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Novel Stimuli to Benchmark and Train Echolocation Skills

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Abstract

Echolocation is a remarkable skill used by some blind people to navigate their surroundings by interpreting echoes from self-made sounds such as mouth clicks. Despite its potential to significantly improve blind travelers' navigational independence and quality of life (Thaler; Norman, Dodsworth, et al.), echolocation remains largely underutilized. This is partly due to limited understanding of its benefits and mechanisms, as well as its steep learning curve and the lack of optimal sensory cues for training. This study describes a carefully designed set of sounds that manipulate specific temporal cues for improved spatial perception, making echolocation more accessible to beginners and potentially speeding up the learning process. These stimuli and findings could be used to develop targeted training programs to accelerate beginners' learning, raise awareness, and promote their teaching more broadly. Furthermore, incorporating these stimuli into echolocation-based assistive devices, virtual platforms, and environments could broaden the reach and impact of echolocation on the lives of blind and visually impaired people.

Keywords

Echolocation, blindness, low vision, mobility & orientation, navigation, training

Introduction

Echolocation is an active sensing strategy that allows blind people to navigate their surroundings. Human echolocators typically emit whistles, hisses, claps, or mouth clicks, whose echoes allow them to detect, discriminate, and localize objects in the environment (Thaler and Goodale; Kellog). Expert blind echolocators typically outperform non-expert blind and sighted individuals in various echo-acoustic tasks, including object detection, object discrimination, and spatial localization (Teng, Danforth, et al.; B. Schenkman and Nilsson; B. N. Schenkman and Nilsson; Kolarik et al.; Teng and Whitney; Teng, Puri, et al.; Rice). While visual experience and echolocation expertise play a significant role in echolocation performance, it remains unclear what precise perceptual processes lead to this advantage. One possibility is that non-experts struggle to differentiate between their own emissions and the returning echoes, particularly in complex localization scenarios (Garcia-Lazaro and Teng; Tirado, Gerdfeldter, Kärnekull, et al.). For example, an echolocation click reflecting from a surface 1 m away will return to the observer in about 6 ms, well within the range of the click duration itself (Schörnich et al.), posing challenges to segregate the uninformative click from the informative but much fainter echo.

Research suggests that sound segregation is facilitated by blindness and training (Park and Fine; Boroujeni et al.; Arias et al.; L. Thaler et al.) and that echoes are easier to localize at greater distances (Tirado, Gerdfeldter, and Nilsson). Expert blind echolocators, in particular, may excel at this because their hearing is finely tuned (Röder et al.), allowing them to separate and interpret individual clicks and echoes more effectively. Similarly, research on echolocation-based assistive device prototypes has shown that artificially slowing down and lowering the frequency of ultrasonic echoes could provide novice users with high spatial resolution information even in noisy environments (Reynolds and Teng; Sohl-Dickstein et al.; Ifukube et al.). Taken together, this research suggests that making temporal information more available can make echolocation more accessible to non-expert practitioners, either as an assistive technique or a training strategy.

Although expert echolocators can attain remarkable spatial acuity and precision, echolocation remains underutilized in broader contexts. Therefore, research should focus on identifying the optimal sensory cues for echolocation training and integrating them effectively into mobility and orientation programs. In this study, we examined whether exposing untrained participants to stimuli designed to increase the click-echo delay—while keeping other acoustic attributes as naturalistic as possible—could improve their spatial localization abilities to a level comparable to that of expert echolocators.

Discussion

This study explored the role of temporal cues in object spatial echolocation. We showed that presenting untrained participants with stimuli specifically designed to increase the click-echo delay—without altering echo intensity—can enhance spatial localization in naive-sighted individuals, bringing their performance closer to that of expert echolocators. These findings underscore the potential of carefully calibrated stimuli to accelerate learning in beginners.

Approach

Stimulus design and testing. We created a series of well-calibrated sounds (clicks and spatialized echoes, Figure 1A), with the time delay between the click and its echo gradually increasing to simulate distances from 1 to 10 meters (1, 2, 4, 6, 8, and 10 m). Clicks were modeled on expert echolocators' recorded clicks (Lore Thaler et al.), and echoes were binaurally spatialized to simulate reflections from an object 1 meter distant, from 5° to 25° to the left or right of center using KEMAR Head-Related Impulse Responses (HRIR) (Gardner and Martin), see Figure 1A. In natural conditions, as distance increases, the echo signal decays as well; however, in this experiment, we kept echo intensity constant, corresponding to a distance of 1 m, while varying the click-echo delay up to ~58.3 ms (corresponding to 10 m) to selectively isolate the effect of increased delay on spatial localization on each condition without altering other acoustic properties (Figure 1B).

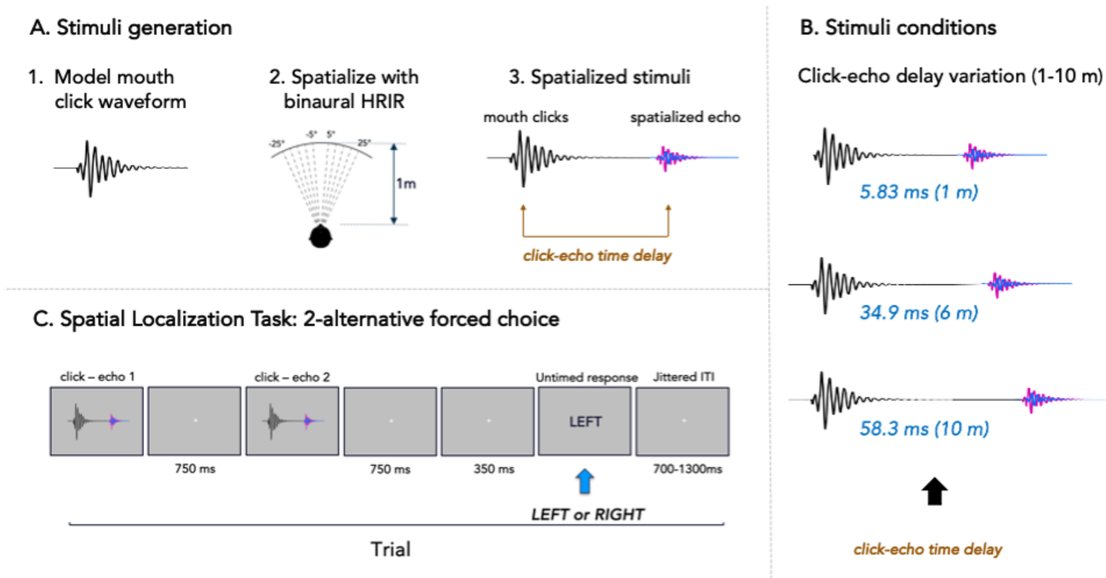

Fig. 1. Stimuli and Task.

A: Stimulus generation. B: Stimulus conditions. C: Spatial localization task.

We tested these stimulus sets on ten sighted participants (mean age = 29 years, range = 18-45 years, 6 male) with no prior echolocation experience. All participants had normal hearing, assessed by pure tone audiometry (250–8000 Hz), and provided informed written consent in accordance with our protocol approved by the Smith-Kettlewell Eye Research Institute Institutional Review Board. The experiment was conducted in a darkened, sound-damped testing booth (Vocalbooth, Bend, OR). Stimuli were binaural and presented dichotically through tubal-insert earphones (Etymotic ER-3A). We used the MOTU UltraLite Mk4 Audio Interface (MOTU Inc., Cambridge, MA) between the stimulation computer and the earphones to ensure precise timing of the auditory stimuli. Auditory stimuli were presented at 64.07 dB SPL. Participants sat 57 cm from a 27" display (Asus ROG Swift PG278QR, Asus, Taipei, Taiwan). We used Psychtoolbox-3 (Pelli) and the audio processing toolbox running in Matlab 2021b (The Mathworks, Natick, MA) for stimulus creation and presentation. Participants completed a two-alternative forced choice (2AFC) task of 6 blocks of 40 trials, spanning all click-echo temporal gap conditions. They listened to repetitions of 2, 5, 8, or 11 stimuli (click-echo) and indicated whether the object was to the left or right (Figure 1), similar to (Garcia-Lazaro and Teng).

Object Spatial Localization is Facilitated when the Click-echo Delay Increases

Our results showed that under natural conditions at a 1-meter distance, untrained sighted participants struggled to accurately locate objects based on echoes (58.9%). This is consistent with our previous findings (Garcia-Lazaro and Teng) comparing blind expert echolocators and novices in a similar task and distance (1 m). However, as the delay between clicks and echoes increased, participants more accurately identified the object's position ($F(5,45) = 7.62$, $p < 0.001$). Untrained individuals reliably localized the reflection at click-echo delays of 11.6 ms ($t = 1.64$, $p < 0.0083$), 23 ms ($t = 1.86$, $p < 0.0083$), 35 ms ($t = 2.09$, $p < 0.0083$), 46.6 ms ($t = 3.13$, $p < 0.0083$), and 58.3 ms ($t = 2.95$, $p < 0.0083$), as demonstrated in Figure 2A. These findings suggest that longer click-echo delays significantly aid spatial localization for individuals new to echolocation.

To further examine these findings, we fitted a parametric (Weibull) psychometric function to results for each participant across the six click-echo conditions, as well as a pooled psychometric function at the group level. This allowed us to compute performance thresholds, defined s as the click-echo delay at which participants correctly identified the object's location 75% of the time. The lapse rate was fixed at 1%, while the slope, width, and threshold were treated as free parameters. Figure 2B displays individual psychometric functions (gray shades) alongside the group-level function (black). The group analysis showed that at 34.8 ms delay (corresponding to a 6-meter distance), untrained participants localized objects with 75% accuracy. This confirms that longer click-echo delays significantly improve spatial localization for novices in echolocation.

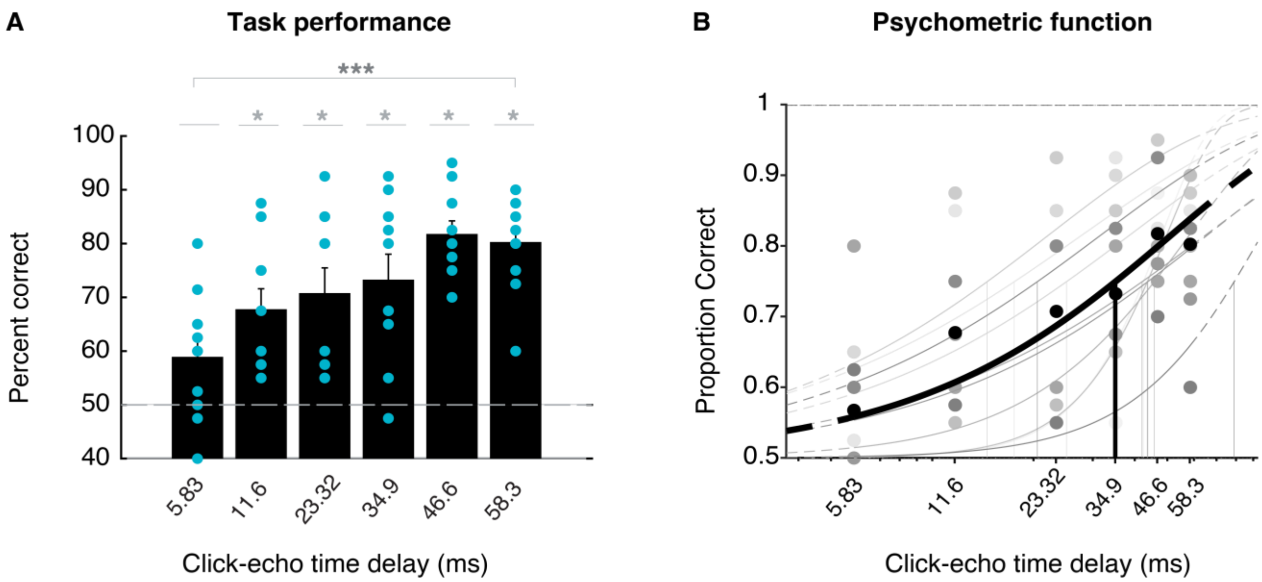

Fig. 2. Task performance across click-echo delay conditions.

Furthermore, we investigated the extent to which the click-echo delays influenced spatial acuity: the degree to which echoes farther from the midline are easier to localize. We aggregated trials from contiguous pairs of conditions to form three distinct groups: *long delays* (46.6 ms and 58.3 ms, corresponding to 8 and 10 meters), *intermediate delays* (23.32 ms and 34.9 ms, corresponding to 4 and 6 meters), and *short delays* (5.83 ms and 11.6 ms, corresponding to 1 and 2 meters). We fitted individual and group-level psychometric functions for azimuthal eccentricity for the three groups of trials.

Spatial acuity varied between individuals and across delay conditions, as shown by individual (thin lines) and group-level psychometric functions (thick lines) in Figure 3A. The three delay conditions are represented as follows: *short delays* in cyan, *intermediate delays* in light blue, and *long delays* in dark blue. The degree of improvement in spatial acuity varied among individuals; however, overall thresholds decreased as the click-echo delay increased (*short delays* = 27.56°, *intermediate delays* = 21.12°, and *long delays = 13.23*°, ($F(2,27) = 6.30$, $p < 0.01$), as illustrated in Figure 3B. To further explore the relationship between click-echo delays and spatial acuity, we fitted a linear model to individual thresholds from the three groups of trials. The linear fit, plotted in magenta in Figure 3B, indicates a systematic improvement in spatial precision as the delay increased. When delays were short (5.83 & 11.6 ms), untrained individuals exhibited a baseline spatial precision of around ~ 27.3° (cyan), which progressively improved with longer delays. This relationship is captured by the equation:

Thresholds = -5.78 x click-echo delay + 31.51, broadly suggesting nearly 6° more precise spatial precision at successively longer delay categories.

Spatial Localization Acuity: Sighted Novices vs. Blind Experts in Comparable Conditions

Next, we compared the spatial localization acuity of untrained individuals at the two above-threshold conditions (the *long click-echo delays*) to that of an expert echolocator who performed the same task with high accuracy (92.81%), but with stimuli in unmodified natural conditions (click-echo delay of 5.83 ms, corresponding to 1 meter) (Garcia-Lazaro and Teng). The expert echolocator showed a spatial precision of 4.71° (green psychometric function in Figure 3A), compared to 13.19° for untrained individuals in the above threshold conditions (long delay in dark blue). It is important to note that while the spatial localization tasks were identical, untrained sighted controls listened to stimuli with *long click-echo delays* (8 and 10 meters), whereas expert echolocator heard stimuli at a 1-meter distance without manipulation. The higher task accuracy in novice-sighted participants in the long delays without previous training underscores the potential of these novel stimuli. Moreover, the performance gap between novices at the long delays and the expert echolocators highlights the capacity for growth in naive participants, suggesting that with proper training, individuals who initially struggle with echolocation could enhance their spatial precision to approach or even reach expert-level performance. Additionally, this comparison highlights the significant advantage gained through expertise, offering insight into how much improvement can be expected from future well-structured training programs.

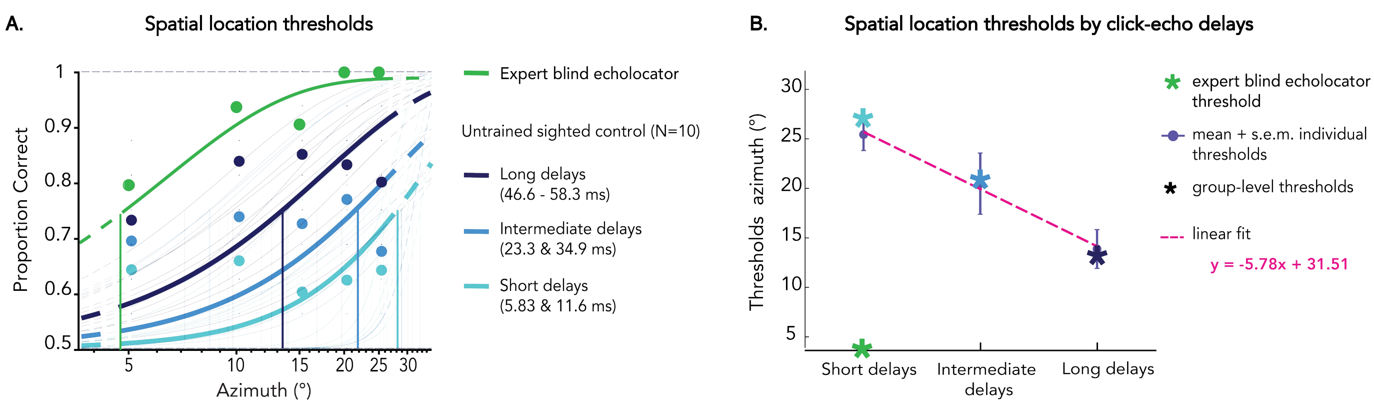

Fig. 3. Relationship between click-echo delays and spatial acuity.

Our results underscore the critical role of click-echo segregation in facilitating spatial echolocation. Unlike most previous studies, which mostly compared expert blind echolocators with sighted people to show differences due to visual experience, our research shows that carefully calibrating temporal cues can aid echolocalization without training, even in novice individuals, regardless of visual status.

Existing research has shed light on the neural plasticity and auditory adaptations associated with vision loss, revealing mechanisms that may underlie the outstanding proficiency in auditory spatial tasks observed in some blind individuals (L. Thaler et al.; Vercillo et al.; Norman, Hartley, et al.; Teng and Whitney; Teng, Puri, et al.). Our findings suggest that similar perceptual improvements (e.g., high spatial acuity) can be achieved in novice individuals by tailoring temporal cues and be further improved by guided practice. This perspective aligns with existing research showing comparable learning rates in sighted and blind novices in echolocation training schemes ranging from a few sessions (3–4 sessions, ~1.5 hrs each session, ~ 6 hrs total) (Teng and Whitney; Tonelli et al.) to several sessions (15-20 sessions, 1 to 3 hrs each, ~ 60 hrs total) (Norman, Dodsworth, et al.; Heller et al.).

Taken together, these findings support the notion that echolocation is not an innate skill limited to individuals with specific visual impairments. Echolocation is a trainable skill that can be learned and refined with appropriate stimuli that preserve the natural features of tongue clicks while selectively optimizing temporal cues to enhance echolocation performance. In this vein, our approach offers a way to systematically calibrate optimal individualized training parameters, including duration, frequency, and intensity of practice, and the long-term retention of these skills. These are fertile avenues for further research, as is the role of individual differences, such as age, auditory sensitivity, visual experience, blindness onset, spatial orientation, and use of other orientation & mobility strategies. Although our current findings are promising, we also acknowledge the limitations of our small sample size; future research should expand it and include a more diverse population to enhance the generalizability of our observations.

Additionally, our approach holds the potential for advancing the development of innovative and cutting-edge training tools with applications in real-world settings. Integrating these stimuli into virtual/augmented reality platforms, mobile applications (Bujacz et al.; Heller et al.), and assistive devices (Reynolds and Teng; Sohl-Dickstein et al.; Ifukube et al.) could accelerate the echolocation learning curve.

Conclusion

Echolocation allows blind individuals to perceive and interpret proximal and distal environmental spatial information, offering significant benefits that could be complemented with existing mobility tools and strategies (canes, GPS navigational systems). Our research underscores the critical role of temporal cues in echolocation and highlights the potential of dynamically calibrated click-echo stimuli to accelerate learning for beginners. The improvement in spatial localization achieved by adjusting click-echo delay suggests that targeted training programs can significantly enhance echo perception and interpretation. These findings have substantial implications for developing more effective, evidence-based training. Integrating these stimuli into ergonomic echolocation-assistive devices, virtual platforms, smartphone applications, and other tools could expand the reach and impact of echolocation, enhancing the quality of life and navigational independence of blind individuals. Future developments could further refine these training methods and explore additional factors influencing echolocation performance, potentially leading to more advanced and accessible echolocation training solutions.

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