Human Echolocation: Blind and Sighted Persons' Ability to Detect Sounds Recorded in the Presence of a Reflecting Object

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Human echolocation: Blind and sighted persons' ability to detect sounds recorded in the presence of a reflecting object

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Abstract. Research suggests that blind people are superior to sighted in echolocation, but systematic psychoacoustic studies on environmental conditions such as distance to objects, signal duration, and reverberation are lacking. Therefore, two experiments were conducted. Noise bursts of 5, 50, or 500 ms were reproduced by a loudspeaker on an artificial manikin in an ordinary room and in an anechoic chamber. The manikin recorded the sounds binaurally in the presence and absence of a reflecting 1.5-mm thick aluminium disk, 0.5 m in diameter, placed in front, at distances of 0.5 to 5 m. These recordings were later presented to ten visually handicapped and ten sighted people, 30 – 62 years old, using a 2AFC paradigm with feedback. The task was to detect which of two sounds that contained the reflecting object. The blind performed better than the sighted participants. All performed well with the object at < 2 m distance. Detection increased with longer signal durations. Performance was slightly better in the ordinary room than in the anechoic chamber. A supplementary experiment on the two best blind persons showed that their superior performance at distances > 2 m was not by chance. Detection thresholds showed that blind participants could detect the object at longer distances in the conference room than in the anechoic chamber, when using the longer-duration sounds and also as compared to the sighted people. Audiometric tests suggest that equal hearing in both ears is important for echolocation. Possible echolocation mechanisms are discussed.

1 Introduction

Blind people use echoes to detect objects and to find their way. In the forties and fifties, Dallenbach and coworkers (eg Cotzin and Dallenbach 1950) showed that the stimulation had to be aural to evoke the sensation of what was then called 'facial vision' (Supa et al 1944). About the same time, it was shown that echolocation is important for species other than humans, such as bats (Griffin 1958). Research on how other animals use echolocation may to some extent generalise to human echolocation. It is also possible to do experiments on human echolocation to gain understanding of how animals like dolphins use echolocation (DeLong et al 2007). However, human ability is less evolved, and the sensory mechanisms used by humans may thus be different from those used by animals (see also Griffin 1973). There is an important difference between animal and human echolocation. Animals mostly use their own emitted sounds and their reflections from an object. A blind person may use his or her self-generated sounds, eg by the voice, but it is also usual to use sounds generated by mechanical means such as the shoes, a cane, or some device like a clicker. This is in line with how the notion of 'echolocation' was used by eg Dallenbach and his team, and by Griffin (eg 1958). When comparing echolocation tasks of bats and dolphins, Au (2004) distinguished between six different tasks that echolocation may have. One of these was target detection in a 'noiseless' environment, which is the focus of the present study.

One much discussed issue is whether blind people are superior to sighted people in echolocation. Does perceptual training in using echoes to gain information about the environment make blind persons more efficient in echolocation than sighted persons?

This issue is important, because it relates to the possibility of systematic training of echolocating ability in newly blind persons. There have been only a few studies that directly compared blind and sighted participants, and the evidence is inconclusive. Kellogg (1962) found that the blind persons were superior to sighted persons in their ability to detect echoes. Rice (1967) reported that both sighted and blind subjects could perform satisfactorily in an echo-detection test. Juurmaa (1969) found that 'obstacle detection' was superior in congenitally blind than in adventitiously blind or sighted persons. However, most other studies on human echolocation have not included both sighted and blind participants. One of the aims of the present study was therefore to directly compare echolocation ability in blind and sighted people under various environmental conditions.

As pointed out by Arias and Ramos (1997), research on human echolocation is scarce and nonsystematic. Therefore, psychoacoustic experiments are needed to clarify environmental conditions under which human echolocation is possible. We employed a rigorous psychophysical methodology together with modern digital instrumentation to explore echolocation in blind and sighted listeners in different environmental conditions, including distance to reflecting objects, duration of emitted sounds, and reverberant properties of the room. Early research showed that human echolocation is strongly dependent on distance to objects (eg Kellogg 1962; Rice et al 1965). However, the interaction between object distance and stimulus duration and reverberant conditions of the room has not been previously determined. Knowledge of such interactions has practical implications, since it may guide the design of environments and aids for visually handicapped people.

In experiments on human echolocation, participants are asked to detect or discriminate between objects using auditory information from emitted sounds and their reflections. In such studies 'echolocation' is defined operationally in terms of detection performance, assessed as the proportion of correct responses or some related sensitivity measure. Ashmead and Wall (1999) pointed out that the term 'echolocation' is sometimes also used for auditory detection of objects, such as nearby walls, based on information in the ambient sound field, without any self-emitted sounds or sounds from external sources. They argued that such phenomena are better discussed in terms of spatial hearing or sound localisation than echolocation. The spectral variations in the ambient sound field may also provide a blind person with information about the surroundings, but this is not a case of echolocation. We agree with Ashmead and Wall (1999) that the term echolocation should be reserved for situations in which discrete, reflected sounds are being utilised. This is the focus of the present study, which is different from that of Ashmead and Wall (1999). In the present experiment, 'echolocation' was operationally defined as the ability to detect which of two sounds recorded in the presence of a reflecting object was the reflected one. It is important to note that human echolocation, especially at short distances, is not just a pulse-echo detection phenomenon, but a perception of a coloration of the sound, where the two sounds, emitted and reflected, together determine how the sound is perceived (Bilsen 1968).

Various psychophysical mechanisms have been proposed for human echolocation, in particular loudness and repetition pitch. When a direct sound is reflected from a nearby object, the direct and reflected sounds are combined with a time separation proportional to the distance to the object. The overall sound level, and thereby the perceived loudness of a sound in the presence of an object, would be higher than without the object, because the overall level of the direct plus reflected sound is greater than that of the direct sound alone, given that the repetition is strong enough to cause a detectable loudness increase. The perceived quality of the sound will also be affected by the reflecting object. When repetition of a sound is added to the sound after a delay, the listener may perceive a coloration of the sound or a pitch. This phenomenon has been called repetition pitch (Bilsen 1968; Bilsen and Goldstein 1974; Schenkman 1985; Yost 1996, 1997; see also Bassett and Eastmond 1964). Arias and Ramos (1997) studied echolocation by the use of repetition pitch in a laboratory setting, and showed the close connection between human echolocation and repetition pitch at close distances. However, all but one of their participants were sighted.

The ability to detect objects by echolocation diminishes with increasing distance and with decreasing size of the object (eg Kellogg 1962; Rice et al 1965). This suggests that echolocation is facilitated by an increase of surplus or redundant information, for example due to a short distance to the object or to a large reflecting object. Often, in perception, redundant information or information from many sources gives a more veridical perception (Gibson 1979). In the following, we will call this the 'information-surplus principle'. This principle may not always hold true, however. For example, short stimulus durations or anechoic environments might in certain situations facilitate detection of the reflected sound, where long durations and reverberant environments may mask the reflected sound. A main purpose of the present study was to explore the validity of the information-surplus principle at different stimulus durations and reverberant properties of the environment. We also explored the effects of personal factors on echolocation ability mainly, of course, visual status (blind versus sighted), but also hearing status, as determined by the participant's absolute hearing thresholds. In studies on other senses, eg odour naming, blind children have been found to have an enhanced performance (Wakefield et al 2004). Also in haptic manipulations, blind people have been shown to have a more efficient handling of objects than blindfolded sighted people (Postma et al 2007).

As the distance to an object increases, the perceived loudness, and also the repetition pitch of the direct plus reflected sound, diminishes. It is therefore difficult from studies using real environmental sounds to determine the relative importance of loudness and repetition pitch for echolocation. A blind person probably uses many sources of potential information to learn about possible obstacles. It is likely that use is made of both pitch and loudness, probably handled by different hearing mechanisms. We believe that a visually handicapped person at close distances to the reflecting object, say < 2 m, will rely more on repetition pitch, with loudness giving some additional information. However, at longer distances, the corresponding pitch will decrease (Bassett and Eastmond 1964), and it is possible that there will be a shift to other sources of information. Studies that take a more psychoacoustic approach, in which loudness and repetition pitch (or other basic auditory attributes inherently correlated in real life) are studied separately, will require artificial stimuli that cannot occur in real life. The primary focus in the present study is on environmental conditions and their effects on echolocation.

The general aim of the present study was to explore effects of environmental and individual factors on echolocation, treated as the ability to detect sounds recorded in the presence of a reflecting object. In particular, our experiments intended to test the following five hypotheses:

(i) If visually handicapped persons are superior to sighted persons in echolocation, then they should detect the presence of reflecting objects with a higher accuracy. Previous research gives some, but inconclusive, support for an enhanced ability of blind compared to sighted persons.

(ii) If the distance between a person and an object influences echolocation, then detection should decrease in an orderly fashion with distance. Previous research shows, as expected, a strong effect of distance on echolocation. However, with the exception of object size, interactions between distance and other environmental factors have not been previously explored in a systematic fashion.

(iii) If signal duration influences echolocation and is related to an information-surplus principle, then long signal durations would be beneficial for echolocation. However, masking of reflected sound by direct sound may give an opposite effect.
(iv) If echolocation depends on the amount of reverberations in a room, then an information-surplus principle would predict that reverberant environments are beneficial for echolocation compared to anechoic environments. However, multiple reflections from walls and ceilings may mask reflections from the object and therefore make echolocation harder.
(v) If echolocation is related to hearing ability, then hearing status should be important for the ability to echolocate. Human hearing deteriorates with eg age. Although our experiment allows only correlational analysis of hearing status and performance on the echolocation task, it may provide suggestions for possible mechanisms.

Earlier experiments testing echolocation have been very cumbersome, involving real rooms with real obstacles or participants walking along special routes (Rice 1967; Schenkman 1985). For practical reasons, such experimental designs cannot use very large numbers of stimulus presentations. A limited number of stimulus presentations precludes the use of advanced psychophysical methods, such as 2-alternative forced-choice (2AFC). Moreover, experiments with real objects make it difficult to ensure that the subjects do not use information other than the intended acoustic (Schenkman and Jansson 1986). Binaural recording technology makes it possible to realistically reproduce environmental sounds in listening experiments (eg Nilsson 2007) and was used in the present experiments, making it possible to study several environmental factors and their interactions under controlled conditions.

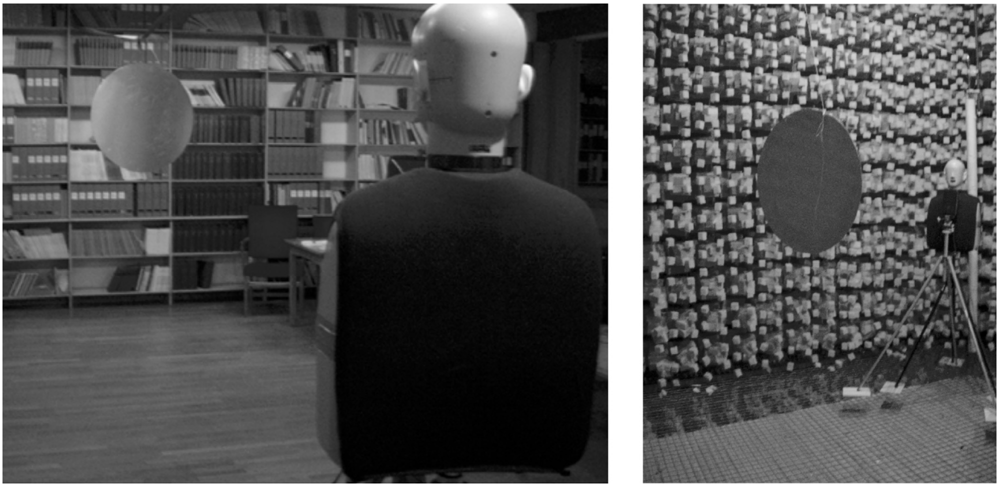
2 Method

2.1 *Sound recordings*

Binaural sound recordings were conducted in two rooms, an ordinary conference room and an anechoic chamber. The setup for recordings in the two rooms was identical. An artificial manikin was used, which was placed with its ear entrances (microphones) at the same height as the centre of the reflecting object, 1.7 m above the floor. The object was a reflecting 1.5-mm thick aluminium disk with a diameter of 0.5 m. Recordings were conducted at a 0.5, 1, 2, 3, 4, and 5 m distance between microphones and the reflecting object. In addition, recordings were made with no obstacle in front of the artificial head.

The following durations of the noise signal were used: 500, 50, and 5 ms; the shortest corresponds perceptually to a click. The rise and fall times of the 5, 50, and 500 ms signals were 0, 5, and 50 ms, respectively. The electrical signal was a white noise. However, the emitted sound was not perfectly white, because of the nonlinear frequency response of the loudspeaker and the system. For each signal duration and obstacle distance, ten measurements were performed with ten different random-noise signals. The sound pressure level of the 500 ms noise signal at the ear of the artificial head, recorded without reflecting object, was 79 and 77 dBA in the conference room and the anechoic chamber, respectively. The object was hanging from a thin nylon wire attached to a plastic cable. The cable was running between the walls of the room at a height of 2 m and the obstacle was moved along it with the centre position constant to the artificial head at each of the specified distances.

A loudspeaker generated the sounds, resting on the chest of the artificial manikin. Its lower edge was 1.42 m above the floor and its upper edge was 1.58 m above the floor. At the time of the recordings, the recording personnel were in an adjoining room. The sound reproduction and recording equipment was located on the floor in the conference room (figure 1a). Behind the artificial head was a large glass window, and in front of it a large bookshelf. The distance from the ears to the window was 2.0 m and to the bookshelf 7.16 m. To the left there was an oblique wall at a distance of 2.44 m and to the right the distance to the wall was 5 m. The height of the room



(a) (b)

Figure 1. Sound recording setup (a) in the conference room and (b) in the anechoic room.

was 2.57 m. The ambient sound level in the room was about 21 dBA. The reverberation time, T_{60}, was 0.4 s. This room had a wooden floor and was not carpeted.

The anechoic chamber had the dimensions of 5 m $\times$ 6 m $\times$ 3.7 m as measured inside of the absorbents. The floor was a metal matrix. The artificial head was placed at the end at one of the diagonals of the room, and the obstacle hung in nylon wires from a cable that belonged to the room. This wire was 3 m above the floor.

The sound generating and recording equipment was located on one of the short sides of the anechoic room, to the left of the artificial head, as viewed from behind (figure 1b).

2.2 *Sound equipment*

In both the conference room and in the anechoic room, the same kind of technical equipment was used for producing and recording the sound. For reproducing the sound (in mono) we used a loudspeaker and an amplifier (Sony SRS-D4 with subwoofer disabled), a high-quality sound card (VXPocket 440), a portable computer (IBM X40), and software for sound reproduction, 24 bit/48 kHz (Sound Forge 8.0).

The equipment used for the binaural recordings of the sounds consisted of an artificial manikin, a Head and Torso Simulator for binaural recordings (Brüel & Kjær type 4100), including two internal microphones (Brüel & Kjær type 4190) and pre-amplifiers (Brüel & Kjær type 2669), a 4-channel conditioning amplifier (Nexus, Brüel & Kjær type 2690 A 0S4), a portable computer (Dolch NPAC-Plus P111), a sound card, two-channel analogue input (LynxTwo Model C), software for sound recording, 24 bit/48 kHz (Sound Forge 6.0), and a calibrator (Brüel & Kjær type 4231 plus adapter model 0887) which, together with an adapter for a binaural head, gives a signal of 1 kHz at 94.5 dB.

The equipment for sound reproduction was a four-channel sound card (VXPocket 440), a portable computer (IBM X40), software for sound reproduction, 24 bit/48 kHz (Sound Forge 8.0), and earphones (Sennheiser HD 580 Precision).

2.3 *Physical characteristics of the sound signals*

2.3.1 *Autocorrelation function (ACF).* Correlation analyses are often used to describe the auditory system (see eg Blauert 1983). The autocorrelation function (ACF) is an essential component of many pitch theories, especially those involving repetition pitch (see eg Bilsen 1968; Yost et al 1996), and is therefore important for understanding echolocation, since echolocation is assumed at least partly to be based on an autocorrelation process.

One may say that the ACF describes the similarity between observations of the signal as a function of the time separation between them and is used for finding repetitions in patterns. A strong peak in an ACF in an echolocation signal would indicate an informative locus for a blind observer. Therefore, the autocorrelation was calculated for all experimental sounds.

For all the different versions of the 36 experimental sounds (3 durations $\times$ 6 distances $\times$ 2 rooms) a quotient was calculated. For each stimulus, the arrival of the first reflection could be determined, since the distance to the object was known, and the sound velocity could be assumed to be 344 m s^{-1}.

The value of the autocorrelation for the reflection of the signal, ACF1, was divided by the value of the autocorrelation at time 0, ACF0. In determining the value of ACF1, we allowed a correction of 5% for calculating the reflection. At the distance of 0.5 m this results in a range of 2.5 cm, and at 5 m in the range of 25 cm. The maximum value within this range was set to ACF1. The quotient used was $Q = \mathrm{ACF1}/\mathrm{ACF0}$. Since there were a number of replicated measures, or versions, of each physical stimulus condition, the average of each quotient was calculated (see Appendix 1).

2.3.2 *RMS values.* Since, as noted above, the perceived loudness of the signals may also provide information for echolocation, a measure of the energy content is also required. Average RMS values are listed in Appendix 1.

2.4 *Participants*

All participants, ten blind and ten sighted, were, or had been, employed at Synskadades Riksförbund (The Swedish Association of the Visually Impaired). Blind and sighted participants were paid for their participation in the experiment. The hearing of all participants was tested with the Interacoustic Diagnostic Audiometer model, AD226. The method used was Hughson Westlake, which is a standard method for measuring pure-tone threshold for detection (American National Standards Institute 1997). It uses ascending and descending methods of limits with a single stimulus for measuring the auditory thresholds. Usually the threshold is set to the lowest level at which a listener detects a signal for 50% of the ascending runs.

The thresholds were measured for both ears for the frequencies of 125, 500, 1000, 2000, 3000, 4000, and 6000 Hz. These may be requested from the authors. To summarise the hearing level values into one value the pure tone average thresholds (PTA4F) at the frequencies 500, 1000, 2000, and 4000 Hz were calculated, as well as the mean of the sum of the absolute differences between the two ears (table 1). The former give

Table 1. Pure tone average threshold, PTA4F, for the frequencies 500, 1000, 2000, and 4000 Hz and also the absolute differences between the two ears of the visually handicapped and the sighted participants.

Visually handicapped		Sighted			
Subject	PTA4F/dB	Absolute ear difference/dB	Subject	PTA4F/dB	Absolute ear difference/dB
A	26.9	11.3	K	6.3	2.5
B	8.8	5.0	L	1.9	1.3
C	12.5	5.0	M	45.6	13.8
D	1.3	2.5	N	6.9	1.3
E	18.8	7.5	O	14.4	1.3
F	11.3	2.5	P	4.4	1.3
G	4.4	1.3	Q	18.1	3.8
H	1.3	2.5	R	15.6	1.3
I	18.1	13.8	S	5.6	6.3
J	35.6	8.8	T	6.9	6.3

a mean value for dB hearing loss for four important frequencies, while the latter are presumably related to the ability to localise sound sources. The sound pressure levels of the stimuli were the same for all participants, so the sensation levels might have been slightly different across them owing to differences in hearing status. However, it is not likely this would strongly influence the results, because the task was to compare stimuli in a 2AFC paradigm and the relationship between two sounds would be the same if equal sensation levels were used instead of equal sound pressure levels.

2.4.1 *Blind participants.* The ten blind participants, five men and five women, were aged between 30 and 62 years (median = 54.5 years) and were all required to be mobile in order to take part in the experiment. If they had any formal training in echolocation, this would have been many years earlier. They had very limited vision—at most the ability to distinguish lightness shifts. Medical records were obtained, with the consent of the participants. They are listed in table 2 where it is also shown how the participants described their own visual perception or their lack of it, as well as their age and age of onset of blindness, ie when they were considered to be blind. Of these participants, seven had been blind since birth, ie early blind, while three became blind later in life. Two of the blind participants, A and J, had mild hearing deficiencies (see table 1).

Table 2. Medical diagnosis of vision deficit for the visually handicapped subjects, together with their own description of their visual status.

Subject	Diagnosis	Visual status (as reported by the participants)	Age at time of test, age at onset of blindness/years
A	brain tumour	right eye: none; left eye: some light perception	59, 17
B	incubator	nonexistent	53, birth
C	congenital glaucoma	some colour perception (own words)	55, birth
D	retrolental fibroplasia; incubator	nonexistent	51, birth
E	right eye: chronic uveit; glaucoma and corneit; left eye: prothesis	right eye: some guiding sight; large colour fields left eye: none	62, 18
F	degenerative	some light perception	54, birth
G	oxygen by incubator	nonexistent; earlier some sight	30, birth
H	retrolental fibroplasia; incubator (participant's own reporting)	very limited light perception	43, birth
I	congenital glaucoma	nonexistent	32, birth
J	colomba retinae-chorodriodinae and iridis.oc.amb, and nystagmus	some light, motion, or shadow perception	61, 38

2.4.2 *Sighted participants.* The ten sighted participants, two men and eight women, were aged between 23 and 60 years (median = 55.5 years). All reported to have normal vision. The sighted participants wore an eye patch over both eyes during the listening tests. One of them had hearing deficiencies in both ears. This participant was equipped with a hearing aid a few weeks after the tests. Two of the sighted participants had hearing deficiencies at high frequencies, both in the right ear (table 1).

2.5 *Experimental design*

We used a mixed design with one between-group variable and three within-group variables. The between-group variable was participant group (blind/sighted). The within-group variables were distance from head to reflecting object (0.5, 1, 2, 3, 4, and 5 m), signal duration (5, 50, and 500 ms), and type of room (reverberating room and anechoic chamber). Thus, the design contained $2 \times 6 \times 3 \times 2 = 72$ experimental conditions.

2.6 *Procedure*

A 2AFC procedure with feedback was used. In each trial, two sounds were presented: one recorded with and one without the presence of the reflecting object. The order of the two signals was random. The task was to detect which of the two signals was recorded in the presence of the reflecting object. The participants were not told beforehand what condition they were to listen to. At the time of signal presentation, the experimental leader did not known the correct response. An interval of 450 ms of silence had been added to each signal, and the interstimulus interval was 400 ms. Thus, the total listening time for one trial for the short 5 ms clicks was 1310 ms ($5 + 450$, 400, $5 + 450$ ms); for the medium 50 ms signals, 1400 ms ($50 + 450$, 400, $50 + 450$ ms); and for the long 500 ms signals, 2300 ms ($500 + 450$, 400, $500 + 450$ ms).

Each participant completed 36 sessions, one for each combination of within-group variables ($6 \times 3 \times 2$). Each session contained 56 trials. Half of the sessions was presented on one day and the remaining 18 on another day. The order of sessions was irregular and different for each person.

The participant listened to the sounds through open earphones, Sennheiser type HD 600, and responded by pressing one of two keys on a computer keyboard. A recorded voice gave feedback after each trial. Feedback was given because previous research had suggested that echolocating performance of blind people may deteriorate if feedback is not given (Rice 1966). The listening tests were conducted in a quiet sound-recording studio. The participants could take any time they needed for responding, but repetition of the sounds of a trial was not allowed. At the end of each session of 56 trials the experimenter reported to the participant the percentage of correct responses for that session.

There was a short pause between each session, and a longer pause between each block of six sessions. The experiment lasted between 2.5 to 3 h per day. The audiometric tests were conducted on a third day. Before the actual experiment, each person had a training session of 20 trials. The sounds had been recorded as described above, but with a different stimulus combination, recorded on a smaller disk, diameter 25 cm, at 25 cm and 5 m distances, that were not used in the actual experiment.

3 Results

3.1 *Statistical analyses*

The results were recorded as the percentage correct, p(c), for each listener and experimental condition. We used the 2AFC method which is insensitive to response biases (Macmillan and Creelman 2005). However, p(c) is unsuitable for statistical analyses of variance (ANOVA), due to heteroscedacity. Heteroscedacity denotes distributions where the variances are not equal for the different levels of the independent variable. This is inevitable in frequency distributions such as p(c). The assumptions of the analysis of variance are thus not fulfilled, which is why an arcsin transformation was used for the ANOVA, as recommended by Howell (1997) and Kirk (1968). We also conducted an ANOVA on d' values, which yielded very similar results as those obtained with the arcsin transformed p(c) values. We present some of the d' values below, but for brevity we show only the statistical analyses on the transformed p(c) values.

3.2 *Individual differences*

The mean percentage of correct judgments of the participants in the two rooms are presented in figure 2. For fifteen out of twenty participants, performance was better for sounds recorded in the ordinary room than in the anechoic chamber. Two blind participants in particular, B and F, had high detection performance. One sighted person, T, performed worse than the other participants. Analysis with this participant excluded did not change the interpretation of the overall results, and this participant's data were therefore included in the group analysis described below. The results presented in figure 2 give a general picture of the performances of the participants. These p(c) values are inflated by the chance level performance at distances greater than 2 m, because many, but not all, participants, were only guessing, when the object was further away. This increases the noise in the data. Partly for this reason, we also performed a threshold analysis (see section 3.3). This analysis was found to agree with the visual impressions from figure 2, namely that the blind participants on average were better than sighted participants, and that the performance of the blind generally was better in the conference room than in the anechoic room, whereas the performance of sighted participants did not differ systematically for the two rooms.

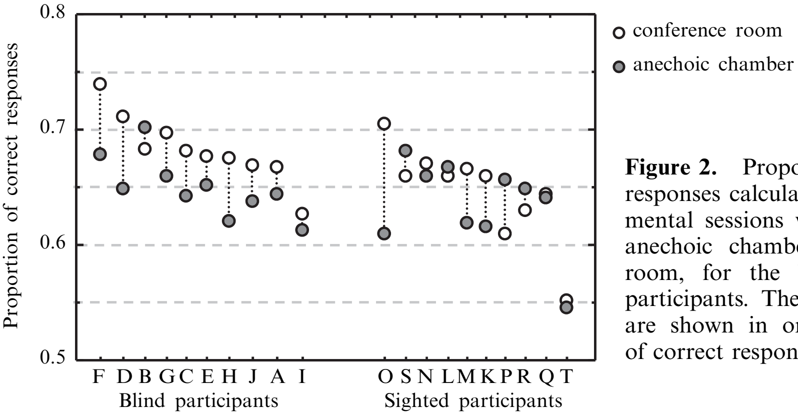


Figure 2. Proportion of correct responses calculated over all experimental sessions with sounds in the anechoic chamber and conference room, for the blind and sighted participants. The individual results are shown in order of proportion of correct response.

For the blind subjects the overall average d' was 1.10, while for the sighted it was 0.86. The individual d' for the blind subjects in both rooms were 1.07, 1.27, 1.03, 1.22, 1.11, 1.41, 1.20, 0.97, 0.75, and 0.94, respectively, while for the sighted they were 0.80, 1.07, 1.02, 0.99, 1.02, 0.78, 0.77, 0.76, 1.14, and 0.22, respectively.

3.3 *Detection analysis*

The average proportions of correct responses, p(c), are shown in figure 3. Results for the anechoic chamber and the conference room are shown in the upper and lower row of panels, respectively. Each column of panels shows the results for one of the three signal durations. Filled and open symbols refer to the average results for groups of blind and sighted participants, respectively.

As seen in figure 3, mean detection was highly dependent on the distance between the observer and the reflecting object. Detection ability decreased dramatically with distance, and was close to chance for distances greater than 2 m. In general, blind participants were superior to sighted participants at distances below 2 m. This agrees with the results of a mixed-design ANOVA performed on the arcsin-transformed p(c) values, which yielded a statistically significant main effect of group ($F_{1,18} = 4.93$, $p = 0.039$) and a significant distance $\times$ group interaction ($F_{5,90} = 2.61$, $p = 0.03$). The full summary of the ANOVA is presented in Appendix 2.

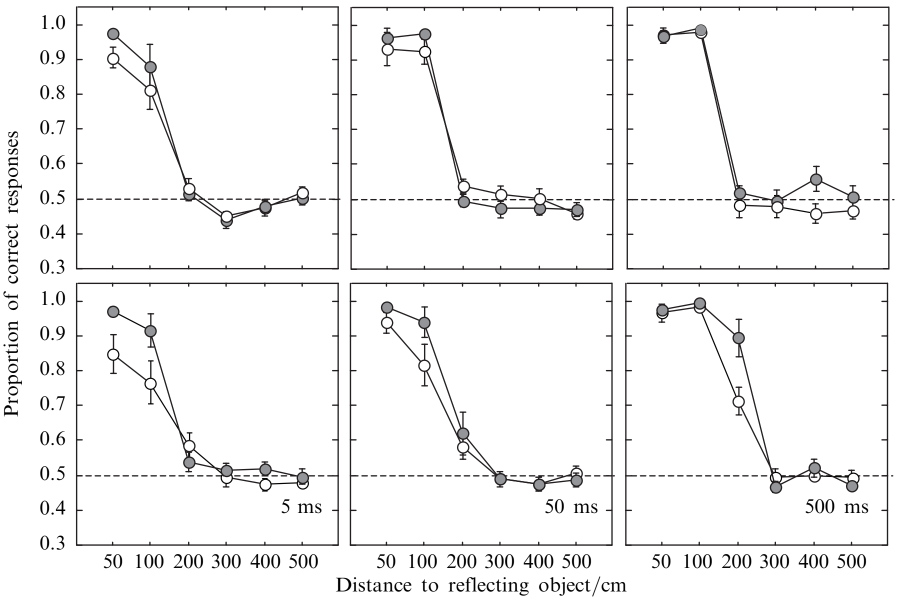


Figure 3. Mean proportion of correct responses with standard errors for sounds recorded in the anechoic chamber (upper row) and the conference room (lower row), separately for signal duration of 5 ms (leftmost), 50 ms (centre), and 500 ms (rightmost), and separately for blind (filled symbols) and sighted participants (open symbols). Distance between reflecting object and recording microphone (artificial head) is given on the *x*-axis.

For both groups of participants, mean detection increased with signal duration ($F_{2,36} = 21.7$, $p < 0.001$). Detection performance was also slightly better for sounds recorded in the conference room than in the anechoic chamber ($F_{1,18} = 7.67$, $p = 0.013$; see also figure 2). This was mainly due to the difference in one condition: 2 m object distance and 500 ms signal duration. In this condition, performance was close to chance for both groups in the anechoic room but above chance in the conference room, especially for the blind (this was also the condition with the greatest difference between blind and sighted participants). Figure 3 shows that in the conference room, detection was clearly possible at 2 m with the 500 ms signal, and there was a weak tendency for improved detection also for the 5 and 50 ms signals. In the anechoic room, mean performance over all observers was close to chance at 2 m for all durations. Thus, the results suggest that for most people, especially blind people, detection may be possible at larger distances in reverberant environments (such as the conference room) rather than in anechoic environments. Probable causes for this are further discussed in section 5.4 below. This interaction effect of distance $\times$ duration $\times$ room was significant ($F_{10,180} = 7.14$, $p < 0.001$).

It is important to determine at what distance with a certain probability, eg $p(\mathrm{c}) = 0.75$, a person may detect an object by echolocation. In a practical situation it is usually best for a blind person to detect an obstacle as early as possible, ie as far as possible. We therefore conducted a threshold analysis, by fitting a psychometric function (cumulative normal) to the group data, $p(\mathrm{c})$ versus log distance, following the procedure described in Macmillan and Creelman (2005, chapter 11). We fitted the cumulative normal function using a logarithmic distance scale, because this gave a slightly better fit than a linear distance scale. The fit, R^2, of the functions ranged from 0.72 to 0.95. Table 3 shows the resulting thresholds obtained for $p(\mathrm{c}) = 0.75$. The thresholds refer to the distance to the object at the point of detection; greater distance implies higher sensitivity. The blind participants' thresholds were greater than the sighted participants',

Table 3. Detection thresholds for duration, room, and listener groups.

Room	Threshold/cm					
	5 ms		50 ms		500 ms	
	blind	sighted	blind	sighted	blind	sighted
Conference	127	84	137	105	179	147
Anechoic	114	92	120	113	144	124

a difference ranging from 8 to 43 cm (mean = 26 cm). Thresholds increased with stimulus duration and, on average, the thresholds were greater in the conference room than in the anechoic chamber. The effect of room was evident for the thresholds of the blind but not of the sighted participants.

3.4 *Association between detection and hearing ability*

For evaluating the association between hearing ability and echolocation we used the non-transformed values of $p(\mathrm{c})$. PTA4F, the pure tone average thresholds at the frequencies 500, 1000, 2000, and 4000 Hz, for the sighted observers had a correlation with proportion correct, equal to 0.03, while for the blind persons it was equal to -0.36. The negative sign means that impaired hearing (high dB threshold) was associated with poor detection performance. However, t-tests performed on these correlations (Howell 1997, page 257) were not significant ($p > 0.05$).

The correlation between mean sum of the absolute differences between the ears and $p(\mathrm{c})$ was -0.21 for the sighted participants, and -0.70 for the blind participants. Only the latter value was significantly different from zero ($p < 0.05$) and would explain approximately 48% of the variance in $p(\mathrm{c})$ for the blind persons (see figure 4).

Visual inspection of the plot of $p(\mathrm{c})$ against PTA4F or the absolute differences of the ears for the two groups of participants showed no serious departures from homoscedasticity for the data.

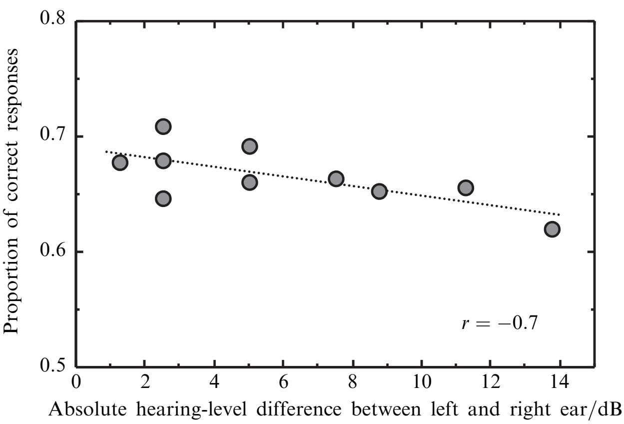


Figure 4. Absolute hearing threshold difference and proportion of correct responses, calculated over all experimental sessions, for the ten blind participants.

4 Supplementary experiment

Three blind participants—subjects B, C, and F—performed well at the 4 m distance in the anechoic chamber [$p(\mathrm{c}) > 0.69$]. This was surprising, given the large distance to the object and the close-to-chance performance for the other participants, blind and sighted, under this condition [$p(\mathrm{c}) < 0.59$]. This suggests that these three participants were able to use some information in the signal for detecting the reflecting object.

Since all three were blind, one might conclude that this ability was related to an efficient use of echolocation. However, it cannot be excluded that the high performance of the three participants was just the result of chance. The probability of obtaining 70% correct or better performance by chance at least once in 36 sessions is 0.08. The probability that at least one of twenty subjects obtains 70% correct or better by chance at least once is 0.81.

In order to exclude the possibility of chance performance in the first experiment, a supplementary experiment was conducted. The supplementary experiment included subjects B and F, who were the two best performing participants over all the conditions (cf figure 2). The two best-performing sighted participants, N and S, participated as controls.

The supplementary experiment consisted of six sessions. The first session was an easy 'warm-up' session. The subsequent experimental five sessions all contained sounds recorded in the anechoic chamber with or without a reflecting object at 4 m distance with the 500 ms signal. The test equipment, procedure, instructions, etc were identical to those in the main experiment. The supplementary experiment took about 40 min for each person. The subjects were reimbursed for their participation.

Figure 5 shows the proportion of correct responses, p(c), in the five experimental sessions, separately for the two blind and the two sighted participants. The blind participants B and F had a mean p(c) over all five sessions of 0.55 and 0.69, respectively. Participant F reached 0.75 correct in her last two sessions, similar to what she received in the first experiment. The two sighted observers, N and S, had a mean p(c) over all five sessions of 0.48 and 0.45, respectively, that is close to chance. We thus conclude that the performance of the high-performing visually handicapped participants in the main experiment was not based on chance or guessing, but reflected the ability to detect a reflecting object at 4 m distances in an anechoic environment.

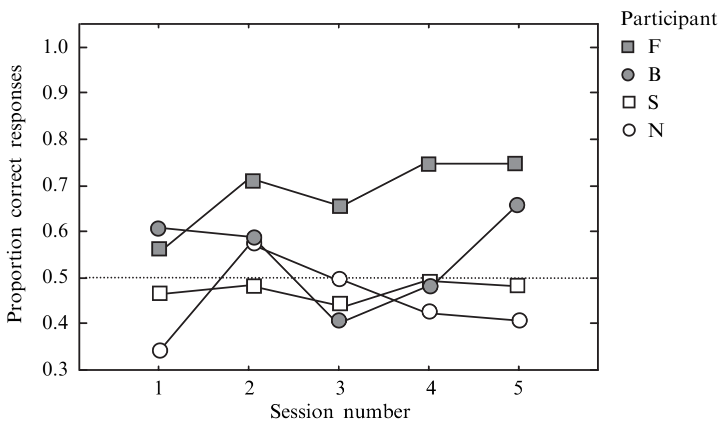


Figure 5. Proportion of correct responses in sessions 1 to 5 in the supplementary experiment for the two blind (B and F) and the two sighted (N and S) observers. All sessions included recordings conducted in the anechoic chamber with an object at 4 m distance and a signal duration of 500 ms.

5 Discussion

Our main results were that (i) overall, the blind persons were superior to sighted persons in detecting sounds recorded in the presence of the reflecting object; (ii) in general, detection was possible for an object distance of 2 m or less for the 500 ms signal, and of 1 m or less for the shorter signal durations; (iii) the detection performance was positively related to signal duration; (iv) detection was possible at slightly larger distances in the reverberant environment (conference room) than in the anechoic room;

and (v) detection performance was associated with hearing ability. We discuss these results in turn below, followed by a discussion of the relations between human echolocation and the ACF, and finally some remarks on methodological aspects of our study.

5.1 *Echolocation in visually handicapped and sighted persons*

Our results showed that the blind observers in general had a better performance than the sighted observers. For objects at distances below 2 m, both blind and sighted participants performed well, although the blind were slightly better. The difference between blind and sighted persons was greatest at the 2 m distance in the conference room. At longer distances, most listeners, sighted as well as blind, performed at chance. However, surprisingly, two of the blind participants could detect sounds recorded in the anechoic chamber with an object at a distance of 4 m. The supplementary experiment showed that this result could be replicated: the two blind listeners performed above chance whereas two sighted listeners did not.

Our result agrees with previous studies that have found blind persons to perform better than sighted in echolocation, using real environments and objects (Juurmaa 1969; Neuhoff 2004; Rice 1969). Some studies have failed to show superior performance of blind people. For example, Burton (2000) found no difference between blind and sighted in gap detection using a long cane, which is an important task for a blind person. He suggested that auditory information might exist, but that this kind of information is neither adequate by itself nor essential for gap judgment.

In real-life situations both motivation and attention are probably necessary prerequisites for high-performance echolocation, but it is not probable that the differences between the blind and sighted persons in our study were related to differences in motivation. We did not measure the motivation of the observers, but it was noticeable that also the sighted persons were motivated to get as high a result as possible. Almost all the observers exhibited frustration when they got a low result at the end of a session. We therefore think it is justified to believe that the differences between the blind and the sighted participants were related to perceptual rather than to motivational differences between the two groups of observers. It is not possible to determine from our study whether the superior echo-detection of the blind participants should be attributed to perceptual or physiological causes, or both. Our research question may be framed as "Do blind individuals hear better?". A similar question was raised by Bavelier et al (2006) for hard-of-hearing people: "Do deaf individuals see better?". They found some selective enhancements in visual cognition, especially for enhanced peripheral visual attention. For deaf people, there are also changes at a neural level, reorganisation of multisensory areas in cortical areas. We surmise that a similar hypothesis may also hold for blind people. They are more attentive to certain acoustic features in the signals, which may be related to cortical reorganisation. This would be in line with a conclusion by Wakefield et al (2004) that the improved attention by blind persons for sensory cues may underlie superior performance on some tasks.

5.2 *Echolocation and object distance*

For objects at distances of 50 or 100 cm, performance was relatively good for both groups of participants for all durations and both rooms. However, the blind participants were excellent at all durations, whereas the performance of the sighted participants declined as stimulus duration decreased. This suggests that the blind individuals were able to make use of information delivered in a shorter time window than sighted individuals. For objects at distances of 50 or 100 cm, there was also an interaction between group and room (shown best for the 5-ms stimuli): blind subjects showed little or no deterioration of performance going from the anechoic chamber to the conference room, but sighted subjects showed a sizable deterioration of performance. For the distances of 0.5, 1.0, and 2.0 m, the repetition pitch ($1/\tau$), where τ is the time delay in ms and assuming the speed of sound is 344 m s^{-1}, would correspond to pitches of a 344, 172, and 86 Hz tone, respectively, which is well within the audible range.

In addition, loudness discrimination could have been an important factor at the 0.5 and 1.0 m distances, because the RMS difference between sounds with and without an object was above the discrimination threshold for noise signals, 0.5 to 1 dB (Yost 2007). However, at the 2.0 m distance, the RMS difference between sound with and without object was less than 0.5 dB, which would be below the loudness discrimination threshold for most listeners. Thus, for this distance, repetition pitch might be the main source of information used in the detection task. Interestingly, the difference between blind persons and sighted persons was greatest at this distance (500 ms signal). It is, however, also possible that blind people have developed a very good loudness discrimination ability. Owing to the covariation of loudness with repetition pitch in our experiment, and in any experiment using realistic sounds with a variation in distance to object, it was not possible to determine definitely the extent to which the blind participants used repetition pitch or loudness discrimination for object detection. In a real-life situation, both sources of information are probably used. For instance, as a blind person approaches an object, both repetition pitch and loudness of reflected sound will provide information, as well as the changes in these sounds produced by the motion of the person, or by movements of the object itself (see eg Wilson 1967).

Two blind participants could detect sounds recorded with a reflecting object at 4 m distance in the anechoic room. The repetition pitch would correspond to a tone of approximately 40 Hz, which may be too low to give a distinct pitch experience. Furthermore, the level of the reflected sound decreases with distance, owing to geometrical spreading. Thus, at a larger distance, the reflected sound would be too weak to produce a detectable repetition pitch. The same is true for the overall level of the sound (original sound plus reflections). As noted above, acoustic analyses showed that the difference between the levels of sound recorded with an object at 2 m distance and sound recorded without an object is less than 0.5 dB, indicating that at this or larger distances object detection could not have been based on loudness information.

Some blind people may have developed remarkable abilities for the detection of repetition pitch as well as loudness discrimination, which may be the case for the two high-performing blind persons. They are both successful in their respective professions, and our impression is that they are active and mobile. They do not use a guide dog, and appear to be very attentive to acoustic information in the environment, including proficiency in object detection.

5.3 *Echolocation and signal duration*

The longer time duration of the stimulus produced a higher detection than the shorter time durations with better than chance performance. This agrees with a general 'information-surplus principle', which predicts that long signal durations are beneficial for echolocation. Thus, our results disagree with the hypothesis that masking of reflected sound by direct sound would give better detection performance for shorter sounds which are terminated before the arrival of the reflected sound. Our results are in agreement with eg Arias and Ramos (1997), who found that noise signals gave more information than click signals.

It should be noted that the number of pulses in the paradigm of repetition pitch is also a factor in the models proposed by Yost and coworkers (eg Yost 1997). In a situation, when only a short signal such as a click is heard, the subject may miss a signal owing to inattention, and may therefore give a wrong answer. If the number of pulses is increased, then it is possible that the echolocating ability of a subject exposed to short pulses would also increase.

5.4 *Echolocation and type of room*

Performance was slightly better for sounds recorded in the conference room than for those recorded in the anechoic chamber. In the anechoic chamber, detection was only possible for an object distance of 1 m or less, whereas in the conference room detection was possible at 2 m distance, at least for the 500 ms signal. This disagrees with the prediction that detection would be more difficult, because irrelevant echoes in the conference room would mask the information available to the listener. Instead, the results support a general 'information-surplus principle' that reflections from the walls, windows, and ceilings provide additional information to the subjects that may be used for echolocation. This result is in accordance with the perceptual theory of Gibson (1979). Rich stimulus information makes the perceptual task easy for the subject, while simple and few-dimensional stimuli make perception ambiguous and difficult.

Threshold distances at which the participants could detect the object, based on fitting the data to a cumulative distribution, showed that the blind group could detect the object at a longer distance than the sighted in all conditions and that the blind displayed longer detection distances in the conference room than in the anechoic chamber at all sound durations. One should remember that a longer detection distance indicates higher performance, since the blind person can then detect an object farther away. However, the sighted had longer detection distances in the anechoic chamber with the 5 ms and 50 ms long durations. We interpret this to mean that the blind, on average, used the rich information in the conference room better and that they were able to attend to small acoustic nuances.

Detection may thus be possible at larger distances in reverberant environments than in anechoic environments. We believe that one of the causes for this is that sound stimuli in the conference room have more a character of white noise, since there are several reflections from the walls that contribute to the emitted signal. In the anechoic chamber, the outgoing signal is coloured by the nonlinear transformations of the system, and there are no walls that can add additional information. If the echolocation at close distances is based on an ACF-process, then the signal acquiring the character of white noise will be easier to perceive, eg as a repetition pitch. In practice, this would mean that training of blind people in echolocation should be made in ordinary rooms with multiple reflections.

5.5 *Echolocation and hearing ability*

The ability to detect objects by echoes appears to have a relation to hearing capacity as measured by hearing thresholds. The correlations of the hearing thresholds with the detection values suggest that it may be important for visually handicapped people to have (equally) good hearing in both ears. The hearing levels in some frequency bands may also have some importance. It has been shown that there are impairments in sound localisation in different types of hearing impairments (Häusler et al 1983). If echolocation is related to sound localisation, then we interpret this to mean that hearing impairments will also be detrimental for echolocation. It should be pointed out, however, that these conclusions are based only on correlations from a relatively small number of listeners. Further studies would be needed in order to determine the role of hearing status for echolocation.

5.6 *Echolocation and autocorrelation function (ACF)*

The reason for using white noise and not environmentally commonplace sounds was to get a general sound that could be used in other experimental situations and that could be used for comparisons of the different participants. To calculate the ACF, one also needs to have a signal as close to a white noise as possible. However, these formal requirements may put a blind listener at a disadvantage, since he or she is not used to the sounds that are presented.

Furthermore, the signals did not have the desired form of white noise. The irregular behaviour of some of the ACFs is likely because the emitted sounds were not pure white noise, and comprised a coloration. The coloration is almost inevitable, since a loudspeaker often introduces nonlinearities to the emitted sound. This coloration is added, together with the properties of the room. Another possible cause of the irregular shape of the quotients for the ACF is that, despite a correction of 5% for the calculation of the value of the reflections, this position may vary as a result of sound velocity, humidity, and the length of the time interval of calculation. The irregular shape of the quotients for the ACFs made it difficult for us to try to relate them quantitatively to the perceptual detection values. The irregularities may also have arisen because of assuming a spherical head, instead of accounting for the influence of the external ears of the dummy head used for the recordings. However, because of the models for psychoacoustics of pitch that successfully use ACF (Bilsen 1968; de Cheveigné 2005; Yost et al 1996), we believe that the ACF is part of the explanation of human echolocation.

This problem is inherent in studies of human echolocation because of the relatively low frequencies that are used, and does not arise when analysing echolocation of eg bats by autocorrelation models because of the high frequencies of their outgoing signals. In laboratory experiments investigating repetition pitch, we assume that these problems do not arise, or are at least not as pronounced, since better control of the sound production is achieved by using headphones, and the properties of external loudspeakers do not influence the results. If human echolocation is at least partly dependent on autocorrelation-based mechanisms, then the more the emitted noise resembles white noise, the easier it will be for a person to detect objects. When emitted noise is (temporally) completely white, the underlying noise signal has undergone no other temporal filtering prior to the filtering caused by wave propagation and the reflecting object (see eg Papoulis 1984). Consequently, any difference between the produced ACF and the Dirac delta function is then entirely due to the wave propagation and the reflecting object.

5.7 *Methodological aspects*

A factor that might have reduced the ability of blind persons was that they did not use self-produced sounds. The use of such sounds would possibly increase the detection rate for blind persons, but not for sighted people. As far as motion is concerned, Rosenblum et al (2000) used an action-based study on echolocation and found that motion improved echolocation. However, Burton (2000) found that active exploration was not crucial for the task of crossability, when relying on a long cane.

It has been found that some bat species as well as dolphins use eavesdropping, ie they listen to the sounds of another individual that echolocates (Balcombe and Fenton 1988; Chiu and Moss 2008). This could be possible for some blind persons in some situations, but we think it is not so common, since for echolocation for many blind at short distances it is necessary to hear the outgoing signal sound. The reason is that repetition pitch can only be perceived, when both the original sound and its repetition are perceived, presumably from being present in a common region of the basilar membrane or the peripheral system (Bilsen 1968; Bilsen and Ritsma 1969/70). Echolocation is probably also facilitated when the blind person is close to the emitting source, since the signal and echo will then be more similar, making it easier to perceive repetition pitch. The reason for a bat to use eavesdropping may eg be to steal a prey from another bat. In the present study we did not use an eavesdropping methodology.

The methodology of the present study would probably be labeled as a 'passive psychophysical method' by Stoffregen and Pittenger (1995). A methodology that also takes into account perception – action couplings might show a higher performance for echolocation, as suggested by these authors. This was a disadvantage in the present setup, since the movements of the subjects did not provide any additional information, as they do in real life (called "auditory scanning" by Kellogg 1962). However, we have demonstrated that echolocation, treated as the ability to distinguish between sounds recorded with or without the presence of a reflecting object, is possible with the available stimulus information even under restricted conditions. A more traditional psychoacoustic approach would presuppose that echolocation is derived from perception of fundamental auditory attributes. However, we believe that echolocation is a direct perception of higher-order information available in the energy of the acoustic stimulus (cf Gibson 1979). In real-life situations, the performance of the blind people would probably be much better than that of sighted, since they would be able to utilise more information. This would be in line with the postulated information-surplus principle.

5.8 *Conclusions*

We tested five hypotheses and found that:

(i) Blind people performed better than sighted people when detecting echoes in a controlled laboratory environment.

An 'information-surplus principle' was supported:

(ii) Detection decreased in an orderly fashion with distance, but was affected by room and signal duration.

(iii) Echolocation increased with signal duration, ie longer sounds were better than short.

(iv) Echolocation was possible at larger distances in a reverberant environment than in an anechoic one, at least for the blind participants.

The results also suggested that:

(v) Binaural hearing status may be of importance for echo detection.

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Appendix 1. Quotients for the average autocorrelation function (ACF) and the average relative RMS values for the experimental sounds (in dB re-recordings with no reflecting object).

Distance/cm	Time/ms	Mean quotient ACF	Mean quotient RMS	Distance/cm	Time/ms	Mean quotient ACF	Mean quotient RMS
Anechoic room				*Conference room*			
50	5	0.27	4.41	50	5	0.28	4.79
100	5	0.21	2.13	100	5	0.12	2.33
200	5	0.39	0.47	200	5	0.05	0.43
300	5	0.26	0.12	300	5	0.07	0.02
400	5	0.25	0.04	400	5	0.05	0.01
500	5	0.27	0.46	500	5	0.06	0.02
50	50	0.17	4.64	50	50	0.19	4.27
100	50	0.11	2.36	100	50	0.07	1.76
200	50	0.13	0.12	200	50	0.06	0.35
300	50	0.17	0.20	300	50	0.13	0.004
400	50	0.27	0.73	400	50	0.18	0.02
500	50	0.10	−0.001	500	50	0.07	−0.003
50	500	0.14	4.65	50	500	0.25	4.27
100	500	0.05	2.37	100	500	0.03	1.84
200	500	0.04	0.04	200	500	0.05	0.31
300	500	0.05	0.06	300	500	0.07	0.0002
400	500	0.03	0.01	400	500	0.03	0.01
500	500	0.04	0.01	500	500	0.04	−0.002

Appendix 2. Summary of the mixed-design analysis of variance (ANOVA) of the arcsin-transformed values for the proportion of correct responses, with one between-group variable (blind/sighted) and three within-group variables (distance of reflecting object, signal duration, and type of room).

Variance component	Degrees of freedom	Mean square	F	p
Between subjects (Group)	1	1.253	**4.93**	0.039
Error (Subjects within groups)	18	0.254		
Distance (*D*)	5	40.367	**396.45**	< 0.001
Distance × Group	5	0.266	**2.61**	0.030
Error ($D \times$ subjects within groups)	90	0.102		
Duration (*T*)	2	1.514	**21.71**	< 0.001
Duration × Group	2	0.046	0.67	0.52
Error ($T \times$ subjects within groups)	36	0.070		
Room (*R*)	1	0.434	**7.67**	0.013
Room × Group	1	0.196	3.46	0.079
Error ($R \times$ subjects within groups)	18	0.057		
Distance × Duration	10	0.384	**9.17**	< 0.001
Distance × Duration × Group	10	0.194	**4.63**	< 0.001
Error ($D \times T \times$ subjects within groups)	180	0.042		
Distance × Room	5	0.625	**16.21**	< 0.001
Distance × Room × Group	5	0.071	1.83	0.11
Error ($D \times R \times$ subjects within groups)	90	0.039		
Duration × Room	2	0.249	**8.05**	0.001
Duration × Room × Group	2	0.024	0.77	0.47
Error ($T \times R \times$ subjects within groups)	36	0.031		
Distance × Duration × Room	10	0.251	**7.14**	< 0.001
Distance × Duration × Room × Group	10	0.063	1.78	0.07
Error ($D \times T \times R \times$ subjects within groups)	180	0.035		

Note: Significant effects ($p < 0.05$) are indicated in bold.

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