A., J. Theeuwes, and R. Van Der Horst. 1996. "Driving Simulator Validity: Some Considerations." *Transportation Research Record: Journal of the Transportation Research Board* 1550 (1): 30–36. doi:10.1177/0361198196155000105.

Lewis, B. A., J. L. Eisert, and C. L. Baldwin. 2018. "Validation of Essential Acoustic Parameters for Highly Urgent in-Vehicle Collision Warnings." *Human Factors: The Journal of the Human Factors and Ergonomics Society* 60 (2): 248–261. doi:10.1177/0018720817742114.

Makous, J. C., and J. C. Middlebrooks. 1990. "Two-Dimensional Sound Localization by Human Listeners." *The Journal of the Acoustical Society of America* 87 (5): 2188–2200. doi:10.1121/1.399186.

Malone, T. B. 1987. "The Centered High-Mounted Brake Light: A Human Factors Success Story." *Applied Industrial Hygiene* 2 (2): 56–86. doi:10.1080/08828032.1987.10389250.

Meng, F., and C. Spence. 2015. "Tactile Warning Signals for in-Vehicle Systems." *Accident Analysis and Prevention* 75: 333–346. doi:10.1016/j.aap.2014.12.013.

Middlebrooks, J. C., and D. M. Green. 1991. "Sound Localization by Human Listeners." *Annual Review of Psychology* 42 (1): 135–159. doi:10.1146/annurev.ps.42.020191.001031.

Mukhtar, A., L. Xia, and T. B. Tang. 2015. "Vehicle Detection Techniques for Collision Avoidance Systems: A Review." *IEEE Transactions on Intelligent Transportation Systems* 16 (5): 2318–2338. doi:10.1109/TITS.2015.2409109.

Parasuraman, R., P. A. Hancock, and O. Olofinboba. 1997. "Alarm Effectiveness in Driver-Centred Collision-Warning Systems." *Ergonomics* 40 (3): 390–399. doi:10.1080/001401397188224.

Patterson, R. D. 1990. "Auditory Warning Sounds in the Work Environment." *Philosophical Transactions of the Royal Society of London. B, Biological Sciences* 327: 485–492. doi:10.1098/rstb.1990.0091.

Pinto, M., V. Cavallo, and T. Ohlmann. 2008. "The Development of Driving Simulators: Toward a Multisensory Solution." *Le Travail Humain* 71 (1): 62–95. doi:10.3917/th.711.0062.

R Core Team. 2018. *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/.

Reimer, B., and B. Mehler. 2011. "The Impact of Cognitive Workload on Physiological Arousal in Young Adult Drivers: A Field Study and Simulation Validation." *Ergonomics* 54 (10): 932–942. doi:10.1080/00140139.2011.604431.

Riener, A. 2010. "Assessment of Simulator Fidelity and Validity in Simulator and on-the-Road Studies." *International Journal on Advances in Systems and Measurements* 3: 110–124.

Spence, C., and C. Ho. 2008a. "Multisensory Warning Signals for Event Perception and Safe Driving." *Theoretical Issues in Ergonomics Science* 9 (6): 523–554. doi:10.1080/14639220701816765.

Spence, C., and C. Ho. 2008b. "Multisensory Interface Design for Drivers: Past, Present and Future." *Ergonomics* 51 (1): 65–70. doi:10.1080/00140130701802759.

Stoner, A. H., L. D. Fisher, and M. Mollenhauer. Jr. 2011. "Simulator and Scenario Factors Influencing Simulator Sickness." In *Handbook of Driving Simulation for Engineering, Medicine, and Psychology*, edited by D. L. Fisher, M. Rizzo, J. Caird, J. D. Lee, 1–14. Boca Raton, FL: CRC Press.

Tran, T. V., T. Letowski, and K. S. Abouchacra. 2000. "Evaluation of Acoustic Beacon Characteristics for Navigation Tasks." *Ergonomics* 43 (6): 807–827. doi:10.1080/001401300404760.

Treeby, B. E., R. M. Paurobally, and J. Pan. 2007. "The Effect of Impedance on Interaural Azimuth Cues Derived from a Spherical Head Model." *The Journal of the Acoustical Society of America* 121 (4): 2217–2226. doi:10.1121/1.2709868.

WHO. 2018. "Road traffic injuries." https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries.