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Review Paper

Review of Methodologies in Recent Research of Human Echolocation

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The presented review discusses recent research on human echolocation by blind and sighted subjects, aiming to classify and evaluate the methodologies most commonly used when testing active echolocation methods. Most of the reviewed studies compared small groups of both blind and sighted volunteers, although one in four studies used sighted testers only. The most common trial procedure was for volunteers to detect or localize static obstacles, e.g., discs, boards, or walls at distances ranging from a few centimeters to several meters. Other tasks also included comparing or categorizing objects. Few studies utilized walking in real or virtual environments. Most trials were conducted in natural acoustic conditions, as subjects are marginally less likely to correctly echolocate in anechoic or acoustically dampened rooms. Aside from live echolocation tests, other methodologies included the use of binaural recordings, artificial echoes or rendered virtual audio. The sounds most frequently used in the tests were natural sounds such as the palatal mouth click and finger snapping. Several studies have focused on the use of artificially generated sounds, such as noise or synthetic clicks. A promising conclusion from all the reviewed studies is that both blind and sighted persons can efficiently learn echolocation.

Keywords: echolocation; blindness; testing methodology.

1. Introduction

Echolocation is the ability of humans and some animals to locate objects basing on reflected sounds. The research on the ability of humans to echolocate has come a long way since first studies that had to clear up misconceptions about the visually impaired using "facial vision" or "obstacle sense" (Supa *et al.*, 1944). By now, numerous experiments demonstrated the effectiveness of localizing obstacles using various reflected sounds.

Research no longer focuses on proving that echolocation works, but more on how it works, especially from the neurological perspective (Fiehler *et al.*, 2015; Thaler *et al.*, 2011), and on the ways to teach or improve echolocation skills (Fundacja Instytut Rozwoju Regionalnego [FIRR], 2019; Tonelli *et al.*, 2016). Because the consequence of blindness is a serious sensory deprivation one should exploit any possible cues to enhance safe mobility capabilities among the visually impaired. Learning and mastering echolocation skills should be an important part of any rehabilitation programme for the visually impaired. Such programmes might benefit if the mechanisms of echolocation abilities and their limitations are well understood. One can observe an increasing number of publications devoted to human echolocation as shown in Fig. 1.

The methodologies in the recent echolocation studies vary greatly – some researchers conducted their trials predominantly with sighted volunteers (Arias, Ramos, 1997; Rychtarikova *et al.*, 2017; Tonelli *et al.*, 2016), others with various sized groups of blind volunteers (Flanagin *et al.*, 2017; Thaler, Goodale, 2016; Tirado *et al.*, 2019), some including or limiting the studies to echolocation experts (Fiehler *et al.*, 2015; Norman, Thaler, 2018). Some trials were in natural (Bujacz *et al.*, 2018) or anechoic (Schenkman, Nilsson, 2010) conditions, while others utilized recordings (Arias, Ramos, 1997), synthesized echoes (Wallmeier, Wiegrebe, 2014) or vir-

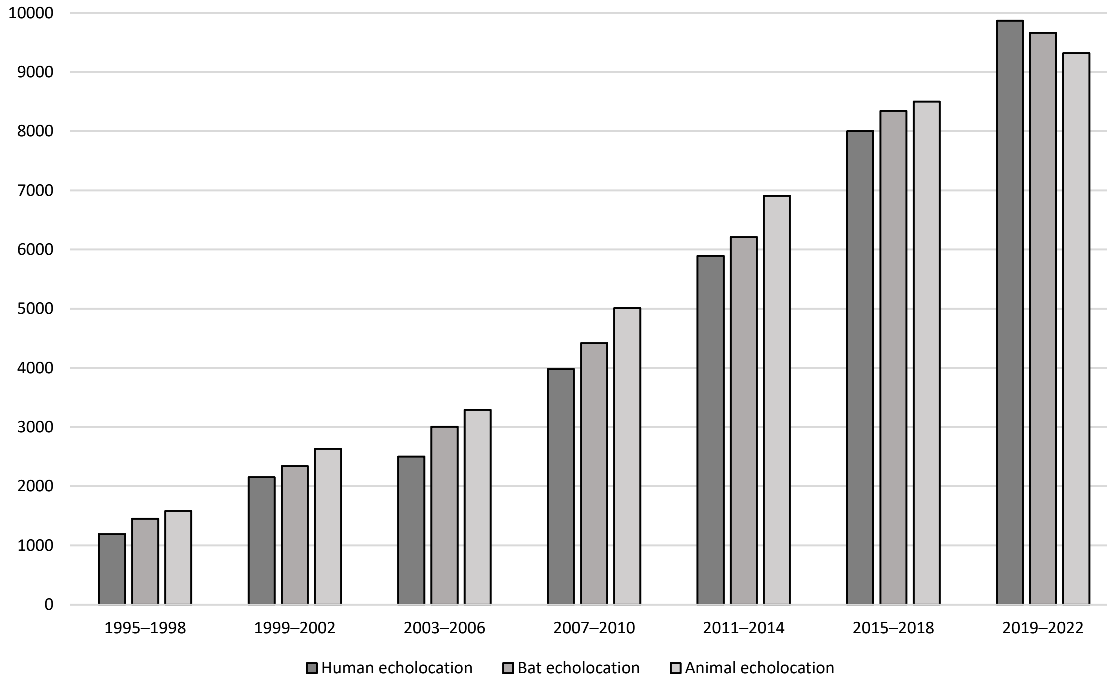


Fig. 1. Number of Google Scholar search results for echolocation related articles and patents.

tual reality environments (Dodsworth *et al.*, 2020). Some studies let volunteers generate their own sound cues (Thaler *et al.*, 2020b) or focused on analyzing those sound cues (Rojas *et al.*, 2009), while others used recordings (Flanagin *et al.*, 2017) or examined the effectiveness of various artificial sounds (Tirado *et al.*, 2019). A full list of compared studies is available in Table 1, then further sections contain smaller summary tables comparing key aspects of the studies.

An emerging issue with human echolocation research is that there has been no common methodology for studying its effectiveness, making it very difficult to compare the outcomes of various studies. Some researchers prefer to use real life tests with obstacles of various sizes (Ekkel *et al.*, 2017) and in different environments (Bujacz *et al.*, 2022a) (e.g., anechoic or semi-anechoic chambers), others synthesize virtual scenes (Arias *et al.*, 2012) or utilize binaural recordings (Schenkman, Nilsson, 2010). Most studies use static tests (Thaler *et al.*, 2018; Tirado *et al.*, 2019) in which a subject just identifies the presence (Nilsson, Schenkman, 2016) or location of obstacles (Tonelli *et al.*, 2016), some studies on the other hand contain dynamic scenarios (in virtual (Dodsworth *et al.*, 2020) or real life (Fiehler *et al.*, 2015) settings) in which participants detected the approach to walls (Bujacz *et al.*, 2022b), obstacles (Schenkman *et al.*, 2016) or navigate simple mazes (Dodsworth *et al.*, 2020). In this review we analyze these different aspects of the methodologies and wherever possible compare and judge the different approaches.

In the last years, dozens of papers on the subject have been published and a growing interest in human echolocation has been observed (Fig. 1). The most recent extensive reviews of human echolocation research have been proposed by Arias *et al.* (2012), Kolarik *et al.* (2014), Thaler and Goodale (2016). A notable mention is an older review by Kish (2003), probably the currently most known echolocator in the world, who reviewed a large number of the earliest echolocation research. Our review is a continuation and extension of the earlier reviews in the following aspects:

- we provide an up-to-date review of new studies that have been published during the most recent years;
- we include a subdivision of the echolocation studies with respect to a number of different criteria and present them in a tabular form for better browsing through fields by the reader;
- we provide a discussion on and compare different methodologies applied for studying human echolocation.

This paper began as part of a project the goal of which is to compare the usefulness of various artificial and natural sounds for human echolocation. Earlier, we completed echolocation trials for the Echovis project aimed at developing a mobile game for teaching echolocation (Bujacz *et al.*, 2018; 2021; 2022) and planned to continue the trials in a way that would allow comparison with other previous studies.

Our previous area of research – virtual sound localization and obstacle sonification – has very similar methodology issues. Many studies tested the influence of various factors, such as personalized Head Related Transfer Functions (HRTFs) or blindness of test participants (Dobrucki *et al.*, 2010), on sound externalization and accuracy of source localization, but it was difficult to compare the results of very different methodologies. The subject complexity is also similar – there can be numerous factors influencing the accuracy of sound localization, just as the accuracy of echolocation. We can often confirm that some factors have little influence on the sound localization or echolocation task, but it may be difficult to objectively measure any specific factor's strength considering the overall large variances. This issue is particularly complex in echolocation studies, because echolocation skills vary greatly between individuals (Arias, Ramos, 1997) and most studies use very small groups of participants (even single subjects to represent expert echolocators (Wallmeier, Wiegrebe, 2014)).

This manuscript is structured to allow a reader to find easily papers that address specific aspects of echolocation. We start by presenting a summary of the collected research (Sec. 2), then go on to compare trials used for the evaluation of echolocation accuracy in static and dynamic scenarios (Sec. 3). Next, we provide an overview of studies analyzing various man-made and synthetic sounds used as echolocation cues (Sec. 4). In Sec. 5, we review research that discusses comparisons of echolocation skills of sighted, inexperienced blind and experienced blind echolocators. Further, we compare the results of the two approaches to echolocation studies (Sec. 6), i.e., in which the researchers conduct live trials and also aid the studies with pre-recorded sounds or renders. Finally, we appraise the review carried out and summarize state of the art of the human echolocation studies.

2. Review of approaches to echolocation research

The selection of scientific papers for the review was an organic process. We searched the main online tools (scholar.google.com, sciencedirect.com, core.ac.uk, and ieeexplore.ieee.org) for research that included testing of echolocation skills or analysis of signals used in human echolocation. Initially, we included only research papers published after 2015, to not repeat information from other reviews, such as (Kolarik *et al.*, 2016). However, many of the test methods or signal analyses were only found in older papers, so we expanded the search back to 2010, as well as added several key earlier studies that were most frequently cited by the reviewed articles.

For all the reviewed echolocation studies we prepared a short summary of the main methodology, utilized sounds and environments, participants and key conclusions. This data is presented in Table 1 with the following cells for each paper:

Cell 1: the cited reference;

Cell 2: the title of the study and a brief summary outlining the key results and the most important conclusions;

Cell 3: category of echolocation trial – static (S) or dynamic (D), or if the study concerned only analysis (A) of echolocation sounds. As well as the utilized obstacle sizes, distances, and types of tasks;

Cell 4: subdivides the studies into three categories: (L) live trials that were carried out in real life indoor or outdoor environments, e.g., with obstacles intentionally positioned at different locations versus the tester, (R) trials with pre-recorded or synthesized sounds, e.g., sounds that were first recorded in real environments using a binaural mannequin and then played-back on headphones for the testers in a laboratory environment or generated by a computer, and finally (V) virtual trials in which the echo-sounds were not simply played back, but were a part of a continuously generated virtual environment usually using HRTF filtering. Quite a few studies combined both live (L) and recording (R) tests;

Cell 5: informs how the sound sources were generated, i.e., whether they were synthesized artificially (A) by an electronic device or in a natural (N) manner by the testers themselves, e.g., the mouth-clicks, finger snaps, footsteps or cane taps;

Cell 6: reports on the number of trial participants and categorizes them primarily into blind (B) and sighted (S) participants, though some studies also distinguished early blind (EB) and late blind (LB) persons. Several studies reported participation of echolocation experts (EE), and although no common definition has been given at what level of experience an echolocator becomes one, their skills clearly stood out from the average novice participant.

To the best of our knowledge the table contains the reported studies on human echolocation with special attention focusing on recent reported studies up to the date of submission of this manuscript, i.e., early 2022.

Recommended review papers on human echolocation and auditory perception of the blind are presented in a separate Table 2. Short reviews of the history of echolocation research can also be found in (Cooper *et al.*, 2020; Stock, 2022).

Table 1. Summary table of reviewed echolocation studies.

1. Author(s), publication date	2. Title – Summary of results and conclusions			
	3. Type of trial: static (S), dynamic (D), analysis (A), not applicable (–)	4. Sound playback: live sounds (L), recordings/ synthesized (R), virtual reality (V)	5. Sound: artificial (A), natural (N)	6. Number of blind (B), sighted (S), early blind (EB) or expert echolocators (EE)
Schenkman, Jansson (1986)	"The Detection and Localization of Objects by the Blind with the Aid of Long-Cane Tapping Sounds" – Accuracy and detection distance improved along with the obstacle size (from 0.2 to 0.75 m^2), but not for the largest objects (1.5 m^2); – Variance in the tapping sound spectra had no impact on efficacy; – It was difficult to use cane tapping sounds alone without additional sources for echoes.			
	D – walking a path with cardboard obstacles (sized 50 × 30 cm to 1.5 × 1 m) at face level	L – the participants generated cane tapping sounds	N – long-cane tapping sound	3B
Arias, Ramos (1997)	"Psychoacoustic Tests for the Study of Human Echolocation" – Echolocation seems to depend on perception of a virtual pitch that appears from the difference between the outgoing and incoming sounds, this pitch is more easily perceivable when presented with repeated trains of sounds; – Musical training did not influence the subjects' performance in these pitch discrimination tests; – Noise signals yielded better echolocation results than click sounds when using recordings of real echoes, but the difference was less significant when the echoes were synthesized.			
	S – testers listen to stimuli on headphones	R – synthetic echoes (2–5 ms delay and –3.5 dB) and recorded echoes (50 cm disk at 35 and 80 cm distance)	A – click-sounds, white noise	30S + 1B
Rosenblum *et al.* (2000)	"Echolocating Distance by Moving and Stationary Listeners" – Participants echolocating more accurately while moving than being stationary; – A follow-up confirmed that this moving advantage was not a function of a specific type of training or the multiple stationary positions available during moving echolocation; – The moving advantage might be a function of echoic time-to-arrival information.			
	S/D – echolocating a 91 × 182 cm wall outdoor while standing/moving	L – the participants generated sounds	N – oral sounds of choice	26S
Rojas *et al.* (2009)	"Physical Analysis of Several Organic Signals for Human Echolocation: Oral Vacuum Pulses" – From the three compared sound types (oral "ch", lip "ch", oral clicks) the palatal clicks were significantly clearer and more intense than alveolar ones and did not interfere with breathing.			
	A – computer analysis	L – the participants generated sounds with their mouths	N – oral "ch", lip "ch", oral clicks	10S
Rojas *et al.* (2010)	"Physical Analysis of Several Organic Signals for Human Echolocation: Hand and Finger Produced Pulses" – The knuckle vacuum pulse was judged as best due to its high frequency and "interesting symmetry", containing similar characteristics of palatal clicks with an even richer content in the high frequency part of the spectrum.			
	A – computer analysis	L – the participants generated sounds with their hands	N – knuckle vacuum pulse, hand clap, finger snap	10S + 1B

Table 1. [Cont.].

SCHENKMAN, NILSSON (2010)	“Human Echolocation: Blind and Sighted Persons’ Ability to Detect Sounds Recorded in the Presence of a Reflecting Object” – Blind participants performed significantly better than sighted participants; – All participants performed well in locating objects at distances of less than 2 m; – Detection increased with longer signal durations (up to 500 ms noise burst); – Performance was slightly better in an ordinary room than in an anechoic chamber.			
	S – 0.5 m disk at distances 0.5 m to 5 m	R – participants listened to binaural recordings taken in an ordinary room and an anechoic chamber	A – 5, 50, 500 ms noise bursts	10S + 10B
SCHENKMAN, NILSSON (2011)	“Human Echolocation: Pitch versus Loudness Information” – Participants listened to original and altered binaural recordings, which artificially removed pitch or loudness information from the echo signal; – All altered recordings worsened the echolocation correctness, but removal of pitch information affected it more than loudness; – When the pitch information was removed the difference between blind and sighted participants disappeared.			
	S – 0.5 m diameter disk at distances 1 m to 3 m	R – participants listened to binaural recordings taken in an ordinary room, some with the pitch or loudness information artificially removed	A – 500 ms noise burst	12B + 25S
THALER *et al.* (2011)	“Neural Correlates of Natural Human Echolocation in Early and Late Blind Echolocation Experts” – Processing of click-echoes recruits brain regions typically devoted to vision rather than audition in both early and late blind echolocation experts; – Brain activation was stronger when listening to echoes reflected from moving targets.			
	S – listening to sounds via headphones in fMRI	R – recordings played back in an MRI machine	A – trains of click sounds with or without echoes	2EE
TENG, WHITNEY (2011)	“The Acuity of Echolocation: Spatial Resolution in Sighted Persons Compared to the Performance of an Expert Who is Blind” – Some, but not all novices quickly learned to echolocate small obstacles at short distances at a level comparable to a blind expert; – The paper additionally presents a short review of the numbers of blind participants in 23 echolocation studies from 1950 to 2010 and only in 5 of them there were more than 10 blind participants.			
	S – sitting 33–75 cm from vertical pair of 5–23 cm disks, judging which is the larger one	L – in a sound-proof, echo-damped room	N – oral clicks	8S + 1EE
SMITH, BAKER (2012)	“Human Echolocation Waveform Analysis” – The mouth click waveform is wideband and complex, with spectrum peaks near 3 kHz and 11 kHz and a high fractional bandwidth; – Spectra of early and late blind echolocators’ clicks differ – LB has a wider central peak, but lower side lobes; – The mouth click of the late blind echolocator seems to contain a Doppler-like frequency shift without actual movement.			
	S – spectral analysis of recorded sounds	R/L – analysis of recorded tongue generated sounds	N – tongue clicks	2B (1 early blind and 1 late blind)

Table 1. [Cont.].

<table>
<tr><td rowspan="2">Schörnich
<i>et al.</i> (2012)</td><td colspan="4">“Discovering Your Inner Bat: Echo–Acoustic Target Ranging in Humans”
– Most participants preferred to use relatively loud, short, broadband tongue clicks with peak frequencies between 5 and 10 kHz (which was noted as much higher than other studies of echolocators’ mouth clicks);
– Participants utilized temporal, timbre and spatial cues to assess the distance to a wall;
– When comparing consecutive sounds, the sighted participants were able to detect changes of 20–30 cm in the distance to a wall.</td></tr>
<tr><td>S – judging distance changes from a wall at 1.7 to 6.7 m distance</td><td>R – artificially generated binaural recordings of echoes with one or two reflective walls</td><td>N – tongue clicks</td><td>5S</td></tr>
<tr><td rowspan="2">Gori
<i>et al.</i> (2014)</td><td colspan="4">“Impairment of Auditory Spatial Localization in Congenitally Blind Human Subjects”
– Auditory spatial localization along the horizontal axis was found to be severely impaired in the early blind in Bisection tasks (hearing three sound sources in order, then determining whether the middle source was spatially closer to the first or last one);
– There was no significant difference between early blind and sighted participants in minimum audible angle resolution tasks (hearing two sounds and determining which one was more to the right).</td></tr>
<tr><td>S – participants sat 180 cm from a perimeter of 23 speakers</td><td>R – sound was generated by a bank of speakers</td><td>A – 500 Hz tone</td><td>27S + 9EB</td></tr>
<tr><td rowspan="2">Milne
<i>et al.</i> (2014)</td><td colspan="4">“The Role of Head Movements in the Discrimination of 2-D Shape by Blind Echolocation Experts”
– Head movements made while echolocating are necessary for the correct identification of 2-D shape;
– Expert echolocators’ performance dropped to chance level when forced to remain still;
– Not only experts can use echolocation to successfully identify 2-D shapes.</td></tr>
<tr><td>S – recognizing four geometric shapes 16–100 cm in size at distance 40 or 80 cm</td><td>L – sounds generated by the participants in an anechoic chamber or echo-dampened room. Head and torso movements were either allowed or forbidden</td><td>N – tongue click, finger snap, speech, hand clap</td><td>6EE + 10B + 10S</td></tr>
<tr><td rowspan="2">Wallmeier,
Wiegrebe
(2014)</td><td colspan="4">“Ranging in Human Sonar: Effects of Additional Early Reflections and Exploratory Head Movements”
– Distance discrimination threshold was below 1 m for all reference distances (0.75–4 m) with the best results (20 cm) for the smallest reference distance;
– Distance discrimination in complex environments can be improved by allowing free head rotation, but head movements provide no significant advantage over static echolocation from an optimal single orientation.</td></tr>
<tr><td>S/D – distance discrimination from a wall 0.75 m to 4 m</td><td>VR – echo generated in virtual echo-acoustic space from participants’ own mouth sounds</td><td>N – chosen by a participant</td><td>6S + 1B</td></tr>
<tr><td rowspan="2">Vercillo
<i>et al.</i> (2014)</td><td colspan="4">“Enhanced Auditory Spatial Localization in Blind Echolocators”
– In similar tests as to (Gori <i>et al.</i>, 2014) the blind participants showed much poorer performance than sighted participants in space bisection tasks, but similar performance in minimum auditory angle tasks;
– Blind echolocators showed better performance in the spatial bisection tasks than non-echolocating blind participants, showing that the use of echolocation improves auditory spatial localization.</td></tr>
<tr><td>S – discriminating between two of 23 speakers at 180 cm distance</td><td>R – sound was generated by a bank of speakers</td><td>A – 500 Hz tones, 75 ms, 60 dB (SPL)</td><td>11S + 9B</td></tr>
</table>

Table 1. [Cont.].

<table>
<tr><td rowspan="2">NILSSON, SCHENKMAN (2016)</td><td colspan="4">“Blind People Are More Sensitive Than Sighted People to Binaural Sound”
– Blind persons show an enhanced sensitivity to inter-aural level difference (ILDs) tests when presented with click pairs in both the leading and the lagging component;
– Blind testers showed an increased ability to unsuppress information in lagging clicks.</td></tr>
<tr><td>S – listening to synthetic clicks on headphones</td><td>R – sounds composed of 125 ms rectangular pulses (clicks) played over headphones</td><td>A – 125 µs clicks, alone or as pairs spaced 2 ms apart</td><td>23B + 65S</td></tr>
<tr><td rowspan="2">FIEHLER, THALER (2015)</td><td colspan="4">“Neural Correlates of Human Echolocation of Path Direction During Walking”
– All participants were able to differentiate between echo and no-echo stimuli;
– Expert blind echolocators performed worse when presented with pre-recorded stimuli during MRI scan;
– The observed neural activity suggests that while blind participants processed echo directional meaning automatically, sighted participants had to process information consciously.</td></tr>
<tr><td>D – navigating a corridor and stating its shape,
S – listening to recorded sounds during fMRI</td><td>L – in indoor and outdoor setup (only 3 blind experts),
R – pre-recorded, binaural stimuli</td><td>N – mouth clicks</td><td>6B + 3S</td></tr>
<tr><td rowspan="2">TONELLI *et al.* (2016)</td><td colspan="4">“Depth Echolocation Learnt by Novice Sighted”
– When judging the distance to obstacles the errors in judgements fell from 35 to 10 cm over the course of two one-hour sessions;
– Errors were significantly smaller in the reverberant room than in an anechoic chamber;
– Participants who used tongue clicks were marginally more accurate than those using finger snaps.</td></tr>
<tr><td>S – subjects sat in front of one of five bars (40–180 cm high and 6–27 cm wide) at five different distances (from 30 cm to 150 cm)</td><td>L – the echolocation sound was naturally produced, using no external device</td><td>N – tongue clicks + finger snaps</td><td>18S</td></tr>
<tr><td rowspan="2">THALER, CASTILLO-SERRANO (2016)</td><td colspan="4">“People’s Ability to Detect Objects Using Click-Based Echolocation – A Direct Comparison between Mouth-Clicks and Clicks Made by a Loudspeaker”
– Success rates at determining the presence of an obstacle were similar or higher when using a head-worn loudspeaker;
– Accuracy in detecting the object was higher at 1 m distance as compared to 2 m;
– Sighted participants showed significant improvement in two consecutive sessions.</td></tr>
<tr><td>S – sitting 1 m or 2 m from a 60 cm disk</td><td>L/R – in a sound-insulated and echo-acoustic dampened room, participants either generated mouth clicks by themselves or the experimenters generated clicks from a head-worn loudspeaker</td><td>N – mouth clicks,
A – 4 kHz clicks played through a head-worn loudspeaker</td><td>27S + 2B</td></tr>
<tr><td rowspan="2">SCHENKMAN *et al.* (2016)</td><td colspan="4">“Human Echolocation - Acoustic Gaze for Burst Trains and Continuous Noise”
– When the obstacle was at 1 m distance the mean accuracy of detecting echoes by blind participants increased with the burst rate (from roughly 60% at 1 burst/500 ms to 80% at 64 bursts/500 ms) and was highest for continuous noise;
– For sighted participants and for blind participants at a longer distance of 1.5 m the accuracy was largest at a rate of 32 bursts/500 ms and fell for higher rates;
– Of the 38 participants in the study top 5 were blind.</td></tr>
<tr><td>S – 0.5 diameter aluminum disk as the obstacle at 1 m and at 1.5 m</td><td>R – binaural echo recordings were made in a lecture hall with reverberations</td><td>A – 5 ms noise trains, 1 to 64 bursts per 500 ms versus 500 ms continuous noise</td><td>12B + 26S</td></tr>
</table>

Table 1. [Cont.].

<table>
<tr><td rowspan="2">Rychtarikova
et al. (2017)</td><td colspan="4">“Auditory Recognition of Surface Texture with Various Scattering Coefficients”
– From numerous wall shapes tested, two were most likely to be recognized by participants: parabolic (due to sound focusing) and a staircase (due to a chirp-like echo).</td></tr>
<tr><td>S – standing at 1.5 m or 10 m from a virtual obstacle</td><td>R – synthetized and spatialized echoes played over headphones</td><td>A – artificial clicks</td><td>16S</td></tr>
<tr><td rowspan="2">Kolarik
et al. (2017)</td><td colspan="4">“Blindness Enhances Auditory Obstacle Circumvention: Assessing Echolocation, Sensory Substitution, and Visual-Based Navigation”
– Blind non-echolocators navigated more effectively than blindfolded sighted individuals with fewer collisions;
– All participants except the blind echolocation expert navigated better with a sensory substitution device than with echolocation.</td></tr>
<tr><td>D – navigating around an obstacle 0.6 × 2 m</td><td>L – participants walked by an obstacle that was directly on or 25 cm off a path. Comparing vision, echolocation and a vibrating distance sensor</td><td>N – mouth clicks</td><td>10S + 8B + 1EE</td></tr>
<tr><td rowspan="2">Ekkel
et al. (2017)</td><td colspan="4">“Learning to Echolocate in Sighted People”
– A statistically significant improvement was achieved after four days of 1-hour sessions;
– The chance to correctly echolocate the position of the larger disk grew proportionally with an angular size difference from 50% (random) for most similar disks to 70% when one disk was 5 cm and the second 25 cm in diameter;
– Test participants that did not move their heads during experiments had chance-level results;
– The improvement in echolocation ability was positively correlated with performance in an attention PASAT test (Paced Auditory Serial Addition Task), but there was no correlation for spatial cognition and memory tests.</td></tr>
<tr><td>S – sitting 50 cm from two disks of different diameters 5–25 cm, determining the position of the larger disk</td><td>L – in a soundproof room with sounds generated by a head-mounted small speaker</td><td>A – 10 ms white noise pulse (80 dB).
As a control, guessing without any sound was also performed</td><td>23S</td></tr>
<tr><td rowspan="2">Flanagin
et al. (2017)</td><td colspan="4">“Human Exploration of Enclosed Spaces through Echolocation”
– Participants produced clicks of the length between 3 and 37 ms and absolute sound pressure levels (SPL) between 88 and 108 dB SPL;
– Active vocalization was associated with better accuracy of the room size classification;
– Visual and parietal activity was observed both in the sighted participants and the blind echolocation expert while performing echolocation.</td></tr>
<tr><td>S – listening to synthetic echoes to judge room size changes
A – analysis of fMRI during active and passive echolocation</td><td>R – participants’ own vocalizations were recorded and convolved with BRIR measurements of a small chapel with highly reflective surfaces</td><td>N – mouth clicks recorded for each participant</td><td>11S + 1B</td></tr>
<tr><td rowspan="2">Heller
et al. (2017)</td><td colspan="4">“Evaluating Two Ways to Train Sensitivity to Echoes to Improve Echolocation”
– Participants were divided into three groups, two trained echo sensitivity using a lab procedure or an app, and the third was a control group;
– Pre and post training tests involved localization of a 0.6 × 1.2 m board at distances from 0.9 to 2.7 m;
– Both training groups showed similar improvement after 15 hours of training, although supervised psychoacoustic training in the lab was marginally better.</td></tr>
<tr><td>S – listening to synthetic echoes for training and localizing a 0.6 × 1.2 m board for pre and post tests</td><td>R – synthetic echo sounds were used for training
L – mouth clicks were used in live pre and post tests</td><td>N – recorded mouth clicks selected to meet optimal characteristics (Rojas *et al.*, 2009)</td><td>13S</td></tr>
</table>

Table 1. [Cont.].

<table>
<tr><td rowspan="2">Thaler
<i>et al.</i> (2017)</td><td colspan="4">“Mouth-clicks Used by Blind Expert Human Echolocators – Signal Description and Model Based Signal Synthesis”
– Analyzed mouth clicks were wideband (up to 10 kHz), consistently very brief (~3 ms duration) with peak frequencies in the range of 2–4 kHz, and maximum energy at 10 kHz;
– MATLAB code to synthesize the model clicks was made available in the supplementary material and has been utilized in a number of later echolocation studies (Bujacz <i>et al.</i>, 2018; Dodsworth <i>et al.</i>, 2020; Flanagin <i>et al.</i>, 2017; Rychtarikova <i>et al.</i>, 2017; Thaler <i>et al.</i>, 2020a; Tirado <i>et al.</i>, 2019).</td></tr>
<tr><td>A – analysis of expert mouth clicks</td><td>L – experts generated clicks in an echo-dampened room</td><td>N – mouth clicks</td><td>3EE</td></tr>
<tr><td rowspan="2">Thaler,
Foresteire
(2017)</td><td colspan="4">“Visual Sensory Stimulation Interferes with People’s Ability to Echolocate Object Size”
– Visual stimulation (white light) decreased the sighted participants’ echolocation performance;
– Tactile stimulation (skin electrode) had no effect on echolocation performance in sighted and blind people;
– The same areas of the brain seem to be involved in processing of both the visual stimuli and echo sounds.</td></tr>
<tr><td>S – sitting 50 cm from two disks 5–25 cm, determining the position (top/bottom) of the larger disk spaced 27 cm apart</td><td>L – carried out in a sound-insulated, and echo-acoustic damped room</td><td>N – mouth clicks</td><td>44S + 3B</td></tr>
<tr><td rowspan="2">Norman,
Thaler (2018)</td><td colspan="4">“Human Echolocation for Target Detection is More Accurate with Emissions Containing Higher Spectral Frequencies, and This is Explained by Echo Intensity”
– Echolocation was more accurate using emissions with higher spectral frequencies – this advantage was eliminated when the intensity of the echoes was artificially equated to correct for the higher reflectivity of the tested object in the higher spectral range.</td></tr>
<tr><td>S – listening to binaural recordings of reflections from 0.5 m diameter disc at distances 1–3 m</td><td>R – recordings made in an anechoic chamber using a custom binaural mannequin</td><td>A – synthetic clicks or noise bursts with 9 dB bursts of 3.5–4.5 Hz frequencies</td><td>12S</td></tr>
<tr><td rowspan="2">Thaler
<i>et al.</i> (2018)</td><td colspan="4">“Human Echolocators Adjust Loudness and Number of Clicks”
– Echolocators accumulate information from multiple samples;
– To locate objects off to the sides, the echolocators increased loudness and numbers of clicks;
– Echolocation in the Frontal Hemisphere is Better than in the Rear.</td></tr>
<tr><td>S – locating a 17.5 cm disk at 100 cm distance and 0–180° azimuth angles</td><td>L – Participants generated clicks by themselves in a noise insulated and echo dampened room</td><td>N – mouth clicks</td><td>8B</td></tr>
<tr><td rowspan="2">Tonelli
<i>et al.</i> (2018)</td><td colspan="4">“How Body Motion Influences Echolocation While Walking”
– Head exploration (i.e., changing head rotation angle while producing sounds) is crucial for acquiring spatial data;
– Echolocation accuracy depends on the distance to an obstacle and the frequentness of head movements during sound emission;
– Average velocity, motion duration, and time of the task completion do not significantly influence the correctness of the echolocation task.</td></tr>
<tr><td>D – walking a 4 m long, 1.1 m wide corridor and stating its shape (closed or open to left or right)</td><td>L – participants generated clicks by themselves in a larger high-ceiling room with a corridor build from plastic panels</td><td>N – mouth clicks</td><td>9S</td></tr>
</table>

Table 1. [Cont.].

Andrade *et al.* (2018)	“Echo-House: Exploring a Virtual Environment by Using Echolocation” – Echolocation provided information on orientation and sense of space that would not otherwise be available; – Echolocation itself did not allow participants to navigate in this environment without additional support, but it did help in locating objects and exploring the environment.			
	D – controlled an avatar in a virtual environment	V – participants controlled an avatar placed in virtual space	A – footsteps, mouth-clicks, hand clapping	5B
Thaler *et al.* (2019)	“Human Click-Based Echolocation of Distance: Superfine Acuity and Dynamic Clicking Behaviour” – Echolocators made more intense and more frequent clicks when dealing with weaker reflections (i.e., the same object at a farther distance, or a smaller object at the same distance); – Number and intensity of clicks were adjusted independently from one another; – Experienced echolocators reliably detected changes in distance of roughly 5% (3 cm at 50 cm, and 7 cm at 150 cm distance).			
	S – localizing change of distance to disks (28.5 cm or 80 cm diameter) placed at 50 cm or 150 cm	L – Participants generated clicks by themselves. A noise insulated and echo dampened room	N – mouth clicks	8B
Tirado *et al.* (2019)	“The Echobot: An Automated System for Stimulus Presentation in Studies of Human Echolocation” – A 50 cm reflecting disk was correctly detected at distances 1 to 3.3 m, with an average of 2 m; – Participants showed a small, but steady improvement over 12 echolocation sessions lasting 6–10 min. each, but only when a synthetic clicker was used; – Participants using their own mouth sounds showed no changes in their detection thresholds.			
	S – sitting in front of a 50 cm aluminum disc repositioned by an automated sled to distances 1–4 m	L – in sound-proofed and padded listening lab	A – synthesized click (Thaler *et al.*, 2017) N – mouth clicks (3 participants)	15S
Thaler *et al.* (2020b)	“The Flexible Action System: Click-Based Echolocation May Replace Certain Visual Functionality for Adaptive Walking” – Echolocation experts walked just as fast as sighted participants using vision; – Participants who made clicks with higher spectral frequency content and higher clicking rates walked faster; – The use of echolocation significantly decreased the frequency of collisions with obstacles at head height, but not at ground level.			
	D – walking across a room and around obstacles	RL – participants generated clicks by themselves in a padded room with two obstacles (80 × 80 cm) at head and ground level	N – mouth clicks	10B + 7EB + 24S
Dodsworth *et al.* (2020)	“Navigation and Perception of Spatial Layout in Virtual Echo-Acoustic Space” – Sighted people after 10-week training in virtual mazes increased their ability to judge the spatial layout of obstacles through sound, avoid collisions and find safe passage; – Blind echolocators performed at a very high level without any training.			
	D – navigation with a computer keyboard	V – passing through virtual mazes with walls 75 cm apart	A – synthesized click (Thaler *et al.*, 2017)	20S + 3B

Table 1. [Cont.].

<table>
<tr><td rowspan="2">Schenkman, Gidla (2020)</td><td colspan="4">“Detection, Thresholds of Human Echolocation in Static Situations for Distance, Pitch, Loudness and Sharpness”
– The repetition pitch was useful for detection at shorter distances and was determined from the peaks in the temporal profile of the autocorrelation function;
– At shorter distances loudness provides echolocation information, but at longer distances, timbre aspects, such as sharpness, might be used to detect objects;
– Results suggest that blind persons may detect objects at lower values for loudness, pitch strength and sharpness and at further distances than sighted persons.</td></tr>
<tr><td>S – recorded reflections from a 0.5 m disk at distances from 0.5 to 5 m</td><td>R – binaural recordings in an ordinary conference room and an anechoic chamber played back over headphones</td><td>A – 5, 50, and 500 ms noise burst from a loudspeaker</td><td>10B + 10S</td></tr>
<tr><td rowspan="2">Norman, Thaler (2020)</td><td colspan="4">“Stimulus Uncertainty Affects Perception in Human Echolocation: Timing, Level, and Spectrum”
– When there was certainty in the acoustic properties of the echo relative to the emission, either in temporal onset, spectral content or level, people detected the echo more accurately;
– Participants were more accurate when the emission’s spectral content was certain, but surprisingly, not when either its level or temporal onset was certain.</td></tr>
<tr><td>S – recorded reflections from a 50 cm disc or a 28 cm bowl at 1.2 or 3 m</td><td>R – binaural recordings</td><td>A – clicks and 500 ms white noise bursts from a loudspeaker</td><td>4EE + 20B + 24S</td></tr>
<tr><td rowspan="2">Tonelli *et al.* (2020)</td><td colspan="4">“Early Visual Cortex Response for Sound in Expert Blind Echolocators, But Not in Early Blind Non-Echolocators”
– Activation in the posterior area of the scalp while echolocating for the sighted was similar to the one observed in early blind experts;
– This activity was associated to sound stimulation and is contralateral to the sound localization in space.</td></tr>
<tr><td>S – participants sat in front of the set-up</td><td>L – live played sound via 23 speakers</td><td>A – 500 Hz 60 dB pure tone, duration of 75 ms</td><td>10B + 5S</td></tr>
<tr><td rowspan="2">Tirado *et al.* (2021)</td><td colspan="4">“Comparing Echo-Detection and Echo-Localization in Sighted Individuals”
– Distinct individual differences in echo-detection and echo-localization abilities;
– Better performance in the echo-detection than the echo-localization task;
– It may be relevant for echolocation training programs to focus separately on the detection and localization.</td></tr>
<tr><td>S – 50 cm disk at distances from 1 m to 4.25 m</td><td>R – synthetic expert mouth clicks played over a loudspeaker in an echo-dampened room</td><td>A – synthesized click (Thaler *et al.*, 2017)</td><td>10S</td></tr>
<tr><td rowspan="2">Andrade *et al.* (2021)</td><td colspan="4">“Echolocation as a Means for People with Visual Impairment (PVI) to Acquire Spatial Knowledge of Virtual Space”
– Various techniques were used to describe the virtual space, including perimeter recognition tactics, listing elements and describing holistic map models;
– People with Visual Impairment could distinguish whether a virtual room was covered with carpet, wood or metal, identify the relative size of a virtual room, and detect the presence of 90° turns to the left or right on average 70% of the time;
– Working with PVI and learning from their lived experience is the most successful way to gain knowledge of technologies accessible to PVI.</td></tr>
<tr><td>D – using the Xbox controller to explore the virtual space</td><td>V – travel through virtual world</td><td>A – pre-recorded sound, echo generated by the footprint of the avatar</td><td>12B</td></tr>
</table>

Table 1. [Cont.].

Castillo-Serrano (2021)	“Increased Emission Intensity Can Compensate for the Presence of Noise in Human Click-Based Echolocation” – The emission intensity increased so that the spectral power of echoes exceeded the spectral power of noise by 12 dB in 4 kHz and 5 kHz frequency bands; – A potential strategy to deal with noise while echolocating is to increase emission intensity to maintain the signal-to-noise ratio of certain spectral components of the echoes.			
	S – recordings of 17.5 cm or 26.5 cm disk at 1, 2, or 3 m	R – binaural recordings made in an echo-acoustic dampened room played through headphones	A – synthetic click (a 4.5 kHz sinusoid multiplied by a decaying exponential)	8B + 3EE + 20S
Kritly *et al.* (2021)	“Discrimination of 2D Wall Textures by Passive Echolocation for Different Reflected-to-Direct Level Difference Configurations” – The discriminability is larger for the walls reflecting with a higher spectral coloration; – Enhancing the reflections as well as removing the direct sound are beneficial to differentiate textures; – The flat wall and the circular wall are the most difficult textures to discriminate, the wall with aperture and the staircase are the most distinguishable textures.			
	S – synthesized reflection from six different wall shapes at distances from 0.8 to 5 m	R – recordings played through headphones	A – a single anechoically recorded click sound with the synthesized echo	14S
Norman, Thaler (2021)	“Perceptual Constancy With a Novel Sensory Skill” – Blind expert echolocators have higher constancy ability than sighted and blind persons novices to echolocation; – Sighted participants improved their capabilities through training; that suggests that constancy also occurs in a domain with which the respondent has had no previous experience.			
	S – recorded reflections from a 50 cm disc or a 28 cm bowl at 1, 2 or 3 m	R – recordings played through headphones	A – variations in the click’s peak spectrum were used: 3.5, 4.0, and 4.5 kHz	10S + 17B + 3EE
Norman *et al.* (2021)	“Human Click-Based Echolocation: Effects of Blindness and Age, and Real-Life Implications in a 10-Week Training Program” – Training improved performance of both sighted and blind participants, but neither group reached the level of experienced experts; – Some sighted participants performed better than the blind novices after the same training, though this can be attributed to younger age and/or superior binaural hearing; – The ability to learn click-based echolocation is not strongly limited by age or level of vision.			
	S – discriminating disc size (Thaler, Foresteire, 2017) or orientation D – navigating a simple virtual T, U or Z maze and a real natural environment	V – virtual mazes with recorded clicks L – live tasks with participant mouth clicks in an echo-dampened room	N – mouth clicks (live and prerecorded)	14S + 12B + 7EB
Bujacz *et al.* (2022a)	“Echovis – A Collection of Human Echolocation Tests Performed by Blind and Sighted Individuals: A Pilot Study” – Better results were achieved for outdoor tests than indoors and the worst in a padded room; – Additional signal emissions marginally helped in determining an obstacle’s direction, but not a distance; – Blind and sighted participants performed similarly in most tests, statistically significant difference was found only for determining the distance to an obstacle; – A high correlation between certainty in answers and their real correctness was noted for all adult participants, but not for blind children; – In dynamic trials the average click rate when using a mechanical clicker was once every 2 seconds.			

Table 1. [Cont.].

	S – localizing a 2 m wooden wall at distances 1–3 m, D – approaching a wall, walking parallel to a wall, localizing an off-the path object	L – similar tests performed outdoors and indoors; static indoor tests were compared in an empty room and in an acoustically padded room, as well as with binaural recordings (R) in the same environments	A – mechanical clicker or synthetized expert click from (Thaler *et al.*, 2017)	10B + 10S (+ 10B children)
Bujacz *et al.* (2022b)	"Comparison of Echolocation Abilities of Blind and Normally Sighted Humans using Different Source Sounds" – Almost all blind and sighted participants performed significantly above random; – Blind participants performed significantly better than the sighted ones; however, the difference disappeared once the blind participants were analyzed as two separate groups – totally blind vs visually impaired; – Legally blind participants that retained any level of light sensitivity performed on average the same as sighted participants; – From the ten analyzed sounds pink and blue noises along with 3 kHz and 4 kHz percussion were significantly best for accuracy of the echolocation.			
	S – localizing a 1 × 2 m vertical wall at distances 1–3 m and directions −45° to 45°	L - outdoors using ten different sounds generated by the participant or played from a BT speaker at waist-height	N – mouth clicks or hand clapping A – 1–5 kHz percussion, pink and blue noise, mechanical clicker, synthetized expert click (Thaler *et al.*, 2017)	12B + 14S

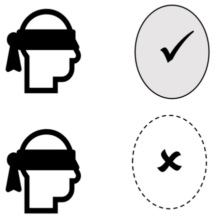
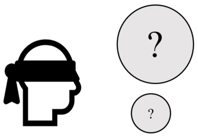
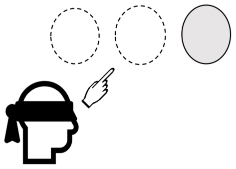
Table 2. Summary table of recent review papers.

Kish (2003)	"Sonic Echolocation: A Modern Review and Synthesis of the Literature" – Paper written by a blind echolocation expert; – Extensive review of the early literature on echolocation, including early misconceptions about "facial vision" from the first half of the XX century and many practical experiments from the 60s and 70s; – Review of studies testing various aspects of echolocation including the use of different targets and different sonic sources; – Review of studies on the learning of echolocation by sighted subjects and proposals of training programmes for the blind.
Arias *et al.* (2012)	"Echolocation An Action-Perception Phenomenon" – Review paper presenting a historical categorisation of the main studies concerning echolocation; – The authors conclude that echolocation is a "closed-loop perception-action behaviour, in which the subject modulates action (self-generated echolocation signals, exploratory head movements) to control perception (auditory Gestalts learned through implicit learning)".
Kolarik *et al.* (2016)	"Auditory Distance Perception in Humans: A Review of Cues, Development, Neuronal Bases, and Effects of Sensory Loss" – A review paper focusing on four aspects of auditory distance perception: cue processing, development, consequences of visual and auditory loss, and neurological bases; – Blind individuals often manifest supra-normal abilities to judge relative distance but show a deficit in absolute distance judgments; – Following hearing loss, the use of an auditory level as a distance cue remains robust, while the reverberation cue becomes less effective.
Thaler, Goodale (2016)	"Echolocation in Humans: an Overview" – A review paper summarizing the history of echolocation studies, analyzing the typical mission signal; – An assessment of distance, direction and size discrimination is provided from several studies; – A large review of neural underpinnings of echolocation, especially the plasticity of the brain to adapt "visual" areas to process echolocation signals.

Table 2. [Cont.].

Kolarik *et al.* (2021)	"A Framework to Account for the Effects of Visual Loss on Human Auditory Abilities" – The paper reviews numerous studies related to the impact of vision loss on spatial and non-spatial auditory perception; – Authors propose a framework comprising a set of nine principles that can be used to predict and explain why given auditory abilities are enhanced or degraded after the loss of vision; – Effects of early, late, partial and full visual loss are also discussed; – The framework includes a Perceptual Restructuring Hypothesis that posits utilization of available cortical resources to provide the most accurate and useful information, sometimes at a loss of some auditory abilities.

Table 3. Static echolocation tests.

<table>
<tr><td colspan="2">Binary – state the presence or absence of an obstacle</td></tr>
<tr><td>Examples:
A disc (50 cm diameter) placed at 1 or 1.5 m (Schenkman <i>et al.</i>, 2016), 0.5–5 m (Schenkman, Niessen, 2010) or at 1–3 m (Schenkman, Niessen, 2011; Norman, Thaler, 2018);
A disc (60 cm diameter) placed directly at 1 to 2 m (Thaler, Castillo-Serrano, 2016), or 1, 2 or 3 m (Norman, Thaler, 2021);
A disc (17.5 cm diameter) placed 1 m at different azimuth angles (from 0°– directly in front to 180° – directly behind) (Thaler <i>et al.</i>, 2018);
A disc (50 cm diameter) placed from 0.7 to 3.9 m and moved further or closer based on the correct or incorrect answer (Tirado <i>et al.</i>, 2019).</td><td>
e.g., "Is there an object in front of you?"</td></tr>
<tr><td colspan="2">Distinguish between objects</td></tr>
<tr><td>A reference disc (diameter 25.4 cm) and 5 comparison discs (diameter 5.1–22.9 cm) placed at different distance 0.33 m, 0.5 m or 0.75 m (Teng, Whitney, 2011);
Four geometrical shapes: rectangle 100 × 16 cm vertically or horizontally, square 40 cm, triangle 52 cm wide and 45 cm high (Milne <i>et al.</i>, 2014);
A reference disc (diameter 25.4 cm) and 5 comparison discs (diameter 5.1–22.9 cm) placed 0.5 m away (Ekkel <i>et al.</i>, 2017);
Two distinct architectural structures from a distance 1.5 m or 10 m (Rychtarikova <i>et al.</i>, 2017);
Distinguish which wall was more reflective (Kritly <i>et al.</i>, 2021).</td><td>
e.g., "Which is the larger object?"</td></tr>
<tr><td colspan="2">Determine direction and/or distance to obstacle:</td></tr>
<tr><td>A wall (1.83 m ×0.914 m × 1.27 cm) placed at 0.91 m, 1.83 m, 2.74 m or 3.66 m from the starting point (Rosenblum <i>et al.</i>, 2000);
A virtual reflective surface placed 1.7–6.8 m in front or 1.7 m at an angle 15–45° (Schörnich <i>et al.</i>, 2012);
Rectangular bars (length 40–180 cm, width 6–27 cm) placed at 0.3–1.5 cm (depending on obstacle size) (Tonelli <i>et al.</i>, 2016);
A disk (28.5 cm or 80 cm diameter) placed 0.5 m or 1.5 m from a participant (Thaler <i>et al.</i>, 2019);
The 1 × 2 m wall at distances 1 to 3 m (Bujacz <i>et al.</i>, 2018; 2022b);
The 60 × 120 cm board at a distance 90 to 270 cm (Heller <i>et al.</i>, 2017).</td><td>
e.g., "Where is the object?"</td></tr>
</table>

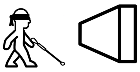
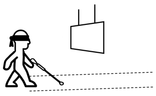
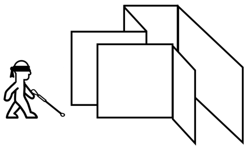
3. Static versus dynamic trails

A good way to subdivide test methodologies are static and dynamic trials. In the static trials the test participant is not moving and localizes real or virtual targets of different types (the most common being circular disks 50 cm in diameter) at different distances (from 30 cm up to 5 m) or directions. In moving trials the echolocator travels through a simple controlled environment localizing one or more obstacles or navigating simple mazes. Tables 3 and 4 summarize the most common types of tests.

Most of the studies devoted to human echolocation are based on static experiments. This is because such tests are more straightforward to plan, carry out, and the results are simpler to analyze and interpret. The participants sit or stand and provide answers about the direction and distance of objects positioned in the environment. Trials that utilize recordings or renders can also be generally regarded as static, though they are discussed in a separate section.

The static tests can be divided into four main categories: binary tests, distance, location or size/type discrimination tests (Thaler, Goodale, 2016). In binary tests, participants simply state the presence of an obstacle or the lack of thereof. A frequently used object for detection is a disc, e.g., 50–100 cm in diameter, and placed 1–2 m in front of test subjects who produce the echolocation sound themselves (Thaler, Castillo-Serrano, 2016) or only listen to the recordings (Schenkman *et al.*, 2016). The disc in the binary test is usually not removed entirely, but rotated 90° as to present a narrow, non-reflecting edge to the participant. The binary test can be modified by placing a disk at an angle to the participants. While an obstacle displacement up to 90° does not affect the overall performance significantly, there was a sudden accuracy decrease observed at 135° (Thaler *et al.*, 2018). Another modification to a binary test was implemented in the study by (Tirado *et al.*, 2019). A distance to an obstacle was modified based on the accuracy of the participants' answers. An obstacle was not removed from a setup, only turned perpendicular to a test subject (non-reflective mode). Correct identification of a reflective mode increased the distance by 0.25 m, correct identification of a non-reflective mode did not change the distance. False-negative identification decreased the distance by 0.25 m and false-positive identification decreased the distance by 0.5 m. While simple in design, the binary tests provide

Table 4. Dynamic trials.

Approach a wall or an obstacle	
Detected a wall (1.8 m × 0.9 m × 1.3 cm) placed at 0.9 m, 1.8 m, 2.7 m or 3.7 m from the starting point while moving along a guide string (Rosenblum *et al.*, 2000); Approached a wall from a random distance (3, 4 or 5 m) to stop at touch distance (Bujacz *et al.*, 2022a).	 e.g., "Walk to the wall and stop before it".
Travel a path and detect obstacles on or off the path	
Navigated the length of the large room (24 × 15 m) with four obstacles (1.46 × 1.03 m, 0.73 × 1.03 m, 0.515 × 0.73 m, and 0.365 × 0.51 m pieces of cardboard, suspended from metal racks so that the obstacle midpoint was placed at 1.44 m from the ground), placed 7, 11, 15, and 19 m from the starting point (Schenkman, Jansson, 1986); Navigated a corridor built of wooden panels (1.85 × 1.1 m) of different shapes (opened to the left or right, closed from both sides) (Fiehler *et al.*, 2015); Navigated the length of the room (5.8 × 9 × 3 m) with two obstacles (80 × 80 cm polystyrene blocks), placed 2.1–4 m from a starting plane at a different height (Thaler *et al.*, 2020a); Localized obstacles placed off the path (car, streetlight, open door, end of wall) (Bujacz *et al.*, 2022a).	 e.g., "Walk the path and avoid the face level obstacle".
Navigate in an artificial "maze" or other environment	
Navigated a corridor built of wooden panels (1.85 × 1.1 m) of different shapes (opened to the left or right, closed from both sides) (Fiehle *et al.*, 2015); Navigated a corridor built of poly-methyl methacrylate panels (4 × 1.1 m) of different shapes (opened to the left or right, closed from both sides) (Tonelli *et al.*, 2018); Navigate a virtual maze (Dodsworth *et al.*, 2020; Norman, Thaler, 2021).	 e.g. "Find the corridor that is not a dead end".

information not only on the range and resolution of effective echolocation, but they also allow to collect information on optimal echolocation sound parameters under controlled conditions (Thaler, Castillo-Serrano, 2016).

Another type of a static test concerns distinguishing between two types of objects, e.g., big and small. The size discrimination test usually takes the form of two-alterative forced-choice task. The two objects are placed at the same distance and presented to a participant simultaneously. The test subject must indicate where the bigger object is located (Teng, Whitney, 2011). Alternatively, in the study by Rychtarikova *et al.* (2017) participants were asked to differentiate between two distinct architectural structures (staircase and different types of walls: parabolic, sinusoid, periodic squared, broad, narrow, convex circular, and a narrow wall with an aperture).

As far as distance discrimination is concerned, the participants are presented with an obstacle placed at a different distance. Their task is to report the relative distance to an object. The obstacles of different sizes can be utilized in this type of test, with the object size increasing along with the distance (Tonelli *et al.*, 2016). Two obstacles of the same size can be also used, the first one as a reference and the second one placed at an angle (Schörnich *et al.*, 2012).

The types, sizes and distances of objects/obstacles are listed in cells 3. of Table 1 for the various echolocation studies as well as summarized in Table 2. Most obstacles/objects range 20–60 cm in size and 1–2 m in distance from the observer, though large walls or panels are also sometimes used.

An important methodology question has been whether to conduct echolocation studies in echoic or anechoic environments (Kolarik *et al.*, 2014). On the one hand, it can be expected that in an anechoic environment a subject could better focus only on the single reflection from an object or obstacle used during the test. On the other, anechoic environments are very unnatural to humans, make loudness judgements more difficult, and provide no background to perceive an "acoustic shadow" – the blocking of more distant echoes (Bujacz *et al.*, 2018). Luckily, this matter has more or less been settled, as a number of studies have demonstrated that obstacle detection in anechoic or acoustically dampened settings is marginally (Bujacz *et al.*, 2018) or even significantly worse than in natural environments (Tonelli *et al.*, 2016).

An important observation was made by Milne *et al.* (2014) who noticed that expert echolocators could determine the shape of objects with exceptional accuracy when they were allowed to make head movements. These results can be explained by other studies that noted that blind people are more sensitive to interaural level (ILD) differences than the sighted individuals (Nilsson, Schenkman, 2016). Also, Wallmeier and Wiegrebe (2014) observed that when it comes to distance discrimination, head movements in a static position did not much improve echolocation performance. On the other hand, when the tester changed its reference positions the distance discrimination of objects has improved.

Here, we can state that, although the static tests have brought important insight into human echolocation abilities, they are far from real live situations in which the visually impaired would use echolocation in practice. The dynamic echolocation tests were carried out mainly with participation of expert echolocators.

An interesting approach to testing echolocation abilities in dynamic settings was proposed by Dodsworth *et al.* (2020) who underlined the importance of "active" navigation tasks for safe mobility and wayfinding. They made binaural acoustic recordings in real environments that were later replayed to test participants, who moved in the replicated virtual spaces. Such an approach is worth further studies because the results show that sighted people after 20 virtual navigation training sessions acquire and generalize navigation abilities using echo-acoustics. Also, the three blind echolocator experts were able to complete similar virtual navigation tasks without any training.

Another recent study by Tonelli *et al.* (2018) has been the first to investigate the influence of the body motion in real environments on echolocation abilities. The authors of the study built a corridor of complex geometries composed of sound-reflecting panels and asked the blindfolded sighted individuals, without prior echolocation experience, to move in such model spaces. The trial participants used mouth clicks to explore the space. The results confirm that kinematic activity of an individual such as walking and a stopping pattern and also head movements allow him/her to successfully navigate in new environments by the use of self-generated echoes.

We can conclude that from numerous studies we have acquired a good understanding of human echolocation abilities confirmed in the static experiments. However, studies of human-echolocation in dynamic experiments, i.e., while the test participant actively explores the environment, are sparse and few. We see two prospective research directions in this context. First, echolocation while moving in virtual reality environments, although difficult to simulate, can be a good solution (Dodsworth *et al.*, 2020). Second, the research initiated by Tonelli *et al.* (2018) should be expanded and concentrate on echolocation abilities while the trial participant is in motion in real environments. Results of such studies can bring new insights into the interrelation between the body motion and space exploration capabilities of the visually impaired.

The key observations from the static echolocation trials carried out with blind and sighted participants are the following:

- echolocation can be learnt and trained by sighted people (Norman, Thaler, 2021);
- experienced echolocators significantly outperform novices (Norman, Thaler, 2020; Vercillo *et al.*, 2014);
- expert echolocators can detect changes in a distance of 3 cm at a reference distance of 50 cm, and a change of 7 cm at a reference distance of 150 cm (Thaler *et al.*, 2019).

The conclusions from a few dynamic echolocation trials are the following (Thaler *et al.*, 2020b):

- echolocation experts walked just as fast as sighted participants using vision;
- participants who made clicks with a higher spectral frequency content and higher clicking rates walked faster;
- the use of echolocation significantly decreased collision occurrences with obstacles at head height, but not at ground level.

4. Sound sources – artificial versus natural

There are numerous ways to produce sound sources that serve as the origin signal for the echoes used in echolocation. Early echolocation research in the first half of the XX century had to verify experimentally that the blind participants of their tests were using sounds (e.g., of their own footsteps or cane taps) to detect obstacles (Kish, 2003). Now that the phenomenon of echolocation is much better understood, there has been a growing interest in determining the influence of a sound source on echolocation, trying to analyze and even potentially optimize it (Thaler *et al.*, 2017).

Currently, the list of sounds used by the blind for echolocation is quite long: there are mouth or hand-made sounds (such as clicks, finger snaps, clapping or knuckle vacuum pulses), mechanical sounds (cane taps, mechanical clickers or castaneta's) and artificially synthesized sounds played from speakers, such as modelled clicks, white or pink noise bursts or rectangular pulses. Table 5 summarizes this division and in this section we discuss key studies related to testing or analyzing sound sources used for echolocation.

All signals that could be used in human echolocation can be categorized into the two main groups: artificial and natural sounds. Research on natural sounds can be divided into mouth and hand-made signals. Rojas *et al.* (2009) have examined many natural generated sounds such as palatal clicks, oral "ch" (sound of tongue moving backwards from teeth), lip "ch" (quick munching), finger snapping and hand clapping, an "iu" sound vocalization or whistling to imitate bat chirps. These natural sounds were analyzed with respect to usability, reproducibility and intensity. The results suggest that the oral produced click is the most suitable for human echolocation. Its spectrum consists of clearly separated frequency bands. The signal energy concentrates on average at a frequency of 1.15 kHz, although the study only tested 10 sighted volunteers. In a follow-up study it was shown that the oral clicks are effective in the presence of ambient noise (Rojas *et al.*, 2010).

In a different study, Smith and Baker (2012) report that the tongue-click generated be an expert echolocator is a complex sound and feature a wide spectrum band. In their group of that the spectrum peak of a tongue-click is located at 3 kHz, and its bandwidth is located within the range of 1.5 kHz to 4.5 kHz. The authors also conclude that it is the large fractional bandwidth (spectrum width) of the click that gives it great range resolution.

Results from the study conducted by Thaler and Castillo-Serrano (2016) show a difference in detec-

Table 5. Commonly tested natural and artificial sound.

Natural	Artificial
Mouth-made sounds: – tongue clicks (Fiehle *et al.*, 2015, 2015; Heller *et al.*, 2017; Rojas *et al.*, 2008; Smith, Baker, 2012; Teng, Whitney, 2011; Thaler *et al.*, 2017, 2018, 2019; Thaler, Castillo-Serrano, 2016; Tonelli *et al.*, 2016, 2018); – oral "ch", lip "ch", whistling (Rojas *et al.*, 2008); – unvoiced consonant "s" (Schörnich *et al.*, 2012).	Mechanical-made sounds: – cane taps (Arias, Ramos, 1997; Schenkman, Jansson, 1986); – mechanical clickers (Arias, Ramos, 1997; Bujacz *et al.*, 2018).
Hand-made sounds: – finger snapping (Rojas *et al.*, 2008); – hand clapping (Rojas *et al.*, 2010; Tonelli *et al.*, 2016); – knuckle vacuum pulses (Rojas *et al.*, 2010).	Computer-made sounds: – synthetic clicks (Bujacz *et al.*, 2018; 2022b; Dodsworth *et al.*, 2020; Heller *et al.*, 2017; Nilsson, Schenkman, 2015; Thaler *et al.*, 2011, 2017 2020a; Thaler, Castillo-Serrano, 2016; Tirado *et al.*, 2019); – noise (white or pink) (Arias, Ramos, 1997; Ekkel *et al.*, 2017; Gori *et al.*, 2014; Schenkman *et al.*, 2016); – transient trains (Arias, Ramos, 1997); – short noise bursts (Arias, Ramos, 1997; Nilsson, Schenkman, 2016; Schenkman *et al.*, 2016).

tion accuracy between the sounds generated by a tongue and artificially generated clicks produced by a head-worn speaker in a sighted participant group. During echolocation sessions with the use of a loudspeaker and an obstacle positioned at a distance of 1 m, echolocators were more accurate in locating an obstacle (M = 0.653, SD = 0.161) than in sessions in which natural sounds were generated with a tongue (M = 0.579, SD = 0.093). However, while performing the same tests at a distance of 2 m object localization accuracies were comparable, with slightly better results obtained with the use of artificially generated clicks. When the tests were repeated, the echolocation precision of the testers improved, with significantly better results for the speaker-generated echolocation sounds.

Thaler and Castillo-Serrano (2016) tested the echolocation abilities of two blind echolocators. The first subject with a longer experience performed perfectly in each trial. The second person was less accurate, but still performed much better than the sighted participants. This person preferred using tongue generated sounds.

Ekkel *et al.* (2017) conducted trials with twenty-three sighted participants in a soundproof room 2 to examine peoples' ability to discriminate size of objects by using echolocation techniques. Among all the tests, they compared results with no sound generated and with the use of white noise produced by a small speaker that was attached to participants' foreheads. Obstacles were positioned at different angular directions. Although, the echolocation results with white noise were better than chance, the authors concluded that the differences were not statistically significant ($p = 0.052$).

In a recent study by Tirado *et al.* (2019) several participants have attempted tests both with synthetic clicks played from a loudspeaker and with their own mouth clicks. The authors observed that sighted participants novices to echolocation generally did better with the synthetic sounds, while the blind participants performed equally well with mouth clicks and with the sound played from speakers. The key might be a lower ability of the inexperienced echolocators to produce repeatable "efficient vocalizations", while loudspeaker-generated sounds are perfectly repeatable.

There is a lack of a clear answer as to the usefulness of noise sounds for echolocation. One of the few studies that compared different types of sounds (Arias, Ramos, 1997) showed that white noise resulted in more correct echolocation answers than click sounds for a group of sighted volunteers in a test with recordings of real echoes, but not with synthetic echoes. On the other hand, in other studies (Ekkel *et al.*, 2017) white noise was a worse sound when compared to clicks, or there was no statistically significant difference between sound types (Norman, Thaler, 2020).

None of the sound-related studies used large numbers of participants, so many conclusions may not be significant; however, the general agreement is that sounds optimal for echolocation should be relatively wide-band with at least some energy in the higher 5–10 kHz range, but with a peak frequency in a range of 1–4 kHz. This is not only because of the sensitivity of the human ears, but also due to the reflectivity of various surfaces in the environment (Norman, Thaler, 2018). Conclusions from older studies (Kish, 2003) show that higher frequencies are the key to localizing objects that are smaller and/or further away, but are not necessary for large and nearby objects. Similar conclusions have been drawn from bat echolocation studies, showing that bats use higher frequency ultrasound for localizing small insects, while lower frequencies for large obstacles and walls (Griffin, 1958, pp. xviii, 413).

Also, the familiarity of the echolocator with the sound, especially its spectral content, plays a key role, as demonstrated by Norman and Thaler (2020). This is likely why repeatability of an echolocation signal is important, and why inexperienced echolocators may prefer artificial sounds over untrained mouth clicks, which vary significantly in spectrum (Bogus, Bujacz, 2021).

A final observation from other studies (Thaler, Castillo-Serrano, 2016) and the authors' own experiences (Bujacz *et al.*, 2021) is that for experienced echolocators the sound source type seems to make little or no difference; however, for novice blind echolocators and sighted persons there are sounds that can give a significant improvement in echolocation accuracy, i.e., sounds with appropriately wide and predictable spectral content.

5. Blind versus sighted testers

From the 42 echolocation studies with volunteer participants reviewed in this paper, 31 were conducted with involvement of blind echolocators and 13 tested only normally sighted volunteers. Only 11 studies had more than 30 participants, while 14 had less than 10 participants. The first thing evident from the review is that the testing groups are usually very small, often too small to draw strong statistically significant conclusions, which has been noticed by previous meta reviews (Teng, Whitney, 2011). The usual textbook advice for parametric tests that expect probabilistic distributions of results is to collect a minimum of 30 samples (Corder, Foreman, 2009). The average number of blind participants in the reviewed studies was 8 and sighted participants 19. It was even more difficult to find experiments with a group of experienced echolocators larger than 3.

Several studies compare the listening abilities of blind and sighted with mixed results. On the one hand, the binaural localization accuracy of blind listeners has been shown to be worse with virtual sources (Dobrucki *et al.*, 2010), which can be attributed to the lack of audio-visual feedback training their perception. On the other hand, the visually impaired are definitely more experienced in interpreting sounds occurring naturally thus their sense of hearing is more trained, increasing the sensitivity to monoaural or binaural cues (Nilsson, Schenkman, 2016) as well as localization abilities in peripheral (Lessard *et al.*, 1998) and far-space (Voss *et al.*, 2004). In the two studies (Nilsson, Schenkman, 2016; Schenkman *et al.*, 2016) 23 and 12 blind testers took part in echolocation experiments, respectively and twice the number of sighted testers. The studies showed that blind people are more sensitive than sighted people to binaural sound-location cues, particularly inter-aural level differences (ILDs). The authors of the study suggest that this observation may be related to the blind person's experience of localizing reflected sounds, for which ILDs may be more efficient than the inter-aural time differences (ITDs). The latter study also shows that, on average, the blind outperforms the sighted testers (noise and bursting type sounds were used). It was also noted, however, that the three best sighted echolocators performed significantly above the mean performance of all the blind participants.

Quick learning capabilities of untrained novices in echolocation were also noted in the studies reported by Teng and Whitney (2011). These sighted testers were able to detect size and location of objects with a surprising precision. A majority of studies (Bujacz *et al.*, 2018; Thaler, Castillo-Serrano, 2016) confirm that blind echolocators perform generally better than the sighted participants, while some show a significant difference only in specific conditions, e.g., when using mouth clicks – compared to a loudspeaker (Thaler, Castillo-Serrano, 2016). Finally, a recent study with 17 blind testers conducted by Thaler *et al.* (2020b) have showed remarkable abilities of expert echolocators, who walked in test environments as fast as sighted (and not blindfolded) participants.

The main conclusion from the reviewed studies is that the main factor in echolocation ability is not blindness or sight, but the experience with the use of echolocation, even if untrained. Research has shown that echolocation skills can be quickly learned by sighted individuals, even to a level that outperforms blind individuals (Norman, Thaler, 2021). This observation suggests that effective echolocation training programmes can be worked out for novice echolocators (FIRR, 2019; Holmes, 2011).

5.1. Learning to echolocate

Several of the reviewed papers focused on the process of learning to echolocate and all came to the conclusion that sighted persons can acquire and demonstrate this skill just as efficiently (Thaler, Castillo-Serrano, 2016) or even better than the blind (Ekkel *et al.*, 2017; Teng, Whitney, 2011; Tonelli *et al.*, 2016), especially better than novice blind children (Bujacz *et al.*, 2018) or blind seniors (Norman *et al.*, 2021). By appropriate echolocation training, both the blind and sighted people can learn to confidently detect the presence and/or location of objects of up to distances of 3–4 m and thus use echolocation for obstacle avoidance and to aid in orientation.

Several publications have been aimed at developing a curriculum for echolocation training (FIRR, 2019; Kish, Hook, 2017; Norman *et al.*, 2021). Typical exercises in such training programs involve first improving awareness of echoes, as our brain intuitively ignores them. Daniel Kish has referred to this step as "unlocking". Other preparatory exercises involve practicing general sound recognition and localization skills to improve overall hearing. Then the practice moves on to the sound source signals (usually mouth clicks) to make them as repeatable as possible and as loud as necessary.

Recently a valuable active echolocation training curriculum for people with visual impairment has been elaborated within the Erasmus+ EU programme titled: Echolocation for people with visual impairment (FIRR, 2019) in which three countries have participated, i.e., Poland, Denmark, and Lithuania. This open access (under a Creative Commons License) curriculum is dedicated to Orientation & Mobility (O&M) instructors as an educational aid for teaching active echolocation. It consists of four parts: basic theoretical information on echolocation, learning to produce tongue-click in basic exercises in using active echolocation inside buildings, active echolocation exercises in an outdoor environment, and finally the use of complex active echolocation skills, and the methods of on route problem solving.

A very recent paper on a 10-week echolocation training of 14 sighted and 12 blind participants (Norman *et al.*, 2021) has made some interesting observations. Throughout the course that included both live and VR exercises, the sighted participants performed better than the majority of the blind. This may be because many of the exercises and tests included virtual sounds unfamiliar to both groups and because the sighted group was overall younger.

6. Conclusions

With the ongoing research we understand the phenomenon of echolocation more and more. Myths of "facial vision" and "obstacle sense" are a thing of the past (Stock, 2022). It is a well-documented auditory based phenomenon that both blind and sighted people can learn with practice (Norman *et al.*, 2021). Since most sounds reflected from the environment fall below the delay threshold to be consciously recognized as separate auditory events, the echolocation skill must be implicitly learned through repeated use (Arias *et al.*, 2012). Neurological studies of blind echolocation experts show that the extremely flexible human brain will start to utilize regions previously responsible for vision to process sounds of environmental echoes (Thaler *et al.*, 2011).

Testing of echolocation performance primarily consists of volunteer subjects determining the presence of nearby objects based upon emission of a source sound. In the majority of studies the subjects are stationary, the objects are disks 1 m or smaller in diameter and at distances from several centimeters up to 4 meters. The simplest tests require declaring the presence or absence of an obstacle (which for ease of procedure is usually a surface rotated to show either the flat or edge "view"), while the more complex ones also ask about the direction or distance, or have participants discriminate between different objects. The tests are best conducted in naturally reflective environments as echolocation performance in anechoic or acoustically dampened rooms is usually lower (Bujacz *et al.*, 2022a; Schenkman, Nilsson, 2010). Although the use of binaural recordings or virtual reality with spatial audio is much more efficient for conducting experiments, the echolocation effectiveness when compared to real-life trials is significantly lower. This doesn't invalidate the results, but lower correctness rates are to be expected in research with recordings than in live experiments.

The sounds most frequently used in echolocation and echolocation-related experiments are oral palatal clicks made by the echolocators, or when using loudspeaker generated sounds either artificial clicks, percussive sounds or short noise bursts. Generally, the ideal sounds for echolocation should be familiar to the echolocator, repeatable, have a peak frequency near the human optimal hearing range (2–5 kHz), but also have a high fractional bandwidth (components in a wider spectrum around the center frequency). New research suggests, the high frequencies may produce better effects simply due to higher intensities of reflected sounds from typical surfaces used in experiments (Norman, Thaler, 2018).

Many of the reviewed studies had a common weak point – a low number of participants. This is understandable due to difficulties in finding visually impaired volunteers, especially those experienced in echolocation. However, this can be remedied using various statistical tools, such as repeated tests for different subgroups (van de Schoot, Miočević, 2020) and calculating the minimum detectable effect sizes for the utilized sample sizes (Norman *et al.*, 2021).

A promising conclusion is that both blind and sighted persons can efficiently learn echolocation. After comparable training courses sighted blindfolded novices outperform inexperienced blind echolocators (Norman, Thaler, 2021). This may be a strong argument to begin echolocation training by persons at high risk of losing eyesight, such as those with progressing cataract or glaucoma.

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