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Vehicle surge detection and pathway discrimination by pedestrians who are blind: Effect of adding an alert sound to hybrid electric vehicles on performance

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Abstract

This study examined the effect of adding an artificially generated alert sound to a quiet vehicle on its detectability and localizability with 15 visually impaired adults. When starting from a stationary position, the hybrid electric vehicle with an alert sound was significantly more quickly and reliably detected than either the identical vehicle without such added sound or the comparable internal combustion engine vehicle. However, no significant difference was found between the vehicles in respect to how accurately the participants could discriminate the path of a given vehicle (straight vs. right turn). These results suggest that adding an artificial sound to a hybrid electric vehicle may help reduce delay in street crossing initiation by a blind pedestrian, but the benefit of such alert sound may not be obvious in determining whether the vehicle in his near parallel lane proceeds straight through the intersection or turns right in front of him.

Keywords

artificial alert sound; blind pedestrian; hybrid electric vehicle; orientation and mobility; pedestrian safety; vehicle detection

Introduction

Global sales of hybrid and battery electric vehicles are expected to reach 5.2 million units by 2020, comprising 7.3 percent of total number of vehicles sold, up from 2.2 percent in 2010 (J. D. Power and Associates, 2010). Currently there are over 140 different hybrid and battery electric vehicles that are commercially available (Hybridcars.com, 2011). In recent years,

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Declaration of Conflicting Interests

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there has been an increase in the popular media that has reported on the potential impact of increasing numbers of hybrid and battery electric vehicles on pedestrians who are blind (Kitamura & Hagiwara, 2009; Motavalli, 2009; Whoriskey, 2009). Most of the reports describe how hybrid and battery electric vehicles pose a hazard to blind pedestrians who often depend on the sound emitted by vehicles to travel safely. However, the claims by many articles have been based on anecdotal evidence and speculation, few empirical studies have been conducted to examine if and how the quieter vehicles may affect the blind pedestrians' ability to travel safely in different surroundings.

Blind pedestrians use traffic sounds in many key orientation tasks (LaGrow & Weessies, 1994; Allen, Barbier, Griffith, Kern, & Shaw, 1997; Hill & Ponder, 1976; Pogrud et al., 1995). For example, a blind pedestrian uses the sounds from the vehicles in parallel and perpendicular streets for correct alignment before crossing a street (Guth, Hill, & Rieser, 1989; Willoughby & Monthei, 1998). They may also use parallel traffic sounds to correct their heading in the event they veer while crossing a street (Allen et al., 1997; Hill & Ponder, 1976). It is also important for a blind pedestrian to detect the presence of an approaching vehicle at a sufficient distance in order to cross a street that has no traffic signals (e.g., residential streets, roundabouts, channelized turn lanes, etc.) (LaGrow & Weessies, 1994; Lawson & Wiener, 2010; Long, Guth, Ashmead, Wall Emerson, & Ponchillia, 2005; Sauerburger, 1995). In addition, traffic sounds are used to identify an appropriate time to initiate crossing at a signalized intersection. That is, blind pedestrians are taught to use the surge of vehicles in their near parallel street to determine an appropriate time to start crossing (Hill & Ponder, 1976; Jacobson, 1993). Furthermore, ability to determine whether the vehicles in the parallel street are turning into one's travel path is critical for the safety of a blind pedestrian since a failure to make correct discrimination may put them in the collision path of a turning vehicle (Jacobson, 1993; LaGrow & Weessies, 1994).

Different vehicles may have different acoustic characteristics, including intensity, frequency, and modulation, and thus some vehicles may be detected more easily than others (Blake & Sekuler, 2006; Fastl & Zwicker, 2007; Goldstein, 2007; Moore, 2008; Palmer, 1995). Higher sound level is related to a sensation of augmented loudness and affects the threshold of hearing (Blake & Sekuler, 2006; Goldstein, 2007; Moore, 2008; Palmer, 1995). Sound frequencies are linked to the perceptual experience of pitch and also affect the threshold of hearing (Goldstein, 2007).

Mechanical noise and tire noise are the two primary components of the sound from a moving vehicle (LeLong, 1999). Engine noise prevails at low speed whereas the tire noise becomes prominent when the vehicle is in high speed (Nelson, 1987). A hybrid electric vehicle (HEV) has been documented to produce a much lower level of sound energy than the comparable internal combustion engine (ICE) vehicle when accelerating slowly from a stationary position (reaching 10 km/h in 5 seconds) (Wiener, Naghshineh, Salisbury, & Rozema, 2006).

Blindfolded sighted participants detected HEV vehicles (2004 Prius and 2006 Prius) 2 to 4 seconds later than the ICE vehicles (2004 Honda Accord and 2005 Ford Mustang) when binaural recordings of vehicles approaching at a constant speed of 8 km/h were played through earphones in a lab (Rosenblum, 2008). Blind participants also missed surges of HEV vehicles that started up from a stationary position more frequently (7.4–45.7%) than those of internal combustion engine vehicles (2.2%) in a moderately busy downtown intersection of a college town (Kalamazoo, Michigan) (Wall Emerson, Naghshineh, Hapeman, & Wiener, 2011). Furthermore, in low speed maneuver conditions, including slowing, stopping, backing up, and entering a parking space, the vehicle-pedestrian accident

rate of HEV vehicles was twice as high as that of the ICE vehicles (National Highway Traffic Safety Administration, 2009).

Different acoustic characteristics of different vehicles may affect not only detectability but also localizability of the vehicles. High frequency sounds are often localized by causing perceptible interaural level difference created by the head-cast sound shadow (Feddersen, Sandel, Teas, & Jeffress, 1957; Hartmann, 1999). In contrast, interaural time difference is often used by a listener for localizing a low frequency sound (Stevens & Newman, 1936; Wightman & Kistler, 1992; Yost, Wightman, & Green, 1971). Amplitude modulation of a sound also appears to affect sound localizability (Henning, 1974). However, we found no published studies that specifically examined whether there is a difference in localizability between the vehicles that have different acoustic characteristics.

Acoustic characteristics of environmental sounds may also affect the detectability and localizability of a vehicle because signals are always detected against a background of activity (Macmillan & Creelman, 2004; Green & Swets, 1966). Difference in frequency characteristics (Fletcher, 1940; Margolis, Dubno, & Hunt, 1981; Moore, 1986) as well as in sound intensity (Good, Gilkey, & Ball, 1997; Lawson & Wiener, 2010) between the signal and background noise appears to affect how well a signal can be detected and localized. A target sound is more easily masked by a background sound if the background sound includes the frequencies at or near those of the target sound (Moore, 1986). It should also be noted that a background sound that contains frequencies slightly lower than the target sound masks the target sound more effectively compared to a background sound composed of frequencies slightly higher than that of the target sound (Buser & Imbert, 1992; Moore, 1986). Wall Emerson and Sauerburger (2008) reported that ambient sound level was the strongest predictor of how early approaching vehicles were detected in a midblock by blind pedestrians. However, no published studies have investigated the interaction effect of the vehicle and environmental characteristics on vehicle detection and localization.

Although more detectable sounds tend to be localized more accurately in some instances, this relationship is neither direct nor consistent (Cohen, 1981; Egan & Benson, 1966; Good et al., 1997; Ito, Colburn, & Thompson, 1982; Robinson & Egan, 1974; Stern, Slocum, & Phillips, 1983). Good et al. (1997) found that the sound localization accuracy was strongly influenced by the reduction in signal-to-noise ratio in the front/back dimension, but the deterioration in localization accuracy was far less noticeable in the left/right dimension. In addition, Cohen (1981) reported that the 250 Hz signal tone was better detected when the masker was interaurally phase inverted than when it was interaurally uncorrelated; however, the same signal tone was the most difficult to localize in the interaurally phase inverted masker. Egan and Benson (1966), Stern et al. (1983), Ito et al. (1982), and Robinson and Egan (1974) also reported that accurate localization of the signal was not systematically related to how well the signal was detected. Given such lack of direct relationship between signal detection and localization, it was important to examine whether the vehicles that were better detected were also the ones that were better localized.

One of the primary purposes of this study was to examine the effect of an added artificially generated alert sound on how well the vehicles can be detected and localized. Another purpose of the study was to investigate how different test sites affect vehicle detectability and localizability as they interact with the effects of different vehicle sounds.

Method

Study design and participants

A repeated-measures design with block randomization was used in this study, in which the participants performed each of the required tasks (described in Research Procedure) under one of the three presented vehicle conditions (described in Apparatus). We used a convenience sample of fifteen adults who were legally blind and travelled independently at least in familiar areas; all of them completed the tasks as outlined by the study protocol. A summary of the participants' demographic information and hearing thresholds are shown in Table 1 and Table 2, respectively.

Apparatus

Three different vehicles were used for each orientation and mobility task: a midsize hybrid electric sedan (HEV)¹, the same make and model hybrid electric sedan with the Vehicle Sound for Pedestrians (VSP) system, and the same make and model internal combustion engine sedan (ICE). The VSP sound has two equally pronounced peaks: 500 Hz and 2.5 KHz (see Figures 1 and 2) with a continuous series of whoosh character designed for futuristic attribute. The VSP sound was emitted coincident with acceleration with virtually no time lag. The three vehicles described above had identical tires. When measured at 2 m in front of the vehicle grill in an anechoic chamber while idling, the sound levels of the HEV, VSP, and ICE vehicles were 48.6 dBA, 58.3 dBA, and 54.6 dBA, respectively. One-third octave frequency spectrum of each of the three vehicle sounds, recorded in an anechoic chamber, is shown in Figures 1, 2 and 3.

Three GPS data logging system units² were used to record the position and velocity of each vehicle every 100 milliseconds during each trial. A total of eleven radio controller handsets³ were used: two for each of the 5 participants, and one for the experimenter who time-stamped the moment the wheel of the stopped vehicle began moving in each trial. The sound level meter⁴ was positioned next to the participant farthest from the stopped vehicle. A laptop⁵ coupled with a National Instruments chassis containing three four-channel data acquisition cards⁶ recorded the sound level meter output as well as each trigger pull and release of each radio controller during all trials. A digital camcorder⁷ was used to record all trials.

Before beginning the experiment, we tested each participant's hearing using an audiometer⁸ in a hearing test room located in Western Michigan University's (WMU) College of Health and Human Services (CHHS) building. We determined each participant's thresholds at 120, 250, 500, 1000, 2000, 4000, and 8000 Hz.

Research procedure

The three vehicle conditions were: 1) a midsize hybrid electric sedan operated in electric vehicle mode (HEV), 2) the same make and model hybrid electric sedan operated in electric

¹All vehicles tested in the study were mass-produced model year 2010 vehicles. Due to the non-disclosure agreement signed between Western Michigan University and the Nissan Technical Center North America, the exact make and model of the tested vehicles could not be reported.

²VBOX Micro RLVBNIC01C, <http://www.vboxusa.com/products.php>

³Traxxas 2.4 GHz, 2 channels,

<http://traxxas.com/gallery/Accessories-Parts/transmitters/TQ-24GHz-High-Output-Transmitter-Traxxas-Link-2-channel-2238>

⁴Casella Cel-490, class 1 SLM, <http://www.enviroequipment.com/rentals/cel490.htm>

⁵Dell Latitude E6500, <http://www.dell.com/us/dfb/p/latitude-e6500/pd>

⁶NI cDAQ-9172, <http://sine.ni.com/nips/cds/view/p/lang/en/nid/202545>

⁷Canon VIXIA HF20, http://www.usa.canon.com/cusa/support/consumer/camcorders/flash_memory_camcorders/vixia_hf20

⁸Beltone Special Instruments 120 Audiometer, <http://www.beltone.com>

vehicle mode with the Vehicle Sound for Pedestrians (VSP) system on, and 3) the same make and model internal combustion engine sedan (ICE) in internal combustion engine mode. Two of the most frequently cited locations where quiet cars may pose threats to blind pedestrians' safety are parking lots and roadways (Nuckols, 2007; Stein, 2005). WMU's CHHS parking lot (see Figure 4) was selected as one of the testing sites given its low ambient sound level (48.7 dBA), which is comparable to the day time sound level in moderately quiet residential areas in a small city such as Kalamazoo, Michigan. A roadway next to the Midlink Business Park in Portage, Michigan (Midlink Drive) (see Figure 5) was selected as the other testing site in light of its moderately high level of ambient sound (55.1 dBA) that is comparable to the sound level at semi-business areas in Kalamazoo, Michigan.

Each participant completed a consenting procedure as approved by WMU's Human Subjects Institutional Review Board before participating in the study. Participants were tested in groups of five over the course of two days (15 participants in total). Wireless communication between each participant and the data acquisition system was made via radio controller handsets held by the participant. Participants pulled the trigger on the controller to register an event. Background sound levels as well as the passing vehicle sound levels were recorded continuously by a sound level meter described above.

Sleep shades were worn by all participants during all trials. Participants were arranged in a group of five near the sound level meter so that the initial vehicle travel path was to the left of the participants. Participants were seated in the general area a pedestrian would be if standing at a corner and waiting to cross the street perpendicular to the path of the approaching vehicle. Cones were used at the CHHS parking lot to replicate the radius of the turn at the Midlink roadway.

At each site, vehicles approached, then came to a full stop approximately 2 m behind the participants where a vehicle might stop at a red light or at a stop sign. After a random amount of time between 5 and 15 seconds, a hand signal was given to the driver who proceeded forward in a normal acceleration up to 15 km/h. According to a randomized schedule given to the drivers, on any given trial the vehicle proceeded straight or turned right in front of the participants. Participants pulled a trigger when they first heard the vehicle begin moving from the stopped position and then pulled the trigger again once they were sure whether the vehicle went straight or turned right directly in front of them; they pulled the left trigger for "straight" and right trigger for "turn". Four trials were completed for each of the 6 vehicle approach conditions, which resulted in 24 trials (3 vehicles $\times$ 2 path conditions (straight, right turn) $\times$ 4 trial repetitions) for each participant at each site. The participants had one practice trial for each of the 6 vehicle approach conditions. Identical protocols were used at both the CHHS parking lot and the Midlink roadway.

The vehicle position and velocity at the times of surge detection and pathway vote by each participant were recorded by three V-Boxes installed on the vehicles. All raw data from the V-Boxes, radio controller handsets, and the sound level meter were fed into a central laptop computer.

Variables

The time from the vehicle "surge"—the moment the wheel of the stopped vehicle began moving—until the time a participant indicated he was aware of it moving by pulling his trigger was defined as the surge detection time lag. Similarly, the time from the surge until the time when a participant indicated he knew which way a vehicle went—straight or turning right—was defined as the pathway vote time lag. A missed surge was defined as a failure to pull the trigger even after 5 seconds had elapsed since the surge. Similarly, a missed pathway vote was defined as a failure to pull the trigger even after 10 seconds had

elapsed since the surge. Such cut-off points were established based on the observation that most right-turning vehicles proceeded far past the participants by the time 10 seconds had elapsed from the surge and thus any pathway discrimination vote after this point cannot be tied to the receding vehicle for any practical street crossing decision purposes; most “straight through” vehicles also proceeded far past the center of the intersection by this time. Finally, out of all trials for a given vehicle condition, the number of correct vehicle path direction votes for each participant was calculated.

Independent variables were the vehicle condition (described in Research Procedure), test site (CHHS parking lot and Midlink roadway), and the type of task (surge detection and pathway discrimination).

Analyses

Upon completing a series of preliminary descriptive statistical procedures, a three-way repeated-measures Analysis of Variance (ANOVA) was conducted. In case of the violation of the sphericity assumption, adjustments were made to the ANOVA results using Greenhouse-Geisser degree of freedom correction. Repeated-measures *t*-tests were used for pairwise post hoc comparisons. For dichotomous variables, Cochran's *Q* tests and McNemar's tests were used for comparison of more than two groups and pairwise post hoc comparisons, respectively. We used a significance level of .05 for all statistical tests (two-tailed) in this study. Bonferroni correction was used for all pairwise post hoc tests. The statistical power was at least .82 for all ANOVA and post hoc *t*-tests when a large effect size ($f = .4$, $d = .8$) was assumed (Cohen, 1988; Erdfelder, Faul, & Buchner, 1996). G*Power version 3.0.10 was used for statistical power analyses, while SPSS version 16.0 was used for all other analyses.

Results

Main effects

No statistically significant interaction was observed between the test site and the type of task, $F(1, 14) = .29$, $p = .601$; therefore, the main effects of these two variables were examined (Keppel, 1991). There was no statistically significant difference in time lag between the CHHS parking lot ($M = 3.98$, $SD = .83$) and the Midlink roadway ($M = 3.87$, $SD = .81$), $F(1, 14) = .43$, $p = .525$, $d = .13$. There was no statistically significant difference between these two sites in respect to frequency of missed surges or votes, either (CHHS = 3.1 %, Midlink = 3.7 %), $p = .596$ (McNemar's test).

In contrast, the time lag for pathway discrimination vote ($M = 6.33$, $SD = 1.31$) was statistically significantly longer than that for surge detection ($M = 1.52$, $SD = .34$), $F(1, 14) = 1,448.20$, $p < .001$, $d = 5.03$. However, there was no statistically significant difference between these two tasks in respect to frequency of missed surges or votes (surge detection = 3.5 %, pathway discrimination vote = 3.2 %), $p = .850$ (McNemar's test).

When the first three trials of each vehicle condition was compared with the last three trials to test for a practice effect, no significant effect was found in either surge detection time lag ($t = 1.249$, $p = .232$, $d = .52$) or pathway vote time lag ($t = -.469$, $p = .646$, $d = .30$).

Interaction effects

Given the significant 2-way interaction between the vehicle type and the type of task— $F(2, 28) = 51.43$, $p < .001$ —as well as the significant 3-way interaction (task $\times$ vehicle $\times$ test site)— $F(2, 28) = 4.89$, $p = .015$ (see Figure 6), a simple interaction between the vehicle type and the type of task was examined for each of the two sites (Keppel, 1991).

CHHS parking lot—In the surge detection task, there was a statistically significant time lag difference between the vehicles, $F(1.25, 17.44) = 32.08, p < .001$ (see Table 3). Post hoc comparisons using repeated measures t -tests indicated that the time lag for the HEV vehicle ($M = 2.52, SD = 1.12$) was statistically significantly longer than that for the ICE vehicle ($M = 1.40, SD = .56$), $t = 5.02, p < .001, d = 1.26$, which was in turn statistically significantly longer than that for the VSP vehicle ($M = .74, SD = .47$), $t = 5.09, p < .001, d = 1.28$. Similarly, there was a statistically significant difference between the vehicles in respect to the number of missed surges (HEV = 7.5 %, ICE = 2.5 %, VSP = 0.0 %), *Cochran's Q*(2) = 10.50, $p = .005$. Pairwise comparisons using McNemar's exact tests revealed that only the difference between the HEV and VSP vehicles was statistically significant, $p = .004$.

There was a statistically significant time lag difference between the vehicles in pathway discrimination vote as well, $F(2, 28) = 12.84, p < .001$. Post hoc analyses showed that the discrimination vote lag for the HEV vehicle ($M = 6.95, SD = .88$) was statistically significantly longer than that for the VSP vehicle ($M = 6.33, SD = .93$), $t = 3.61, p = .003, d = .68$, and that for the ICE vehicle ($M = 5.94, SD = .84$), $t = 3.97, p = .001, d = 1.17$. However, there was no statistically significant difference between the VSP and ICE vehicles, $t = 2.39, p = .032, d = .44$. When the number of missed pathway votes and that of false pathway decisions (i.e., indicating “straight” when the vehicle turned right, or indicating “turn” when the vehicle proceeded straight) were combined for comparison between the vehicles, there was no statistically significant difference (HEV = 5.9 %, VSP = 6.8 %, ICE = 10.2 %), *Cochran's Q* = 1.91, $p = .385$.

Midlink Drive roadway—There was a statistically significant time lag difference between the vehicles in surge detection task, $F(1.23, 17.17) = 20.36, p < .001$ (see Table 3). Post hoc tests indicated that the time lag for the HEV vehicle ($M = 2.25, SD = 1.34$) was statistically significantly longer than that for the ICE vehicle ($M = 1.34, SD = .79$), $t = 4.83, p < .001, d = .83$, which was in turn statistically significantly longer than that for the VSP vehicle ($M = .88, SD = .47$), $t = 3.04, p = .009, d = .71$. Similarly, there was a statistically significant difference between the vehicles in respect to the number of missed surges (HEV = 9.3 %, ICE = 1.7 %, VSP = 0.0 %), *Cochran's Q* = 17.17, $p < .001$. Pairwise comparisons using McNemar's exact tests indicated that the surge miss rate for the HEV vehicle was statistically significantly higher than that for the ICE vehicle ($p = .012$) and that for the VSP vehicle ($p = .001$). However, there was no statistically significant difference between the ICE and VSP vehicles ($p = .500$).

There was a statistically significant time lag difference between the vehicles in pathway discrimination vote as well, $F(1.43, 20.02) = 20.54, p < .001$ (see Table 3). Post hoc analyses revealed that the pathway discrimination vote lag for the ICE vehicle ($M = 5.43, SD = .69$) was statistically significantly shorter than that for both the VSP vehicle ($M = 6.58, SD = .68$), $t = 8.41, p < .001, d = 1.68$, and that for the HEV vehicle ($M = 6.74, SD = 1.25$), $t = 5.29, p < .001, d = 1.30$. However, there was no statistically significant difference between the VSP and HEV vehicles, $t = .62, p = .546, d = .16$. When the number of missed pathway votes and that of false pathway decisions were combined for comparison between the vehicles, the difference was not statistically significant between the vehicles (HEV = 9.3 %, VSP = 5.1 %, ICE = 3.4 %), *Cochran's Q* = 4.33, $p = .115$.

Interaction between vehicle type and hearing impairment—The interaction between the type of vehicle and hearing impairment was examined purely descriptively with no inference to the corresponding population because of the small number of participants who had hearing impairments ($n = 3$); therefore, utmost caution is needed in interpreting the results in this regard. Within the sample, the added sound (VSP) helped the participants who

had hearing impairments more than it did the normal hearing group (see Figures 7 and 8). Such interaction was observed in both surge detection and pathway discrimination tasks.

Discussion

We found that, in surge detection, the VSP vehicle performed significantly better than the ICE vehicle, which did, in turn, significantly better than the HEV vehicle. However, no vehicle stood out in pathway discrimination task. There was no significant performance difference in either surge detection or pathway discrimination between the two test sites despite the 6 dB difference in overall ambient sound level. When analyzed purely descriptively with no inference to the population, addition of the VSP sound helped those with hearing impairments more than those with normal hearing.

Interaction effect of task and vehicle type

The vehicle with the VSP sound was detected significantly earlier than the other vehicles once it started to move from a stationary position. In fact, none of the surges made by the VSP vehicle was missed by any of the participants whereas an average of 8.4 percent and 2.1 percent of the surges made by the HEV and ICE vehicles were missed, respectively. In addition, average effect size of the difference between the VSP and ICE vehicles in surge detection lag ($d = 1.00$), as well as that between the ICE and HEV vehicles ($d = 1.05$), was very large. This may be a result of the fact that, by design, the VSP sound turns off automatically 2 seconds after the vehicle comes to a complete stop and then kicks back on upon the vehicle's forward movement. This mechanism might have given the participants a distinct cue for detecting the surges made by the VSP vehicle.

In contrast to surge detection, the pathway discrimination task results were mixed. Although the pathway discrimination vote lag was the shortest for the ICE vehicle, there was no significant difference in the number of missed pathway votes or false pathway decisions between the vehicles. In other words, despite up to 10 dB difference in sound level between the vehicles, there was no significant difference in the accuracy of the pathway discrimination vote between the vehicles. This may be because of the fact that the left/right sound localization accuracy is not as strongly affected by the reduction in signal-to-noise ratio as the front/back localization (Good & Gilkey, 1996). That is, by the time the participants cast the pathway votes, which ranged from an average of 5.7 seconds for ICE to an average of 6.8 seconds for HEV, the turning vehicles were already close to the median plane of the participants, and thus what was required of the participants was to localize the sound primarily in the left/right dimension rather than in the front/back dimension. Lack of direct relationship between surge detection performance and pathway discrimination performance is consistent with the literature on this topic, which reported that accurate localization of the sound is not systematically related to its detectability (Egan & Benson, 1966; Ito et al., 1982; Stern et al., 1983).

Interaction effect of hearing impairment and vehicle type

Although the analysis was purely descriptive with no intention of making an inference to the population, the participants with hearing impairments were aided more by the VSP sound than those with normal hearing. One of the possible explanations may be that the sound level in the 500–700 Hz range was much higher for the VSP vehicle than those of the ICE and HEV vehicles. In other words, given the fact that all 3 participants with hearing impairments had either normal or near-normal hearing at the 500 Hz frequency, the VSP vehicle's emphasis on the 500–700 Hz band sound level could have contributed to helping the participants with higher frequency hearing loss perform almost as well as the normal hearing group when the VSP vehicle was presented.

Effect of test site

Absence of significant difference in performance between the two tests sites, despite the 6 dB difference in overall sound level, was contrary to our prediction. It is possible that this result is related to the fact that the surrounding sound at the Midlink roadway was more predictable than that at the CHHS parking lot. That is, the traffic sound from the nearby 4-lane busy street and the expressway was the dominant background sound at the Midlink roadway, while the surrounding sound at the CHHS parking lot was composed of a number of different sounds, including traffic sound, noise from a power plant, bird chirping, noise from occasionally passing airplanes from a distance, and sounds from intermittent student activities, including marching band practice from a distance and conversations from students that passed by. It has been documented that uncertainty in frequency and intensity of the masking sound negatively affects how well a target sound is detected (Neff & Green, 1987; Neff & Jesteadt, 1996). Given such, lack of predictability of the surrounding sound at the CHHS parking lot might have contributed negatively to the participants' performance.

Another possible explanation may be that, at the Midlink roadway, the primary masking sound came from the opposite side of where the test vehicles were positioned before the start of each trial, whereas in the CHHS parking lot, two of the noticeable background noise sources—a busy street and the stadium where the marching band was practicing—were located in the same general direction of where the test vehicles started. Previous studies have reported that masking reductions of 5–18 dB occurred when the signal was horizontally separated (i.e., in azimuth) from the masking sound by 90–180 degrees (Gilkey & Good, 1995; Good et al., 1997).

Strengths and limitations

Hybrid electric vehicles were compared to similar size ICE vehicles in some of the previous hybrid electric vehicle detection studies (e.g., Toyota Prius vs. Honda Accord). In such comparison, differences between the vehicles other than vehicle size, including tire size and transmission, might have confounded the results. The vehicles compared in this study were of the same make and model. Particularly, the HEV and VSP vehicles were identical except in regards to whether the vehicle was equipped with the VSP system or not. Furthermore, careful driver training as well as the selection of low-speed maneuver conditions made it possible for the vehicles to operate precisely as required by the study protocol. For instance, at all times during all trials, the HEV and VSP vehicles were operated without engaging their internal combustion engines, which allowed us to investigate the effect of the VSP system after controlling for the type of engaged powertrain.

This study had many limitations. First, we were not able to identify specific acoustic characteristics that significantly affected the surge detection and pathway discrimination performance because only one artificially generated sound was included in the study. Second, some of the key orientation and mobility tasks involved in blind pedestrians' everyday travel such as vehicle gap detection and alignment with the traffic in the parallel street were not included in this study. Third, the study's small sample, particularly its over-representation of certain etiologies and under-representation of those with substantial residual vision and recent vision loss, prevented us from examining the interactions between participant characteristics and vehicle type or environment. Even in regards to the interaction effect of hearing impairment and vehicle type, inclusion of only a small number of hearing-impaired participants prevented us from making any inferences to the corresponding population. Fourth, the study's small convenience sample also limits the generalizability of the findings. Last, ambient sound level difference of 6.4 dB between the two test sites might not have been sufficient to produce a meaningful difference in Orientation and Mobility (O&M) task performance.

Implications and recommendations

Although the VSP vehicle was superior to the ICE and HEV vehicles in surge detection, there was no significant difference in pathway discrimination performance between the vehicles. In other words, although the participants were able to detect the initial movement of the VSP vehicle quicker than the other vehicles, this did not directly translate to more accurate discrimination of the vehicle paths. Since it is the accurate pathway discrimination that is more directly related to reducing the risk of collision with right turning vehicles, this study does not provide evidence that adding an artificially generated sound at a sound level selected in this study would significantly reduce the risk of collision with right turning vehicles.

However, it is worth noting that earlier and more reliable surge detection can help reduce delay in street crossing initiation by a blind pedestrian in certain situations. That is, in many signalized intersections, a pedestrian phase, which include walk and clearance intervals, is linked to the vehicular phase, which is indicated by green light for the vehicles in the near parallel lane. At intersections where the vehicles in the near parallel lane are not allowed to turn right, for example when the perpendicular street is a left-bound one-way street, more reliable surge detection can help pedestrians reduce the number of missed crossing opportunities and quicker surge detection can shorten the delay in crossing initiation.

Given the fact that the vehicle with an added artificial sound was detected more reliably when it started to move from a stationary position, auto manufacturers may consider equipping hybrid electric and battery electric vehicles with a system that emits a sound to alert pedestrians in low-speed maneuver conditions. Nevertheless, it is not our claim that adding an artificially generated sound will eliminate or reduce all the potential threats posed to blind pedestrians by quiet vehicles. Neither do we claim that the best way to address the issue of blind pedestrians' safety due to the advent of quiet vehicles is adding artificially generated sounds. Instead, a comprehensive set of orientation and mobility tasks needs to be tested with different types of artificially generated sounds as well as non-acoustic countermeasures in order to present comprehensive solutions to the problems emerging from the rapidly growing fleet of quiet vehicles in our streets. In addition, systematic inclusion of hearing-impaired individuals and those with significant residual vision may allow us to examine the interactions between these participant characteristics and vehicle sound or environment.

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Figure 1.

One-third octave frequency spectrum of HEV vehicle.

Note: Each line graph indicates a representative one-third octave frequency spectrum of each test site. HEV = hybrid electric vehicle.

Figure 2.

One-third octave frequency spectrum of VSP vehicle.

Note: Each line graph indicates a representative one-third octave frequency spectrum of each test site. VSP = hybrid electric vehicle equipped with the Vehicle Sound for Pedestrians system.

Figure 3.

One-third octave frequency spectrum of ICE vehicle.

Note: Each line graph indicates a representative one-third octave frequency spectrum of each test site. ICE vehicle = internal combustion engine vehicle.

Figure 4.
Aerial view of CHHS parking lot.

Figure 5.
Aerial view of Midlink Drive roadway.

Figure 6.

Three-way interaction (vehicle type $\times$ type of task $\times$ test site).

Note: Error bars indicate standard errors. Like superscripts within each task indicate nonsignificant differences between means.

Figure 7.
Interaction between vehicle type and hearing impairment in surge detection task.

Figure 8.
Interaction between vehicle type and hearing impairment in pathway discrimination task.

Table 1

Participant demographic information.

Participant No.	Gender	Age	Visual Acuity	Onset of VI	Etiology
1	F	43	NLP	Age 33	Uveitis
2	F	51	NLP	Birth	Retinopathy of prematurity
3	F	49	LP	Birth	Retinopathy of prematurity
4	M	18	LP	Birth	Lieber's amaurosis
5	M	61	NLP	Birth	Retinopathy of prematurity
6	M	68	LP	Age 8	Retinitis pigmentosa
7	F	77	LProj	Age 56	Retinitis pigmentosa
8	M	29	L	Birth	Unknown
9	M	22	LP	Birth	Unknown
10	F	25	NLP	Birth	Glaucoma
11	M	52	NLP	Age 6	Glaucoma
12	M	42	NLP	Age 31	Diabetic retinopathy
13	M	21	HM @ 2 feet	Age 10	Chemical burn
14	F	59	20/400	Age 54	Retinal detachment
15	F	23	20/200	Age 20	Retinal detachment

Note: NLP = no light perception. LP = light perception. LProj = light projection. HM = hand movement.

Table 2

Participant hearing thresholds (dB).

Participant Number	125 Hz	250 Hz	500 Hz	1 KHz	2 KHz	4 KHz	8 KHz
1	20	20	20	20	20	30	30
2	20	20	20	25	20	25	25
3	20	20	20	20	30	20	35
4	20	20	20	20	20	20	20
5	20	20	20	20	20	30	30
6 ^a	20	20	20	20	30	45	70
7 ^a	30	30	30	30	40	65	80
8	20	20	20	20	20	20	20
9	20	20	30	20	20	20	30
10 ^a	30	30	35	40	45	45	55
11	20	20	20	20	20	20	25
12	20	20	20	20	20	20	20
13	20	20	20	20	20	20	20
14	20	20	20	20	20	20	20
15	20	20	20	20	20	20	20

^aHearing impaired participants.

Table 3

Surge detection and pathway discrimination by different types of vehicles ($N = 15$).

Independent Variables	Time Lag (seconds)				Surge Misses			Path Vote Misses + False Path Judgments ^a		
	<i>M</i>	<i>SD</i>	<i>p</i>		<i>n</i>	%	<i>p</i>	<i>n</i>	%	<i>P</i>
CHHS Parking Lot	HEV	2.52 _a	1.12	<.001	9 _a	7.5	.005	NA	NA	
	VSP	.74 _b	.47		0 _b	0.0		NA	NA	
	ICE	1.40 _c	.56		3 _b	2.5		NA	NA	
Pathway Discrimination	HEV	6.95 _a	.88	<.001	NA	NA		7	5.9	.385
	VSP	6.33 _b	.93		NA	NA		8	6.8	
	ICE	5.94 _b	.84		NA	NA		12	10.2	
Midlink Drive Roadway	HEV	2.25 _a	1.34	<.001	11 _a	9.3	<.001	NA	NA	
	VSP	.88 _b	.47		0 _b	0.0		NA	NA	
	ICE	1.34 _c	.79		2 _b	1.7		NA	NA	.115
Pathway Discrimination	HEV	6.74 _a	1.25	<.001	NA	NA		11	9.3	
	VSP	6.58 _a	.68		NA	NA		6	5.1	
	ICE	5.43 _b	.69		NA	NA		4	3.4	

Note: Differing subscripts within each measure indicate significant differences between means at $\alpha = .17$ (Bonferroni correction). Like subscripts within each measure indicate nonsignificant differences between means.

^aFalse path judgment = participant's indication of a "straight" path when the vehicle turned right, or indication of a "turn" path when the vehicle proceeded straight.