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Physical Analysis of Several Organic Signals for Human Echolocation: Oral Vacuum Pulses

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Summary
Active human echolocation can be an extremely useful aid for blind people. Active echolocation can be trained with both artificial and organic signals. Organic signals offer some advantages over artificial ones. Very detailed studies of organic signals in animals have been done. However, in the case of humans, the scientific literature is very scarce and not systematic. This is the first paper of a series on the properties of several suitable sounds for human echolocation. In this work, we offer a detailed analysis of these sounds, comparing their merits from a physical point of view. The results of this study have important applications to design systematic and optimized training protocols for accurate echolocation awareness.

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1. Introduction

Human echolocation is a very important factor for correct orientation in both blind and sighted people. More importantly, active echolocation, a kind of human sonar, can be trained to produce accurate spatial awareness and object detection in blind individuals. Some recent famous cases, like Dan Kish and Ben Underwood, prove the extremely high level of spatial information which can be achieved with this technique.

The phenomenon of active echolocation in animals, specially bats and dolphins, has been actively researched since World War II. These studies have important applications in biology, acoustics and sonar design. It is known that dolphins and the Egyptian Fruit Bat (*Rousettus aegyptiacus*) make clicks for active sonar. In contrast, microbats use laryngeal sounds, generally CW and/or FM chirped ones, to echolocate.

However, the study of the physical characteristics of the most accessible organic sounds for human echolocation is very scarce. Rice, [1], [2], found that blind participants were able to use a variety of artificial signals, but performance was always highest when those artificial signals resembled those to which the participants were accustomed. Kellogg, [3], Kish, [4], Magruder, [5], McCarty and Worchel, [6], Myers and Jones, [7], Rice, [1] and Schenkman and Jansson, [8], mention the oral click as a useful signal for echolocation. Unfortunately, none of these works specify the kind of click used in the experiments.

More recent work, [9], [10], [11], is mainly oriented towards artificial signals and simulated virtual environments. The advantages of artificial signals are the fine control and excellent reproducibility of the sounds. While natural echolocation is based on echo differences, artificial systems can use the full spectrum of sound parameters to optimize the echolocating experience. In spite of this, natural echolocation is as important as ever, for several reasons.

1. Natural echolocation is independent of any technological means. This can be extremely important in critical situations. A simple battery or electronic failure could be very dangerous even in common daily activities.
2. Safety and comfort. A natural echolocator needs no additional devices.
3. Individual acoustic signature. Our hearing sense is optimized for our own produced sounds.

In order to fill this gap in the literature, this work analyses several types of organic sounds suitable for echolocation. These sounds are easily reproduced with little practice and none requires artificial means. The studied sounds are:

1. Oral “ch” sound, produced by a quick backward movement of the tip of the tongue from the teeth.
2. Lip “ch” sound, produced by a quick vacuum between the closed lips.
3. Oral click, produced by a quick vacuum between the tip of the tongue and the front of the hard palate, without touching the teeth.
4. Finger snapping.
5. Hand clapping.

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6. Quick vocalization of the “iu” sound, similar to some bat chirps.
7. Quick whistles with a frequency decrease, similar to the “iu” sounds.

The analysis should cover at least the following parameters of the sounds:

- Intensity.
- Reproducibility.
- Duration.
- Spectral content.
- Usability.
- Adaptativeness.
- Noise immunity.

This is the first paper in a series devoted to the physical analysis of suitable signals for human echolocation. Due to the length of this study, only the vacuum oral pulses are analysed here. This includes the oral “ch” sound, the lip “ch” sound and the oral (tongue) click.

Most studies of human echolocation have been done in controlled or anechoic conditions. While this procedure is optimal for sound recording, it is impractical in real situations for blind people. For this reason, we have decided to record the sounds in a complex environment with sources of noise. The selected place is a typical computer room. The computers have been used as a convenient noise source. An absolute calibration effort of the recorded waveforms has not been performed. Instead, all the sounds have been normalized with respect to the same recorded noise level.

The sound recording has been performed with inexpensive equipment, a simple microphone connected to a standard sound card inside a commercial PC. The use of inexpensive and readily available instruments is justified by future developments of simple and cost effective biofeedback mechanisms for echolocation training. Several different microphones were used to verify the consistency of the recorded sounds. The sampling frequency was set to 192 kHz in order to achieve maximum temporal resolution. The recording, analysis and figures have been done with the *Praat* program, [12].

We have not performed an exhaustive statistical study of psychoacoustical parameters related with the recorded sounds. A quick summary of the most relevant perceptions associated with each sound, collected among ten people, will be presented with the results. These people are normal sighted subjects, selected among several colleages and students. They were trained in basic echolocation skills for several days until they were able to generate and clearly perceive the studied sounds and their echoes.

The qualitative analysis of each sound was performed assigning one of the following values to the proposed parameters: bad, poor, good, very good and excellent. The final parameters in this study correspond to the mean of ten values. In order to calculate the mean, it was assumed that the qualitative scale could be put in correspondence with numerical values ranging from 1 (bad) to 5 (excellent).

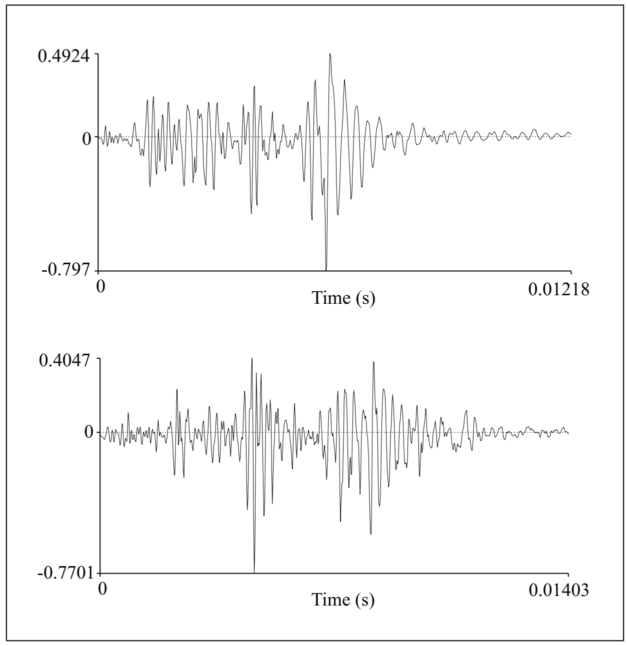

Figure 1. Waveforms of two samples of oral “ch” sound.

2. Physical analysis of the different sounds

2.1. Oral “ch” sound

The oral “ch” sound is easily produced moving backward the tip of the tongue from the closed teeth in a straight line, without touching any other part of the inner mouth. Two typical waveforms of this sound can be seen in Figure 1. The intensity of the sound in arbitrary, normalized units, is roughly between 0.5 and -0.80. The observed waveforms are complex and difficult to reproduce. This makes the physical modelling and interpretation of the results very difficult in general.

The complete duration of the pulse is generally between 12 and 15 ms, if we include the exponentially decaying final tail. If we only consider the main modulated part of the pulse, the duration can be as short as 5 ms. The pulse is formed by several (four of five) AM subpulses. The oscillations inside the subpulses have a duration of roughly 0.15 ms, although some of them could be shorter. The raise time of each oscillation is approximately 0.06 ms, but varies considerably among different oscillations. The decaying time of each oscillation is a little more uniform, near 0.05 ms. At full speed without pulse degradation, the minimum interval between pulses is 270 ms. The repetition period is relatively stable, but tends to be longer with time.

The frequency spectra, Figure 2, show a rich set of absorption bands, which cover practically the entire audible range. The rich set of frequencies is advantageous from the point of view of echolocation, because the higher the spectral content, the greater the information we can extract from the echoes. However, the bands are not stable between different performances of the sound. This reflects the lack of uniformity of the different waveforms.

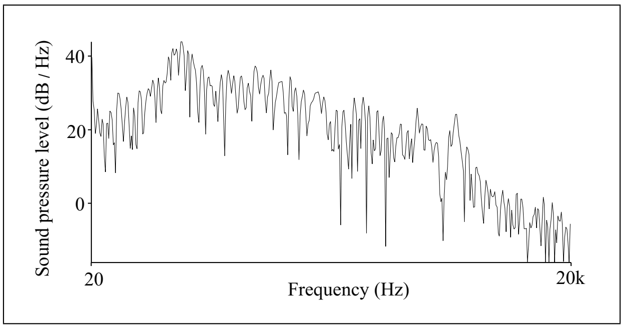

Figure 2. Frequency spectrum of an oral "ch" sound.

This sound is very easy to perform, although the quality of the sound tends to degrade after a few minutes of constant performance, due to the progressive dryness of the mouth. The final sound tends to be fairly amortiguated and furry. The intensity also decreases considerably. This reduces the effectiveness of this sound for regular echolocation.

Subjective appreciation of the sound by several individuals shows that this type of sound is useful for the first stages of echolocation learning, especially at close distance of the echoing objects. This is due to the clear difference in pitch between far and near echoes. However, this sound and its echo are easily hampered by ambient noise. The "ch" sound is specially difficult to discriminate when moderate levels of ambient noise are present. Human speech and heavy rain, for example, affect very negatively the reception of the echoes.

Two steps of a sequence of pulses is shown in Figure 3 while the subject's head is approaching a flat computer monitor from a distance of 45 cm. The pulses are very variable and a clear pattern cannot be extracted from the waveforms.

Summary of oral "ch" sound characteristics:

- Intensity: Good.
- Reproducibility: Poor.
- Duration: Good.
- Time interval between pulses: Good.
- Spectral content: Good.
- Usability: Good.
- Adaptativeness: Good, pitch and intensity can be easily varied.
- Noise immunity: Poor.

2.2. Lip "ch" sound

The lip "ch" sound is produced by a quick separation of the lips, previously pressed. Their physical characteristics are similar to the oral "ch" sound, but they are even more complex. In Figure 4 a typical waveform is observed. The most important feature is the little sound bump observed approximately 100 ms after the main pulse is emitted.

A detail of the main pulse can be seen is Figure 5. It shares most of the characteristics of the oral "ch" sound. Its intensity is very similar, but it degrades quickly with time, because it is very dependent of the lip moisture level.

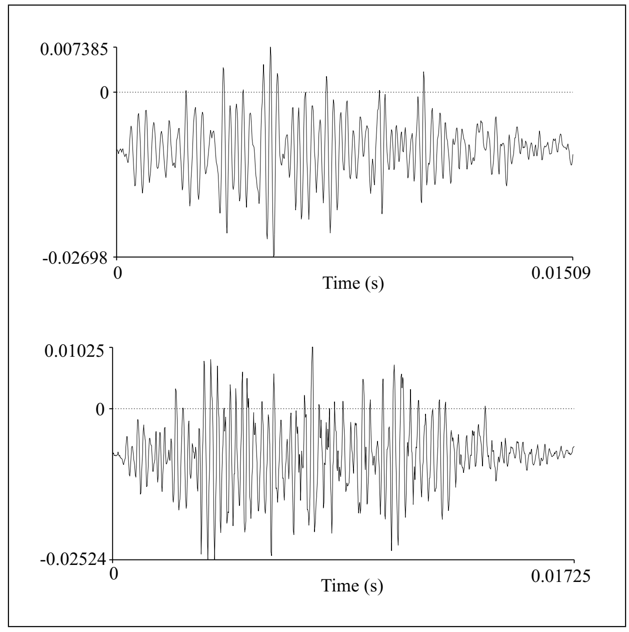

Figure 3. Waveforms of oral "ch" sound for a head approaching a flat computer monitor from a distance of 45 cm and 25 cm respectively.

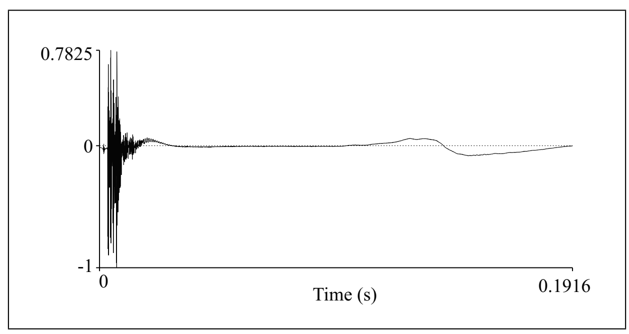

Figure 4. Waveform of a typical lip "ch" sound.

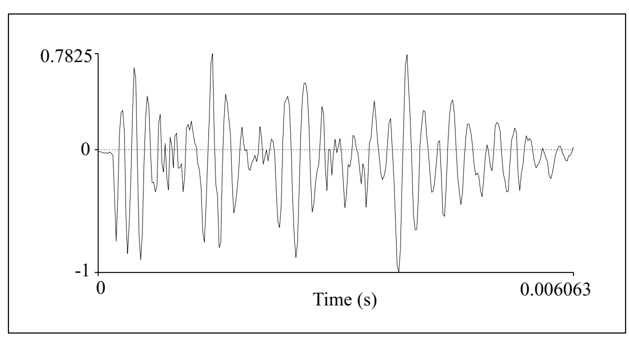

Figure 5. Detail of the main pulse of a typical lip "ch" sound.

It is also more much uncomfortable to sustain for extended periods than the oral "ch" sound. Besides, from a social and aesthetic point of view, it is far less convenient, because it forces the face expression. In contrast, both the oral "ch" and click sounds can be performed without appreciable facial expression forcing in most cases.

The frequency spectrum for the lip "ch" sounds are also similar to the oral ones, but with more frequent and deep absorption bands.

Summary of lip "ch" sound characteristics:

- Intensity: Good.
- Reproducibility: Poor.
- Duration: Poor, if we consider the secondary pulse.
- Time interval between pulses: Poor.
- Spectral content: Good.
- Usability: Poor.
- Adaptiveness: Poor, pitch and intensity cannot be appreciably varied.
- Noise immunity: Poor.

2.3. Oral click

Empirical research by Kish, [4], has shown that tongue oral clicks can be considered almost ideal candidates for echolocating organic signals. Our study confirms these findings. The sound is produced by a quick release of the vacuum produced by the tip of the tongue in the upper end of the hard palate. These palatal clicks are significantly clearer and more intense than alveolar ones. In Figure 6 two samples of palatal clicks are shown. Alveolar click waveforms are represented in Figure 7. The study of the waveforms reveals that palatal clicks are clearly superior to alveolar ones in terms of intensity and uniformity.

Palatal clicks can achieve a normalized intensity between -1 and 1, more than the "ch" sounds. This is over the noise level of a typical human conversation or heavy rain. Less intense pulses tend to decay more slowly than more intense ones. The intensity and pitch of the clicks could degrade if mouth dryness is allowed. The waveform is very stable and is similar to a J Bessel function or to a sinus modulated by a decaying exponential. This similarity is suggestive, because spatial Bessel beams are non diffracting. In this case, only the temporal behaviour has been recorded. If both temporal and spatial Bessel beams could be propagated, the applications for highly accurate echolocation would be immediate.

Each pulse is formed by a set of decaying oscillations with very regular time separations between successive maxima of approximately 0.85 ms. During this time, the sound would travel roughly a distance of 29 cm in air. The raising time of each pulse varies a little, but it is near 0.4 ms in all cases. The decaying time of each oscillation is slightly longer, but the mean is 0.45 ms. These measures prove that palatal clicks can be used as a good reference for distance estimation. The minimum interval between successive pulses is less than 250 ms. Such quick repetitions could be necessary to echolocate in certain circumstances. These repetition rates can be sustained comfortably with good accuracy for several minutes without significant performance degradation. Rates of 2 pulses per second can be sustained almost indefinitely. An additional advantage of clicks is that they do not interfere with breathing, because they do not use the expelled air to generate the sound.

The spectral content of palatal clicks can be seen in Figure 8. The spectrum is formed by a set of clearly separated bands. The main peak is situated in this case at 1150 Hz, but a large amount of energy is spread among several bands along the entire audible range. This rich spectral feature is very important for accurate echolocation in complex environments. The combination of a relatively simple waveform and rich spectral content makes palatal clicks almost ideal signals for human echolocation.

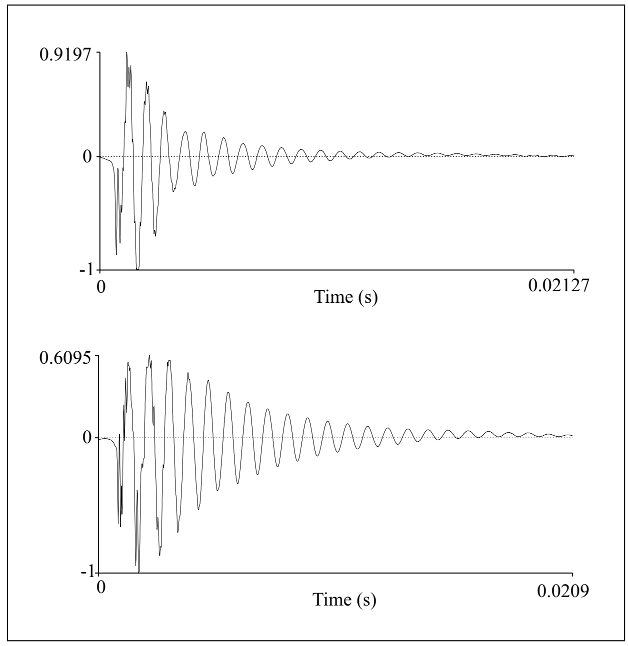

Figure 6. Waveforms of two samples of palatal click sound.

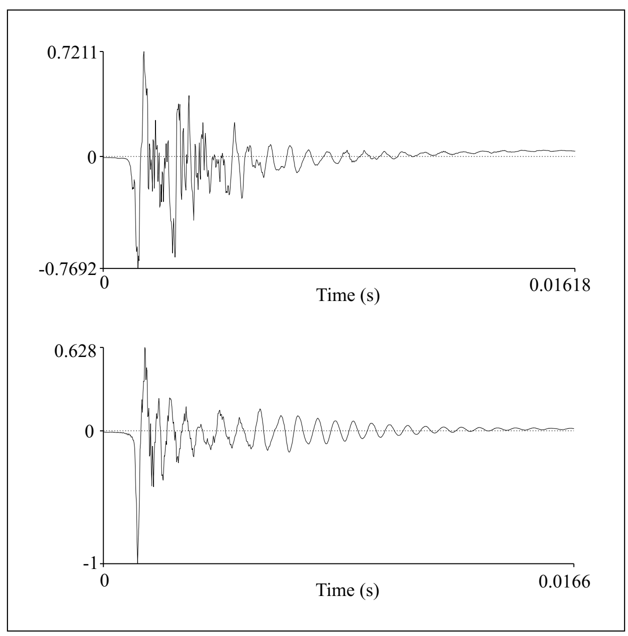

Figure 7. Waveforms of two samples of alveolar click sound.

Palatal clicks offer an additional, very important advantage. The spectral content of the palatal click is different for each individual, almost constituting a sound signature for the echolocating person. This sound is easily recognized by the subject due to its very distinctive properties.

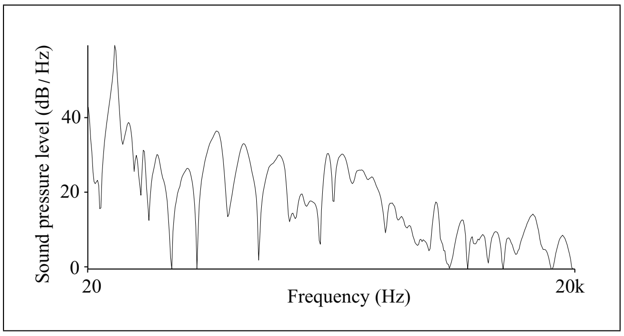

Figure 8. Frequency spectrum of a typical palatal click.

All these characteristics make palatal clicks far more immune to ambient noise than most other signals, including artificial ones. Generally, much less intensity is necessary to perceive an echo from a palatal click than for any other organic signal.

Echoes from palatal clicks are easily interpretable and provide a direct temporal reference. In Figure 9 a sequence of clicks from a head approaching a flat computer monitor is represented. Three representative pulses are shown at distances of 45, 25 and 5 cm from the monitor. The conditions were the same as in Figure 3. It is observed that echoes manifest themselves as interferences (modulation) of the emitted pulses. These little oscillations increase in frequency as the emitter approaches the obstacle. These interferences move towards the origin as the head approaches the monitor, as it would be expected. Pulses affected by near pulses are a little longer than pulses with far echoes. Intensity also varies, and seems to show a modulated pattern, although no definitive conclusions can be drawn from natural sources only. Future studies with artificially synthesised stable sounds will answer this question.

Separation between the echo oscillations modulated by the individual oscillations of the palatal click is approximately 0.1 ms very near the object. These extremely short echo oscillations are not individually identified by the unaided ear, but can be clearly heard and recognized when they are isolated in the *Praat* program. This is very convenient for the future development of biofeedback assisted echolocation teaching protocols. The sound propagates approximately 3.4 cm in air during the 0.1 ms of each echo oscillation. However, 0.1 ms is very near the temporal resolution limit of our experiments, so even shorter oscillations could exist. It should be noted that such distance, approximately 3.5 cm, is just the interval in which subjective differentiation of the pitch of the echoes is clearly differentiated. More research is needed to know if a spatial interval of 3.5 cm is a natural limit for distance perception by means of echolocation. Our limited subjective tests would suggest that pitch differentiation is quantized in this sense, but much more complete and controlled statistics are needed to provide a complete answer. This quantization limit, if confirmed, would not be absolute, however. Our preliminary experiments seem to indicate that separations involving interfaces of different materials as small as a few mm can be detected. This study would be the subject of future works.

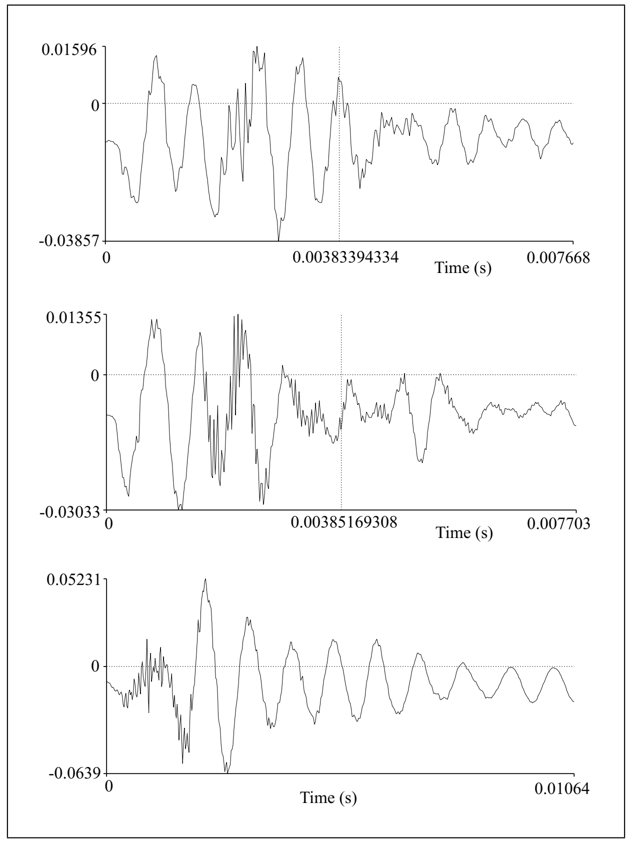

Figure 9. Three pulses of a sequence of palatal clicks for a head approaching a flat computer monitor from distances of 45, 25 and 5 cm respectively.

Summary of palatal click characteristics:

- Intensity: Very good.
- Reproducibility: Very good.
- Duration: Excellent.
- Time interval between pulses: Very good.
- Spectral content: Good.
- Usability: Excellent.
- Adaptiveness: Very good, pitch and intensity can be easily changed across a complete octave at least.
- Noise immunity: Excellent.

3. Conclusions

We have presented the first detailed study of the physical properties of some organic sounds suitable for human echolocation. In this work, we have limited ourselves to the tongue and lip vacuum generated “ch” and click sounds. Other natural sounds will be analysed in future works. The results confirm the empirical and subjective opinions of previous research about the convenience of palatal clicks for human echolocation. Other oral sounds can be used in the first stages of echolocation learning, but any serious student should move to palatal clicks. Also, it has been proven that palatal clicks are superior to alveolar clicks in general. Waveform analysis shows that accurate distance estimation is possible with palatal clicks, in fact, plenty enough for common tasks. However, additional psychoacoustical data that could clearly determine which sound is the most efficient to detect an obstacle in front of the head or which sound improves the accuracy of the approach towards an obstacle are necessary. These questions will be addressed in future studies. The results of this study are the beginning of a systematic treatment of human echolocation possibilities and several new research lines are suggested.

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