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PSYCHOACOUSTIC EVALUATION OF LISTENER LOCALIZATION ACCURACY FOR BROADBAND AND CONVENTIONAL REVERSING ALARMS

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Two psychoacoustic tests were assessed to determine if the location and direction of vehicle-mounted alerting devices having broadband noise characteristics could be more accurately localized than those having a harmonic frequency spectrum. Reversing conditions were simulated by moving sample backup alarms on a linear sliding platform at a specified velocity. The tests moved the alarms at "direct hit" or "near miss" trajectories toward a KEMAR Manikin, with recordings repeated at 5^0 azimuthal increments. Participants listened to trajectories over headphones and selected the closest match from depictions of all possible trajectories. The tests revealed little or no substantive improvement in localization acuity for the alarm emitting a broadband noise signal.

1. Introduction

A primary function of auditory warning devices is to heighten a listener's sense of danger and state of preparedness to react appropriately. For warning devices such as vehicle reversing alarms, functionality can be evaluated by measuring a listener's ability to infer correctly the vehicle's direction and rate of approach and, if necessary, to take appropriate evasive actions. If the number of accidents can serve as a rough index of the effectiveness of reversing alarms – 342 pedestrian workers fatally injured by a commercial vehicle in the United States in 2007[1], with nearly one quarter of all such deaths involving work vehicles occurring while the vehicle is moving in reverse[2] – it is clear that such warning devices do not perform their function optimally. The fact that most reversing accidents also occur within the first 10 feet of travel[3] reinforces the need for reversing alarms to provide precise and accurate localization cues as rapidly as possible.

The current commercial standard for audible reversing alarms in the United States is the conventional beeping alarm. For example, the Occupational, Safety, and Health Administration (OSHA)[4] and the Mine, Safety, and Health Administration (MSHA)[5] mandate audible reversing alarms for most vehicular equipment used at construction and mining sites. Alarm standards for this equipment are set by the Society of Automotive Engineers[6], while American Society of Mechanical Engineers (ASME) standards govern forklifts[7]. Conventional beeping alarms have a harmonic frequency spectrum with a fundamental frequency of 1.1 kHz and a bandwidth of approximately 17 kHz. The effectiveness of these alarms has been questioned, despite considerable research to optimize

their acoustic properties.[8,9] Especially problematic appear to be environments where workers must wear ear protection that limits their ability to interpret alarm cues[10]. Moreover, the frequency with which backup alarms are sounded in commercial applications may induce auditory habituation[9]. An analysis of recent OSHA accident records[11] revealed that audible backup alarms were ineffective in preventing two-thirds of all reported backup accidents.[12,13]

Recent applied research in reversing alarm technology has focused on developing so-called "broadband" alarms.[14] These alarms generate a frequency spectrum akin to filtered broadband noise. Proponents of these alarms claim that conventional vehicle alarms have restricted bandwidth and therefore do not fully engage auditory localization mechanisms. Past laboratory studies and field trials of broadband alarms that evaluated vehicle sirens and signaling devices for emergency egress from buildings[15,16] indicated that broadband alarms were more easily localized and were less perceptually intrusive than conventional equivalents. A series of broadband alarms, manufactured by Brigade Electronics under license from Sound Alert Technology, Inc., has recently been marketed in Europe.[17]

Based on their frequency spectra, both alarms types – conventional and broadband – contain sufficient bandwidth for auditory localization mechanisms to extract both interaural intensity differences (above 2 kHz) and, to a lesser extent, time differences (below 1200 Hz)[18] and they appear to contain sufficient high-frequency content (above 4 kHz) for the auditory system to infer vertical location through the complex spectral transformations produced by the head and torso[19]. Therefore, it is not immediately apparent from a psychoacoustic perspective why broadband alarms should be more accurately localized. In localization identification tasks where a listener is presented with a single broadband sound source and is asked to indicate its spatial position, errors range from 5^0 to 10^0 directly in front of the listener and from 10^0 to 25^0 toward the listener's side.[20] Although past studies do not appear to have measured horizontal localization identification for sources approaching the listeners along a radial trajectory, we suspect that the introduction of radial source movement would tend to increase the localization error ranges noted above.

The goal of the current study was to evaluate empirically claims of improved localization of broadband alarms by simulating the acoustic conditions that prevail when a vehicle equipped with either a conventional or broadband reversing alarm is in motion. A linear sliding platform (LSP) was constructed to move an alarm at a specified velocity for a set distance. The sound trajectories were recorded on a KEMAR Manikin at different orientations and displacements in the horizontal plane. By comparing the magnitudes of listeners' localization errors for both alarm types, we could determine whether the positioning of broadband alarms could be more accurately localized.

2. Experiment 1

2.1 Method

2.1.1 Participants

Forty-seven undergraduates (10 males, 37 females) at Washington State University Vancouver (WSUV) received extra credit in their courses in return for serving as participants. All prospective participants were administered a hearing test using a Benson Medical Instruments CCA-100e Audiometer in a double-walled audiometric test chamber (Industrial Acoustics Corporation 140ACT Series).

2.1.2 Linear Sliding Platform

To simulate a vehicle equipped with a backup alarm moving in reverse, an LSP was constructed using wood from Apple-Ply for structural strength; other parts were sourced from H2W Technologies (see Fig. 1). The LSP used a stepper motor to move a small platform at a specified velocity (maximum = 4 m/s) and distance (maximum = 4 m) along a slide rail using a belt drive mechanism. The backup alarm was mounted on the platform. The positional precision of the alarm

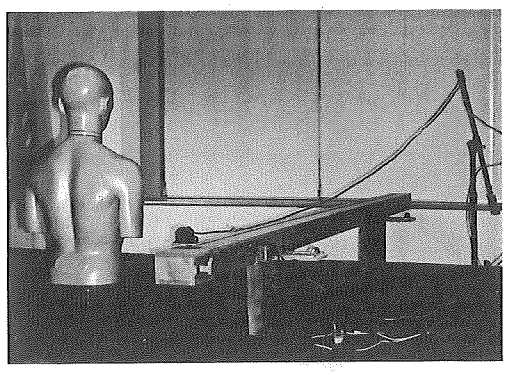

Figure 1. Recording setup for Experiment1 1 with KEMAR Manikin and platform shown in foreground.

was greater than .01 mm. The unit was lined with 1" foam for sound isolation. Software to control the LSP was written with macros provided by H2W Technologies.

2.1.3 *Alarm Recordings*

A KEMAR Manikin (Type 45DA; Gras Sound & Vibration) was fitted with ½-inch condenser microphones (Type 40AG) and ¼-inch preamplifiers (Type 26AC) that were attached to the head with RA0143 connector assemblies. Large pinna simulators (Ear No. KB0065 and KB0066) were used. A Type 12AR power module was used with a Presonus preamplifier to boost and calibrate the alarm signals for recording.

Recordings were made in a 200-seat auditorium on the WSUV campus. The KEMAR Manikin was positioned 1 m from the termination point of the LSP track, and the alarm sounds were digitally recorded on a computer at a 44.1 kHz sampling rate. Two alarm types were recorded: A bbs-tek® broadband alarm and an ECCO conventional beeping alarm at 87 dBA. For each alarm, a total of 72 trajectories were recorded by changing the LSP's orientation in 5^0 increments relative to the location of the microphones (Fig. 2). Recordings were made at platform velocities of 2 and 4 m/s, respectively. A grand total of 288 recordings (2 alarms x 2 velocities x 72 orientations) were made.

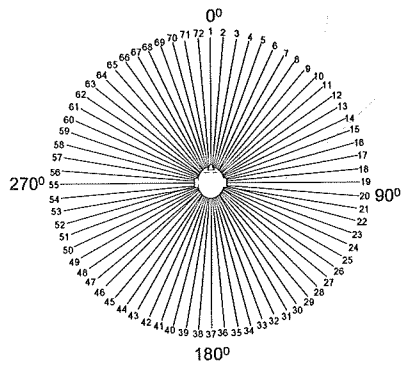

Figure 2. Alarm trajectory azimuths recorded for Experiment 1.

2.1.4 *Procedure*

Participants were tested in an audiometric test chamber and equipped with Sennheiser HD25 headphones. The listening test was created with E-Prime (Psychology Software Tools). On each trial, participants heard an alarm trajectory and selected an orientation from Fig. 2 that they felt matched that of the sound. Feedback regarding response correctness followed. Participants completed 20 practice trials before the experiment began. Sessions lasted 90 minutes.

One significant compromise associated with the headphone presentations of virtual alarm sources as outlined above was that they did not include individualized HRTF's and associated headphone compensation, and therefore were likely to yield an increase in the frequency of front-back confusions over procedures that include such calibrations. Given the exploratory nature of the current study and the fact that localization of vehicle backup alarms realistically occurs under non-optimal listening conditions (e.g., supra-aural hearing protection devices that reduce or eliminate spectral filtering cues by the pinnae), we opted instead to address front-back confusions at the data analysis level.

2.1.5 Procedure

Data files were merged using E-DataAid (Psychological Software Tools) and statistical analyses were performed using SPSS 15.0. Localization error was computed as the angular difference between the actual trajectory and the trajectory selected by the participant. Trials on which this angular difference was greater than 90^0 were considered evidence of front-back confusion and removed from initial analyses. Data sets with and without these trials were compared using analysis of variance (ANOVA) to determine whether the removal of trials indicative of front-back confusion would differentially affect results for the two types of alarms. The localization errors were then pooled to compute mean errors for each LSP orientation and additional ANOVA's were conducted to measure the effects of alarm type and velocity.

2.2 Results

For the purpose of identifying likely front-back reversals, we calculated at each trajectory azimuth the percentage of trials on which participants' identification of direction differed from the actual direction by more than 90^0. Evaluated by this criterion, front-back reversals occurred on 54.5% and 44.3% of trials at 0^0 and 180^0 azimuth, respectively. At azimuths 30^0 and 45^0 in either direction from these two locations, the frequency of reversals decreased to about 11% and 5%, respectively. An ANOVA conducted to evaluate whether the removal of such trials from the data set would differentially affect results for the two alarm types across the range of trajectory azimuths proved non-significant [$F(1,284) = .015$, $p = .902$], and therefore these trials (17.1% of the judgments in the original data set) were excluded from subsequent analyses.

Fig. 3 displays mean localization errors (degrees) for the two alarm types, plotted as a function of the LSP's azimuth. Mean localization errors were of moderate size for both broadband

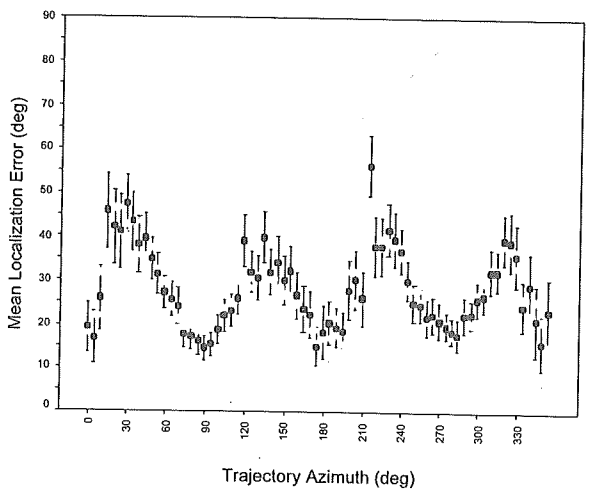

Figure 3. Mean localization errors (degrees) in Experiment 1 plotted as a function of trajectory azimuth of LSP. Results are pooled across 2 m/s and 4 m/s LSP velocities. Black and grey circles depict errors for broadband and conventional beeping alarms, respectively.

(M= 27.5°) and conventional (M = 28.4°) alarms, with error rates declining to 18-20% at 0°, 90°, 180°, and 270° azimuth. The localization advantage for broadband alarms across trajectory azimuth was small (<1°) but statistically significant [F(1, 71) = 6.55, p <.011]. The small effect of Cohen's estimated d^{21} obtained for the current sample (0.039) indicates that there was little or no *substantive* difference in localization between the two alarms, even though the large number of trials submitted for analysis makes this difference *statistically* significant. No significant main effects due to alarm velocity were observed [F(1,10337) = 2.45, p = .118], nor was there an interaction between alarm type and velocity [F(1,10337) = 1.40, p = .237]. Since this experiment revealed a small but significant difference in localization acuity between the two alarm types in the "direct hit" trajectory, it was decided to examine conditions that simulated an alarm-equipped vehicle following a "near miss" trajectory with respect to the listener to determine if the broadband alarm would be superior in this case.

3. Experiment 2

3.1 Method

3.1.1 Participants

Sixty-five undergraduates (12 males, 53 females) at WSUV participated after successfully completing the hearing test. Of these participants, 25 were assigned to Condition 1, and the remaining 40 to Condition 2.

3.1.2 Alarm Recordings

The recording setup from Experiment 1 was retained; however, the KEMAR Manikin's position was varied along an imaginary line perpendicular to the LSP's principal axis in order to generate a series of off-axis or "near miss" recordings (see Fig. 4). The recordings were made

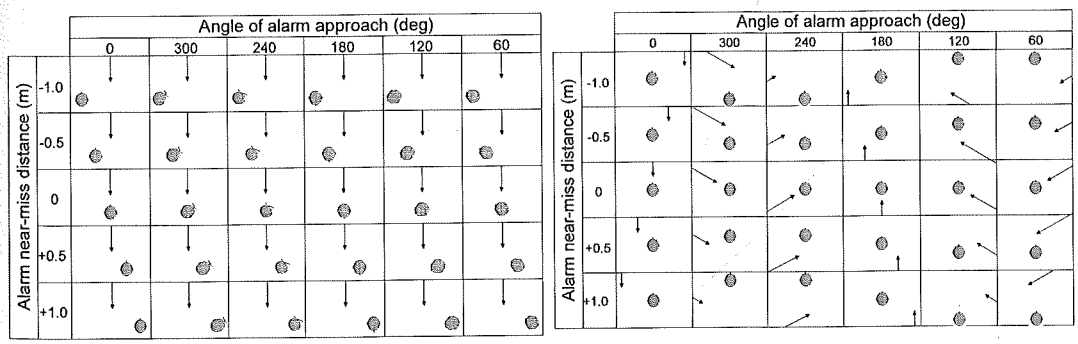

Figure 4. Images of alarm trajectories shown to participants in two conditions of Experiment 2. The relative position of LSP and KEMAR Manikin was varied so that the LSP's trajectory coincided with either a "direct hit," collision course with the Manikin or with a "near-miss" course 0.5 or 1 m to either the Manikin's left or right. Six angular positions of the Manikin relative to the LSP's orientation were tested at each displacement (0°, 60°, 120°, 180°, 240°, and 300°). Participants in Condition 1 saw perspectives fixed with respect to the Manikin's position (5a), while those in Condition 2 saw perspectives fixed with respect to the trajectory (5b).

with the KEMAR Manikin at the four off-axis positions – 0.5 and 1 m to both the left and right of the LSP's axis, respectively – as well as the on-axis, "direct hit" position. At each of these five positions, KEMAR was rotated to six orientations – 0° (parallel to LSP's axis), 60°, 120°, 180°, 240°, and 300°— during the recording session. Thus, a series of 120 recordings were created for Experiment 2 (2 alarms x 2 velocities x 5 on/off-axis positions x 6 orientations).

3.1.3 Procedure

The psychoacoustic testing procedures from Experiment 1 were retained. The first 25 participants (Condition 1) selected their responses from a diagram consisting of 30 possible orientation-displacement combinations between the KEMAR Manikin and the LSP, with the perspectives of each of these 30 images fixed with respect to the Manikin's position (Fig. 4a). The remaining 40 participants (Condition 2) selected their responses from 30 images in which the perspectives were fixed with respect to the location of the trajectory (Fig. 4b). Given the complexity of the response space for Experiment 2, we felt it prudent to introduce the nature of the listener's perspective in the images (i.e., fixed or varying) as a nuisance variable. Experiment sessions lasted approximately 45 minutes per participant.

3.2 Results

Fig. 5 displays polar coordinate plots representing participants' mean identification accuracy at each linear displacement of the trajectory relative to the recording location, with radii representing identification (percent correct) and azimuth representing KEMAR's orientation

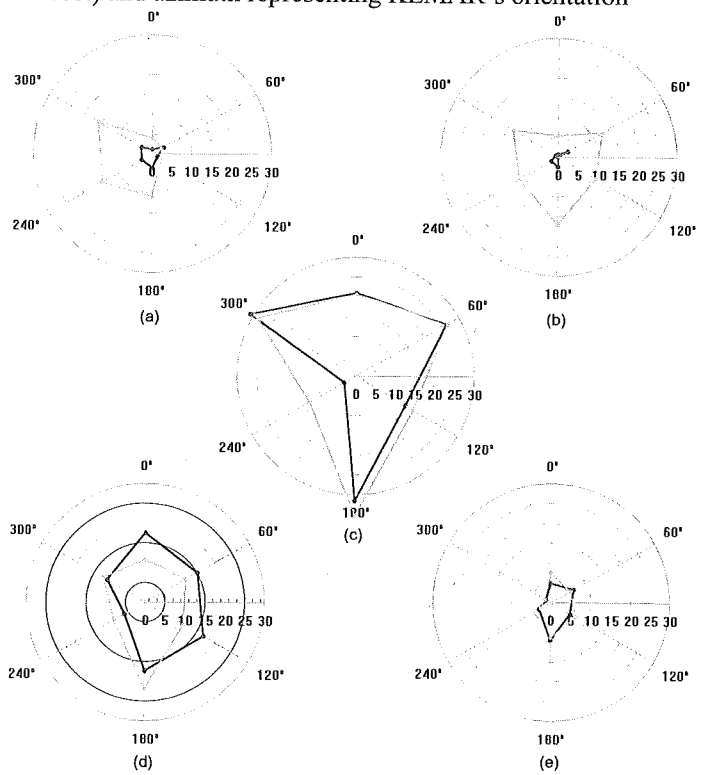

Figure 5. Polar coordinate plots depicting identification accuracy (percent correct) for the five Manikin-LSP displacements tested in Experiment 2: (a) 1 m left; (b) 0.5 m left; (c) center; (d) 0.5 m right; (e) 1 m right). Polar coordinate radii plot identification accuracy while angles represent the six angular positions of the Manikin at each displacement. Black and grey circles depict accuracies for broadband and conventional alarms, respectively.

relative to the LSP. Results were pooled across Conditions 1 and 2 in Fig. 5 since there were no significant pairwise interactions between the image type shown to participants (i.e., observer- vs. trajectory-centered) and alarm type [$F(1,120) = 3.67$, $p = .058$], trajectory angle [$F(5,120) = 1.49$, $p = .197$], or displacement [$F(4, 120) = .484$, $p = .747$]. Identification accuracy for the KEMAR-LSP displacements and angles tested was relatively poor overall ($M = 10.7\%$). A small main effect for alarm type was observed, with greater identification accuracy for the conventional beeping alarm (M

= 12.5%) than its broadband equivalent (M = 8.9%) [$F(1,120) = 19.93$, $p < .001$]. The advantage for the conventional alarm was apparent as a function of displacement, with a significant interaction between displacement and alarm type [$F(4,120) = 6.76$, $p < .001$], rather than as a function of angle, where the interaction between angle and alarm type was non-significant [$F(5,120) = 1.88$, $p = .102$].

4. Conclusions

The results of Experiment 1 revealed an improvement in localization identification of $<1^0$ with the broadband alarm for "direct hit" trajectories, a statistically significant, but unsubstantial effect; no advantage for this alarm was observed for "near miss" alarm trajectories in Experiment 2, and indeed it performed worse than the conventional alarm. Mean errors obtained in Experiment 1 were well above difference limen of approx. 1° to 4° measured for the azimuth of stationary sinusoidal signals[22] or moving stimuli[23] using forced-choice tasks, and somewhat above localization error rates of 10° to 25° for stationary signals using identification tasks, a result undoubtedly due in part to the fact that participants listened to trajectories over headphones instead of hearing them in their original acoustic context, and in part to the complexity of the decision space. On the other hand, the methodological limitations of this study that were likely to have adversely affected localization may be more indicative of the listeners' perceptual states within actual work environments. For example, commercial vehicle operators may be required to wear hearing protection devices that limit localization cues, or they may be focusing on multiple tasks that limit their ability to pay attention to the path of a moving, alarm-equipped vehicle, thus increasing the complexity of their detection task.

A key argument in favor of broadband alarms (e.g., Withington and Paterson 1998) is that conventional alarm signals cover an insufficient bandwidth to provide a full set of auditory localization cues. However, conventional alarms, including the one tested here, typically contain harmonics between 1 and 14 kHz, and so such alarms should also provide adequate cues for localization in both the horizontal and vertical planes. In this sense, broadband alarms do not possess a broader frequency bandwidth than the conventional alarms despite their greater spectral density. Although this study did not show any improvement in the ability to localize broadband alarms, such alarms may still prove superior when evaluated against other criteria, such as detectability in the presence of noise or annoyances, and in situations where there is a tendency toward sensory adaptation. Also, laboratory testing of alarm attributes in isolation from one another may obscure how these attributes contribute collectively to the detection of alarm-equipped vehicles in real-world settings. A follow-up study currently underway uses rear-mounted cameras on vehicles equipped with conventional and broadband alarms to record the reactions of pedestrians when the vehicle travels in reverse. Through analysis of pedestrians' reactions, including the speed and accuracy of orienting motions, we aim to obtain an improved assessment of each alarm's alerting characteristics.

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