Discrimination of enhanced echoes in blind and sighted individuals

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Abstract

Echolocation, while a useful skill for visually impaired people, is difficult to learn because humans naturally suppress environmental echoes. However, if the echoes are enhanced compared to environmentally normal echoes, they may therefore help to ease echolocation learners into the learning process. Blind and sighted participants discriminated enhanced echoes in two 2-interval forced choice (2IFC) tasks, one testing distance and the other testing left/right localization. We report that blind participants had lower left/right thresholds than sighted participants, while sighted participants had marginally lower distance thresholds than blind participants. As there is a precedent for enhanced spatial hearing in blind individuals in the literature but no such precedent in sighted individuals, we find the distance result surprising. The age and hearing abilities of our participant groups likely contribute to these results, and better-matched groups would allow us to obtain more conclusive data.

Introduction

Visually impaired people use sound and other sensory cues to navigate, compensating for their loss of vision. In rare cases, they develop the skill of echolocation, in which users self-generate tongue clicks in order to gain information about the surrounding environment. These source, or referent, clicks reflect off of surrounding objects and travel back to the ears, allowing echolocators to perceive information about the location and characteristics of the reflecting object. Early research on echolocation most often concerned bats and dolphins; however, there is a recent increase in effort to study human echolocation and other navigational techniques to inform navigation devices for the visually impaired population (Kolarik et al., 2014).

Echolocation is one of several navigational options for visually impaired individuals. The long cane, which is held by the user and rests on the ground in front of them, is commonly used to detect obstacles and identify steps and other drop-offs. By tapping the cane on the ground, visually impaired individuals can detect and localize objects in front of them; however, this task is difficult to perform solely on the basis of the tapping sounds (Schenkman & Jansson, 1986). Another common mobility tool is the guide dog, which performs many of the same functions as the long cane. The dog is trained to take direct paths between objects, often making it more efficient than the long cane. In recent years, electronic tools have been developed to supplement these tools. Sonar attachments to long canes, laser-based devices, and GPS-based devices extend the range of detection and identification (Giudice & Legge, 2008).

Although these tools are very useful, they have drawbacks. Both the long cane and guide dog require the use of the hands and can sometimes be unwieldy. In addition, the long cane and guide dog are limited in their detection such that they are most effective in perceiving proximal objects. Furthermore, tapping sounds from a long cane may be difficult to interpret depending on the type of cane and the size of reflecting objects (Schenkman & Jansson, 2008). Supplementary sensory devices can extend the range of detection; however, these devices can be quite expensive. Their signals and interfaces may also be difficult for users to learn, and it may take considerable training before effective use can occur (Giudice & Legge, 2008).

Echolocation using tongue clicks, however, does not have these drawbacks. The only devices necessary are the head, mouth, and ears, so echolocation is neither expensive nor unwieldy. Furthermore, although the sounds emitted by long canes can vary as a result of several factors, echolocators have substantial control over their own tongue clicks. They can also move their head in order to emit clicks in varying directions, which allows them to more precisely detect objects on their left or right. For these reasons, training to use echolocation can help many visually impaired people navigate independently.

Despite these positives, echolocation is not a commonly used mobility tool, probably because it is an acoustically difficult task. In a reverberant environment, when a tongue click is produced, it reflects off of the surrounding objects. When it returns to the ears, several binaural computations occur to determine information about the sound. A sound coming from the left side of the listener, for example, arrives at the left ear before arriving at the right ear (Moore, 2012, pg. 247). These interaural time differences (ITDs), on the order of microseconds, are computed by the brainstem as sound arrives to either ear. Additionally, sound loses intensity, and therefore loudness, the longer it travels (Moore, 2012, pg. 247). Sound further loses intensity when it reaches the ears because, depending on the frequency of the sound, the head may cast a “shadow” on the sound, making it even quieter. These interaural level differences (ILDs) are another source of information used to localize sound

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information. Furthermore, individuals' outer ears, or pinnae, are uniquely shaped to amplify certain frequencies and attenuate others. Moreover, the location of a listener's head, relative to a sound source, will alter the sound arriving at the ears. Both the head and pinna come together to form a complex direction-dependent filter (Moore, 2012, pg. 264). This filtering of incoming sound is known as a head-related transfer function (HRTF), and it can predict how sound from a certain direction or location will be localized by a certain listener. These computations occur simultaneously for all incoming sounds, and in a reverberant environment, it can be difficult to localize the various overlapping sounds.

The echoes of clicks, specifically, are difficult to localize due to the precedence effect. First described by Wallach and colleagues, the precedence effect describes the localization of two sounds occurring in short succession. When two similar sounds with a small delay between them are played from different locations, both are heard to have come from the location of the first sound (Wallach et al., 1949). This gives precedence to the location of the first sound. As an echo is simply a quieter version of a referent click, the precedence effect clearly applies to echolocation. An alternative definition of the precedence effect is that it suppresses the location information of the second sound. This effect has been quantified in an echolocation context by Wallmeier and colleagues, where participants localized echoes reflected by a single sound reflector and the leading and lagging of two reflectors (Wallmeier, et al., 2013). Surprisingly, they found that the leading and lagging reflectors seemed to have equal precedence, when one would expect the leading reflector to have precedence. This shows a difference from the normal precedence effect in echolocation, and it provides justification for the success of trained echolocators.

It has been shown that blind and sighted individuals have different spatial hearing abilities. Early-blind individuals have been shown to localize binaural sounds as well as or better than sighted individuals (Lessard et al., 1998). More interestingly, the same study also showed that early-blind individuals localize monaural sounds, or sounds presented to only one ear, much better than sighted subjects. This result indicates that blind individuals may be more aware of spectral cues in sounds and that they use those cues to localize sounds. These results hold for late-blind individuals as well (Fieger et al., 2006). This increased sensitivity is thought to occur as a result of the reorganization of cortex that follows a total loss of visual information, resulting in auditory spatial information being processed in the visual system (Collignon et al., 2009; Voss et al., 2011).

Furthermore, blind individuals have also been shown to have higher sensitivity to non-self-generated echo cues. Dufour et al. (2005) compared blind and sighted individuals on a left/right discrimination task of sounds reflected by a wooden board, and the blind subjects showed significantly better performance. Additionally, the two groups of participants also performed a localization task, where blind participants performed better than sighted participants at the task when they were closer to a wall than when they were in the center of a room. This suggests that the blind participants were sensitive to echo cues from the walls, which led to better task performance, while the sighted participants were not.

However, not all studies show this pattern of results. Congenitally blind individuals have also been shown to perform worse than sighted individuals in a spatial bisection task, with several performing at chance (Gori et al., 2014; Vercillo et al., 2015). However, these individuals perform as well as sighted individuals in a minimum audible angle task, suggesting that the deficit is specific to the spatial bisection task. In the same study, Vercillo et al. showed that blind expert echolocators had even higher spatial acuity than the sighted participants (Vercillo et al., 2015). This suggests that although blind individuals may have enhanced spatial hearing in some tasks, this does not apply to all tasks. As spatial bisection tasks are designed to test the calibration of auditory spatial maps, these results suggest that these maps may be impaired in blind individuals (Gori et al., 2014).

Surprisingly, both blind and sighted individuals can be trained to echolocate. Studies comparing the two populations often compare blind expert echolocators, blind non-echolocators, and sighted individuals. Teng and Whitney (2011) showed that after four hours of training, sighted participants could use self-generated clicks to discriminate the size of an object as well as a blind expert echolocator could. Additionally, Schenkman and Nilsson (2010) showed that blind participants were better able to report a sound that had been recorded in the presence of a reflecting object, compared to sighted participants; however, both blind and sighted participants could perform the task after training.

Although it has been shown that both blind and sighted individuals can perform simple echolocation tasks, the majority of them have to be trained before they can do so. For individuals who use echolocation on a daily basis, this training process can take many years. We hypothesized that blind and sighted individuals would be able to discriminate enhanced echoes, echoes that may be easier to learn, with little training. As echolocation has been shown to have functional benefits for its users, the process by which individuals become proficient echolocators would ideally be as easy as possible (Thaler, 2013). In this study, we investigated whether blind and sighted individuals can discriminate these enhanced echoes in a variety of discrimination tasks and whether there is any difference in discrimination ability between the two groups. Participants discriminated close echoes from far echoes and left echoes from right echoes. Based on the described enhanced spatial ability of blind individuals, we hypothesize that they will perform better at these tasks than sighted individuals.

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Methods

Participants: We tested 18 sighted individuals and 8 blind individuals in this study. The sighted participants (mean age 19.2 years, SD 1.25; 7 male) were Carnegie Mellon undergraduates who were recruited through an online participant pool. They were given course credit for their participation. Nine of these participants had prior musical experience or training. The blind participants (mean age 55.6 years, SD 7.69; 6 male) were recruited via email through the Pittsburgh Blind and Vision Rehabilitation Services. Six of these participants had prior musical experience or training. They were paid for their participation.

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Consent: The participants responded to a questionnaire asking demographic information, their level of music training, and their experiences using environmental sounds to navigate. All participants also verified via self-report that they had normal hearing. In addition, the blind participants provided information about the length of their blindness and its extent. Written consent was obtained from all participants, and the study protocol was approved by the Carnegie Mellon Institutional Review Board (IRB).

Stimuli: Palatal mouth **referent clicks**, recorded by undergraduates, were used as a foundation for the stimuli. These clicks were recorded in an empty echo treated, sound attenuating chamber at Carnegie Mellon University with Roland CS-10EM binaural microphones. Over 50 clicks were recorded, but only the 17 clicks with waveforms similar to the palatal clicks described by Rojas were used (Rojas 2009). A custom echo generation program, written in Matlab, was applied to each of these clicks to generate realistic echoes. The echo was generated by copying the referent click. A delay between the referent and the echo, corresponding to the distance of the reflecting object, was then implemented. The

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referent sound travels to the reflecting object and back to the listener before it is interpreted as an echo, so it travels twice the distance between the listener and the object. Then, using a speed of sound of 343 m/s, an echo from an object 5 m away, for example, would occur 29 milliseconds ((2 * 5) m / 343 m/s) after the onset of the referent. In addition, ILDs were implemented in the left and right channels by attenuating one channel according to the angle and distance of the reflecting object. The maximum ILD, used when an object was 90º to the left or right, was 10 dB. ILDs for angles between 0º and 90º were ((1/9) * angle) dB, and the level of the echo decreased in both channels by an additional 6 dB each time distance was doubled relative to 1m. For example, then, an echo 90º to the left, 2m away, would be attenuated in the right channel by 10 dB from the ILD and by an additional 6 dB due to the 2m distance for a total of 16 dB of attenuation compared to the left channel. Following our hypothesis, echoes were then amplified by either 3 or 6 dB, depending on the condition of the experiment. Determination of the echo levels at which the tasks could be performed at a medium difficulty level for the average person occurred during pilot testing. Echoes were generated at every 10-degree interval between -90º (90º to the left) and +90 (90º to the right). In addition, echoes were generated at distances between 1 and 5 meters at 0.5-meter increments. Within one trial, the reference click was the same for both intervals; the only difference between the intervals was the timing and level of the echo that accompanied each click. Between trials, clicks were chosen randomly from the 17 clicks described previously.

Procedure: After providing written consent and demographic information, participants were informed about the structure of the tasks and were given the opportunity to ask questions. They were also instructed not to focus on any one cue in the stimuli and to close their eyes during the experiment. They performed the experiment while seated at a computer in the aforementioned listening chamber. Participants listened to the stimuli through Sennheiser HD 600 headphones.

There were two main tasks: distance and left/right. All participants performed these tasks in the described order. Each of these tasks was a 2-interval forced choice (2IFC) task in which the order of the intervals was randomized. During the distance task, each interval of a trial contained a referent click, which was centered (no ILDs were applied) and whose channels were normalized relative to each other, followed by an echo generated according to the aforementioned parameters. All echoes in this condition were amplified by 3 dB. Within a trial, the angle of both echoes varied between -90º and +90º at 10-degree increments. Angles were randomly chosen between trials. Participants discriminated a click with a close echo from a click with a far echo and reported which interval, 1 or 2, contained the closer echo by pressing the corresponding key. The close echo had a distance of 1m in all trials.

Each interval in the left/right condition contained a referent click from 1m away followed by an echo. All echoes in this condition were amplified by 6 dB; however, if participants performed extremely well in the 6 dB condition, they performed the same task but with the echoes amplified at 3 dB. Participants discriminated a click with a left echo from a click with a right echo. In the left/right condition, participants reported whether the echoes in the two intervals moved from right to left or from left to right by pressing the 1 or 2 key, respectively.

Additionally, participants performed a lateralization task between the distance and left/right tasks. This condition was similar to the left/right task; however, the clicks in this condition contained no echoes. Click angle varied from -90º to +90º at 10-degree increments. This task served as a measure of baseline left/right discrimination performance. Results from pilot testing showed that if participants could not lateralize a click without an echo, they could not lateralize an echo itself. Therefore, if participants could not perform the left/right task, the lateralization task helped determine whether this performance was due to an inability to lateralize echoes specifically or an inability to lateralize sounds in general.

During each trial of the 2IFC tasks, participants were shown a sentence reminding them of the correct key presses ("Which click contained the closer echo? (1 2)" in the distance condition, for example). They then heard two clicks separated by 500 ms of silence. For example, a trial in the distance condition could contain a click with an echo from 1 m away, followed by 500 ms of silence, followed by a click with an echo from 4.5 m away. The next trial was determined using a three-down-one-up staircase paradigm (Leek et al., 2001). The staircase paradigm allowed for the determination of a threshold at which participants responded accurately to about 78% of the trials. At the beginning of all three conditions, the staircases started at the easiest level (distance: 5m, lateralization and left/right: 90 degrees). If participants correctly answered three trials in a row, the subsequent trial increased in difficulty by one level. If participants incorrectly answered a single trial, the subsequent trial decreased in difficulty by one level. The track ended after 11 reversals were observed or if the track lasted for over 70 trials without 11 reversals. Here, reversals are defined to be points during the track where participants answered correctly three times after answering incorrectly on the previous trial, or points where participants answered incorrectly once after answering correctly on the previous trial, as indicated in Figure 1. Participants performed 2-5 tracks per condition, totaling an hour of testing time for all three conditions. A threshold for each track was calculated by computing the average of the final 6 reversals, as shown on Figure 1 in solid circles. A condition average for each participant was calculated by computing the average of each of that participant's tracks. If the track did not contain 6 reversals or if the participant performed more than 3 trials at the easiest level during any

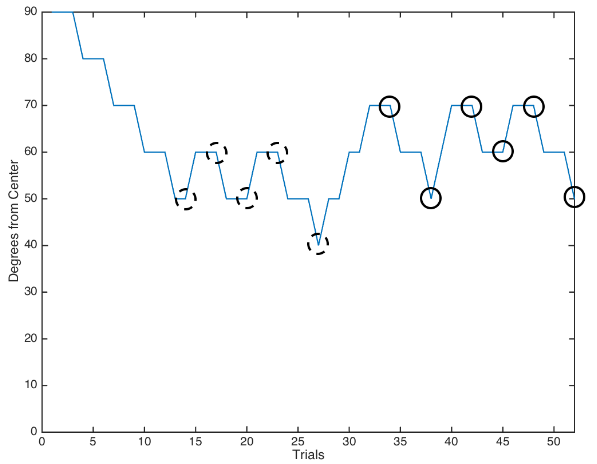

Figure 1. A typical track in which reversals are circled. The track ends after 11 reversals have completed. Reversals averaged to obtain the threshold calculation are circled with a solid line.

given reversal in the last 6 reversals, that track was not included in the participant's threshold calculation.

Statistical Tests: We ran a mixed model ANOVA with Bonferroni post-hoc corrections for the two echo discrimination tasks (distance, left/right) and two participant groups (blind, sighted) to test whether there was an interaction between sightedness and task performance. We followed up the ANOVA with independent samples t-tests for each of the two tasks to test the differences between groups in each task. In addition, we correlated distance thresholds with left/right thresholds. As several of our participants were musically trained, we included musicianship as a binary, between-subjects variable. We then performed a mixed model ANOVA on only the musically trained participants to determine whether the same trend was found in this group of participants as in the overall group of participants. To determine the extent to which left/right performance could be explained by lateralization

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performance, we ran an ANCOVA including lateralization as a covariate. Finally, we tested whether the distributions of thresholds in the two groups were significantly different with a chi-square goodness of fit test.

Results

Covariates considered were age, gender, and musicianship. Because the blind group was significantly older than the sighted group, age was a natural covariate included in the group variable, so a separate analysis of it would be redundant. The small sample size and skewed gender ratios among groups made gender highly correlated with sight so that gender as a covariate removed effects of sightedness. Musicianship is discussed later in this section.

Per our track exclusion criteria, 4 participants in the blind group and 7 participants in the sighted group obtained no valid tracks for one or both tasks. We included these participants in the omnibus ANOVA with maximum threshold values (5 for distance; 90 for left/right). The inclusion of these participants more accurately represents the distribution of task performance in both groups. In addition, we performed an ANOVA with only the participants who obtained valid tracks for both tasks, which determines whether sightedness played a role among participants who could perform the tasks.

In the omnibus mixed model ANOVA, we found a trivially significant effect of task ($F(1, 20) = 45.252$, $p < 0.0005$). As the distance task was measured on a significantly smaller scale than the left/right task, it does not make sense to directly compare the means of the two tasks. We found no main effects of sightedness ($F(1, 20) = 1.287$, $p = 0.27$) or musicianship ($F(1, 20) = 2.859$, $p = 0.106$). Additionally, there was no interaction between task and sightedness ($F(1, 20) = 2.021$, $p = 0.171$) or task and musicianship ($F(1, 20) = 2.557$, $p = 0.125$). As musicianship did not significantly affect the results, we tested musically

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trained participants in a separate ANOVA and removed this factor from the overall ANOVA.

After removing musicianship, we found a marginally significant main effect of sightedness (F(1, 22) = 3.413, p = 0.078). In addition, we found a significant interaction of task and sightedness (F(1, 22) = 4.628, p = 0.043). This interaction manifested in 21.6º better thresholds in the left/right task in the blind group and 1m better thresholds in the distance task in the sighted group, as lower thresholds indicate better performance. These differences are shown in Figures 2a and 2b. However, in post-hoc t-tests, neither differences were quite significant; both were marginally significant (distance: t(22) = 1.8218, p = 0.082; left/right: t(22) = 1.9959, p = 0.059).

Among participants who obtained valid thresholds for both tasks, we found a marginally significant main effect of sightedness (F(1, 13) = 4.284, p = 0.059). Additionally, there was a significant interaction of task and sightedness (F(1, 13) = 5.256, p = 0.039). Distance thresholds between the two groups were not significantly different (t(13) = 1.094, p = 0.294); however, left/right thresholds between groups were significantly different (t(13) = -2.180, p = 0.048). These differences are shown in Figures 2c and 2d.

Among all participants, distance thresholds and left/right thresholds were not significantly correlated across sightedness (r = 0.303, t(24) = 1.557). This correlation is shown in Figure 3a. Distance and left/right thresholds were also not correlated across sightedness among participants who could perform the tasks (r = 0.268, t(13) = 1.004), as seen in Figure 3b. However, distance and left/right threshold were highly correlated for sighted participants who could perform the tasks (r = 0.659, t(9) = 2.318).

In the mixed model ANOVA on the musically trained participants, the pattern of results was not different from those of all participants. There was still a significant main

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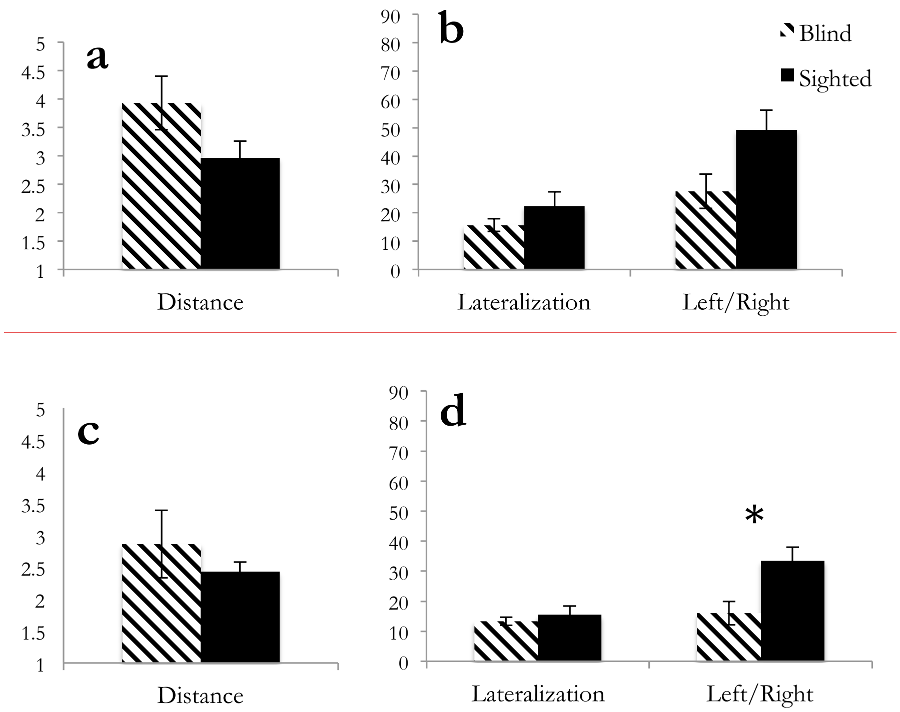

Figure 2. Average thresholds for (a) distance, in meters, for all participants, (b) lateralization and left/right, in degrees, for all participants, (c) distance for only the participants who could perform the tasks, and (d) lateralization and left/right for only the participants who could perform the tasks. Significance (a < 0.05) indicated with an asterisk. Error bars indicate mean standard error.

effect of task ($F(1, 13) = 22.929$, $p < 0.0005$). The interaction between task and sightedness was marginally significant ($F(1, 13) = 4.239$, $p = 0.06$), indicating that when musicianship was no longer a factor, there was still an effect of sightedness. Additionally, blind and sighted mean thresholds for both tasks among musically trained participants did not differ from those among all participants (blind, distance: $t(12) = 0.4845$, $p = .6368$; sighted, distance: $t(23) = .7095$, $p = .4851$; blind, left/right: $t(12) = .8988$, $p = .3864$; sighted, left/right: $t(23) = .3746$, $p = .7114$).

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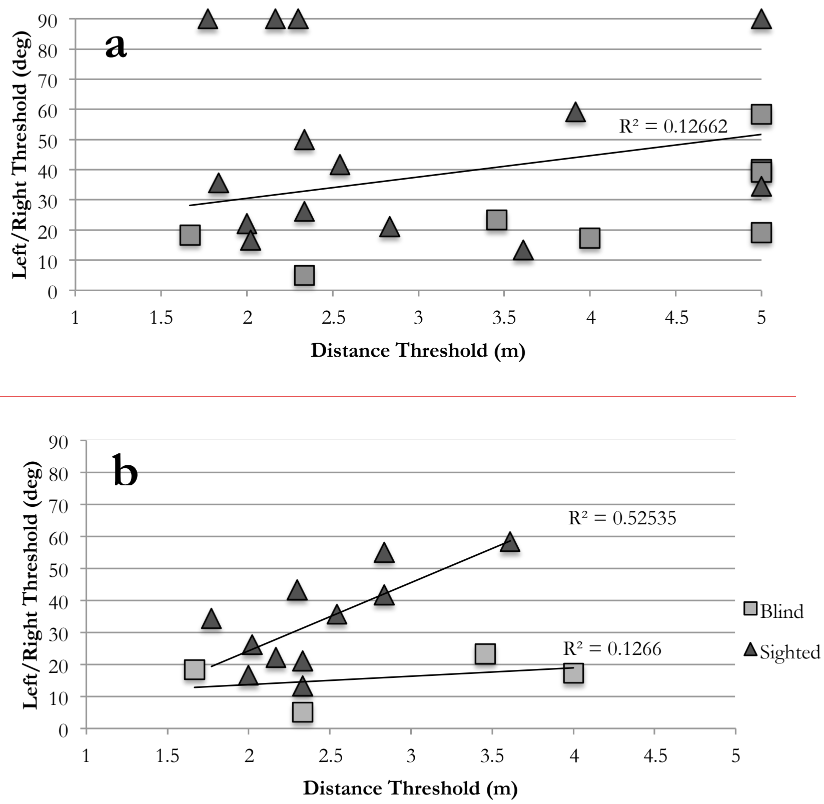

Figure 3. (a) Correlation of distance thresholds with left/right thresholds for all participants. (b) Correlation of distance thresholds with left/right thresholds for only those participants who could perform the tasks.

In the ANCOVA investigating the covariance between lateralization and left/right performance for all participants, we found a highly significant interaction between lateralization and echo task ($F(1, 21) = 12.95$, $p = 0.002$). Despite this interaction, we still found a marginally significant interaction between task and sightedness ($F(1, 21) = 3.698$, $p = 0.068$). This suggests that although much of the variance in left/right echo discrimination can be explained by a common factor (such as spatial ability) that also affects lateralization

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performance of sound sources without echoes, sightedness still had an effect on echo discrimination performance.

When we performed this ANCOVA with participants who could perform both tasks, we again found a highly significant interaction between lateralization and echo task (*F*(1, 12) = 10.031, *p* = 0.008). Despite this interaction, task and sightedness significantly interacted (*F*(1, 12) = 6.707, *p* = 0.024). We draw the same conclusion from these results as we did for the previous results: sightedness is still a factor in echo discrimination performance even when that performance can be somewhat explained by lateralization threshold.

According to the chi-square goodness of fit test, the distributions of thresholds in the two groups were significantly different in both the distance and left/right tasks ($\chi_{2\,(0.05)}(3) = 7.815$; distance: $\chi_2(3) = 8.0833$; left/right: $\chi_2(3) = 9.3000$), but not in the lateralization condition ($\chi_2 = 6.6545$).

Discussion

In this study, we investigated the performances of blind and sighted individuals on echolocation tasks involving enhanced echoes. Without providing prior training to participants, we were able to find group differences on a distance echolocation task and a left/right echolocation task. Blind participants had marginally lower thresholds in the left/right task, and sighted participants had marginally lower thresholds in the distance task. These results were not explained by prior musical experience or training. Among participants who successfully performed the echo discrimination tasks, blind participants had significantly lower thresholds in the left/right task while sighted participants had marginally

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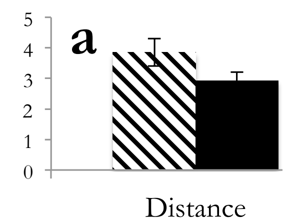

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lower thresholds in the distance task. Some of the left/right performance was explained by general lateralization ability; however, there was still an effect of sightedness.

Because of the evidence supporting enhanced blind spatial hearing mentioned earlier, the fact that blind participants had lower thresholds in the left/right task is not surprising. Blind individuals are more reliant than sighted individuals on auditory information for spatial navigation, so it is possible that this reliance results in a higher sensitivity to echo information (Voss et al., 2011; Dufour et al., 2005). If this is the case, it is likely that with additional training, our group of sighted participants could have approached the thresholds attained by the blind participants.

However, we did not expect that sighted participants would have lower thresholds in the distance task. As no sighted participants reported using auditory information while navigating in daily life, we are unsure of the causes for this result. It was additionally surprising that several of the blind participants had thresholds of 4.5 meters or above, essentially indicating that those participants could not distinguish close echoes from far echoes. This also shows widely varying performance within our sample. We hypothesize that this may have occurred for several reasons. First, blind individuals may not rely as heavily on auditory distance cues at such high distances, as their mobility devices that provide auditory distance cues, such as the long cane, only give information about proximal obstacles. In this case, however, our blind participants should have been easily able to recognize a close echo. Second, blind individuals may not use distance cues in the form that we presented in our stimuli. Finally, as the echo level in the distance task was 3 dB lower than that in the left/right task, which was informed by pilot data, it is possible that age-related hearing differences among the blind participants may have prevented them from hearing the echo at all, making the task impossible. We further discuss issues with hearing loss later in this

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section. If this were the case, more research would be required to test these participants with louder echoes to determine whether task performance would increase.

The majority of participants were able, with no prior training, to discriminate echo angles and distances. The thresholds in the lateralization task were used as a baseline, given that lateralization was included as a control measure. Left/right thresholds were, on average, a mere 15° higher than the corresponding lateralization thresholds. This supports our hypothesis that these echoes would be useful in introducing naïve individuals to echolocation training. In particular, as echolocators became more proficient, we would make the echoes more like those one would hear in real life to transition them to harder echoes. In future experiments, we will attempt to determine the effectiveness of training with enhanced echoes on performance in an active echo localization task.

In this study, the only echo cues included in the stimuli were ILDs. However, people also rely heavily on ITDs and HRTFs to localize sound, and the inclusion of those cues would make the echoes more comparable to those one would hear in daily life. If participants were accustomed to hearing those other cues when making judgments about echoes in daily life, the lack of them in our stimuli may have been confusing. In future research, we plan to create stimuli with those cues, as well as more realistic room impulse responses, in order to more accurately simulate auditory spatial information.

As previously mentioned, the two groups differed significantly in age and education level. The age difference manifests most relevantly in potential hearing differences between the two groups. Hearing ability on average decreases with age of a population. Although self-report of hearing loss is reliable (Sindhusake et al., 2001), and none of the participants in this study reported any hearing loss, blind participants may have had slight hearing loss of which they were unaware. We did not systematically measure the hearing abilities of all participants.

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As previously mentioned, this may have accounted for performance differences in the distance task, as the blind participants may not have been able to hear the echoes. Our sighted participants may have also had slight hearing loss; however, the participants were much younger, making hearing loss at that age much less likely. In the future, we plan to use better matched groups so that factors like age and education level would not affect echo discrimination performance.

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Many of the studies mentioned earlier compared early-blind individuals with late-blind individuals (Fieger et al., 2006; Gori et al., 2014; Lessard et al., 1998). Additionally, it has been shown that within blind expert echolocators, there is a strong correlation between age of blindness onset and echolocation acuity (Teng et al., 2012). As our sample size was small, we did not run an analysis on the effect of age of blindness onset on performance. In future studies, we would like to determine whether age has an effect in the discrimination of these enhanced echoes.

In conclusion, we determined the thresholds of blind and sighted participants using enhanced echoes in two echo discrimination tasks, one discriminating distance and the other discriminating left/right. We found surprising group differences, as the blind participants were able to better discriminate left/right echoes while the sighted participants were able to better discriminate distance echoes. These enhanced echoes may be useful in training new echolocators and more quickly familiarizing them with the echo cues necessary to perform echolocation in daily life.

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