

Physical analysis of several organic signals for human echolocation: Hand and finger produced pulses

Juan Antonio Martínez Rojas, Jesús Alpuente Hermosilla,
Rocío Sánchez Montero and Pablo Luis López Espí

Department of Signal Theory and Communications,
Universidad de Alcalá, Escuela Politécnica Superior,
Campus Universitario, Ctra. de Madrid-Barcelona, km 33.600,
28871 Alcalá de Henares, Spain

`juanan.martinez@uah.es`

March 4, 2010

Abstract

In the first part of this work we studied several oral signals suitable for human echolocation. Palatal clicks were proven to be optimal pulses for this task. In the second part of this series, we analyze, from a physical and psychoacoustical point of view, the sounds produced by hand clapping and finger snapping. One additional sound is studied: a loud sound made by clapping one finger against the vacuum space between fingers near the knuckles. The results of our experiments show that these sounds are fairly good for echolocation. The best one is the knuckle vacuum pulse, due to its extraordinary acoustical properties. This sound has many of the good characteristics of palatal clicks with an even richer content in the high frequency part of the spectrum. Besides, this sound exhibits an interesting symmetry in the ultrasound range, which palatal clicks do not have. Experimenters noticed that, in spite of their sound quality, hand and finger produced pulses were inferior to palatal clicks, mainly due to difficulties in the relative orientation between the head and the hands, without sight clues, lack of reproducibility and muscle fatigue during long sessions. Some people with basic echolocation skills, however, found these sounds useful for distant sources, because they were able to make such pulses louder than palatal clicks.

1 Introduction

The study of the physical characteristics of the most accessible organic sounds for human echolocation is very scarce,[1]. Rice, [2], [3], found that blind participants were able to use a variety of artificial signals, but performance was always

highest when those artificial sounds resembled natural sounds which were familiar to the participants. Kellogg, [4], Kish, [5], Magruder, [6], McCarty and Worchel, [7], Myers and Jones, [8], Rice, [2] and Schenkman and Jansson, [9], mention the oral click as a useful signal for echolocation. Most authors consider the applications of human echolocation, for example, [10] and [11]. However, until now, researchers have been more interested in the psychoacoustical study of echolocation than in a physical analysis of the echo signals.

In order to fill this gap, this work analyses several types of organic sounds suitable for echolocation. These sounds are easily reproduced with little practice. In this work, we study several sounds made by clapping hands, snapping fingers or one finger striking some suitable hand part. Artificial sounds will be added in future publications.

The same physical and psychoacoustical parameters as in [1] were used: intensity, reproducibility, duration, spectral content, usability, adaptability and noise immunity.

The most relevant psychoacoustical perceptions have been collected among ten people with basic echolocation skills, acquired after some days of training. All participants are sighted people. They were covered with suitable blindfolding masks for the experiments.

We shall use palatal clicks as the sound of reference for the rest of the our study, comparing the results of this study with [1].

2 Methodology and experimental procedure

The recording environment and devices are reasonably simple and low cost. Our main aim is to develop accessible tools for echolocation training through human-computer feedback. In this regard, we are trying to avoid very costly devices like anechoic chambers and professional measurement equipment. These resources cannot be realistically afforded by individuals interested in learning echolocation.

The experiments were performed in a computer room with dimensions of approximately $15 \times 15 \times 3$ m. The reverberation constant (30 dB below the level of the direct sound), RT_{30} , is 0.10 ± 0.01 s, measured as the average and standard deviation of 10 recordings of the sound of a loud impulsive noise. The computers have been used as a convenient noise source. The average noise spectrum and level can be seen in figure 1. No sound processing or enhancement has been done to study the echo signals. An absolute calibration effort of the recorded waveforms has not been necessary. Instead, all the sounds have been normalized with respect to the same recorded noise level.

As previously mentioned, the sound recordings have 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 the consistence and accuracy of the results. Several different microphones and two sound cards were used to verify the waveform of the recorded sounds. The microphones were three low cost Genius and Creative Labs designs for PC use. A few comparative measurements were done with a high quality Sennheiser microphone to assure that no serious errors were present in the recordings. Two different sound cards, one from Realtek and one from Creative Labs were used and compared. No noticeable differences were

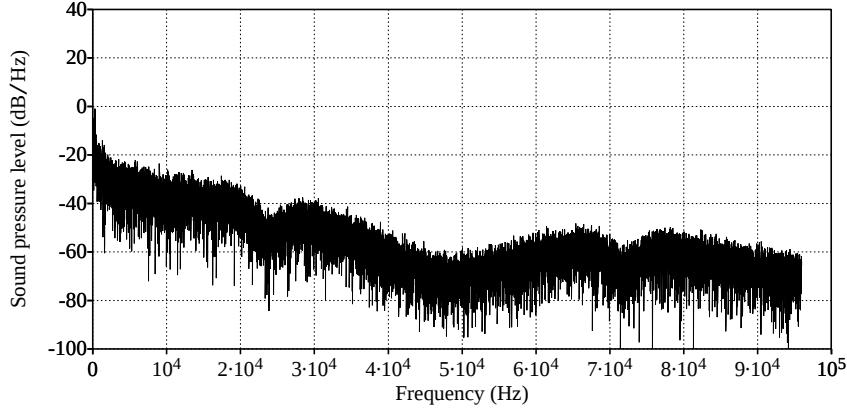


Figure 1: Frequency spectrum of the noise floor in the recording room.

observed. All measurements agreed within a 5% of standard deviation or best. The sampling frequency was set to 192 kHz in order to achieve the best available temporal resolution. The recording, analysis and figures have been done with the *Praat* program, [12].

Our main goal is the development of optimal echolocation teaching protocols. Human echolocation has a great potential for both blind and sighted people, so these protocols should be valid in both cases. However, studies of echolocation in blind people can be misleading for our initial purposes. Blind people generally have adapted themselves to individual optimizations of their hearing abilities. These adaptations can be very specific and not based on scientific principles, but on personal preferences or circumstances. For this reason, we have asked ten sighted volunteers to participate in this study. None of them had a previous knowledge of human echolocation. They have normal vision and hearing. This approach should minimize biasing errors due to previous echolocating skills. A similar methodology has been used by other notable human echolocation researchers, [15] and [16].

For example, sighted people try to relate their echolocating perception with their visual images as a reference. However, blind people can use their touch sense to maximize their echolocating experience, [17], due to the lack of visual references. Both touch and echolocation are generally active means of exploring our environment and are based on very similar physical principles, mainly vibrations in comparable spectral ranges. On the contrary, vision is passive and based on detection of electromagnetic radiation of much greater frequency than its echolocating counterparts. So, it is reasonable to assume that the learning process of echolocation in sighted people can be very different from the case of blind individuals. Future experiments will resolve these differences, trying to discover if universal principles can be applied to teaching and learning active echolocation in humans, both sighted and blind. Multimodal interaction of other senses in the echolocating perception of people with different sensory disabilities could produce vastly different "images" of the echolocated environment.

For our present experiments, echolocating distances were less than 10 meters,

so participants were unable to separate the echo from the emitted sound. This would generally be the case in most real life environments. A 14 inches flat computer monitor was used as an obstacle for the final results. The interference between the original sounds and the resulting echoes, forming a kind of acoustic combo filter, is heard instead. Recordings approaching the obstacles from less than 0.5 m were finally used to illustrate the differences among the studied sounds.

Echolocation training and sound recordings were purposely performed inside a 15×15 meters computer room with noise and a complex echo background, because we are interested in training echolocation in real environments. We were interested only in relative measurements from different kinds of sounds, so an absolute calibration effort was not performed. We could calibrate our system by measuring the level of the background noise, if necessary. Detection of large objects in the open air, more similar to anechoic conditions, were allowed to verify the usefulness of some sounds, like hand clapping, for distant echolocation. Anechoic measures would be very useful for testing the limits of human echolocation. However, large chambers would be surely necessary, due to the long range of the echoes.

The psychoacoustical data have been recorded from questionnaires collected among the ten experimental subjects. The questionnaires included questions about the objective difficulties of hearing sound variations in front of a flat rectangular obstacle and subjective appreciations of the quality of the sounds used, based on the following scale:

- Poor (= 1).
- Medium (= 2).
- Good (= 3).
- Very good (= 4).
- Excellent (= 5).

The questions, in the original Spanish form, were:

"Por favor, responda a las preguntas sobre el experimento usando el siguiente baremo: *malo, regular, bueno, muy bueno o excelente*, sin usar calificaciones intermedias o ambiguas."

- "Indique el nivel de intensidad del sonido producido."
- "Califique la facilidad con la cual es capaz de reproducir el sonido sucesivamente de forma lo más similar posible."
- "Analice si el sonido es lo suficientemente breve para evitar solapamientos entre pulsos consecutivos."
- "Indique si el sonido le proporciona suficiente información para reconocer los objetos por medio de la ecolocación."
- "Califique la comodidad en el uso de este sonido."
- "Indique la facilidad con la cual puede adaptar la intensidad y tono del sonido a diversas situaciones."

- "Califique su capacidad para distinguir el sonido empleado del ruido ambiente."
- "Finalmente, comparando los diversos sonidos empleados para detectar la pantalla usando ecolocación, indique el que le ha resultado más conveniente en general, considerando todos los aspectos anteriores."

A numerical equivalence of each result is also shown, but the participants were not aware of it. Averages were computed using these numerical values. However, we did not use the numerical equivalences directly in our questionnaires, because we have found that experimental answers were more consistent and reliable when presented in a literate and qualitative form. Our experience is that people tend to be falsely detailed and indecisive when full numerical questions are allowed. For example, a number of people tried to use fractions of the scale, such as 3.5. We have observed this kind of bias in many cases, both in previous experiments and in our daily teaching experience. This misleading accurate behavior is avoided using a qualitative scale.

Training was necessary because most participants were not able to notice their echoes at first. Echolocation learning was reduced to the detection of some different flat surfaces (walls, wooden panels and flat monitors) from distances no more than 10 m away. To test the quality of various sounds used to detect distant objects, an experiment was made to try to detect a building in the open air from 100 m. This test was performed after indoor echolocation training was completed. Most participants were able to detect walls after two sessions of training of one hour of duration each or less. After two hours of training, all the participants were able to detect the walls and were able to stop just 0.5 m away from them.

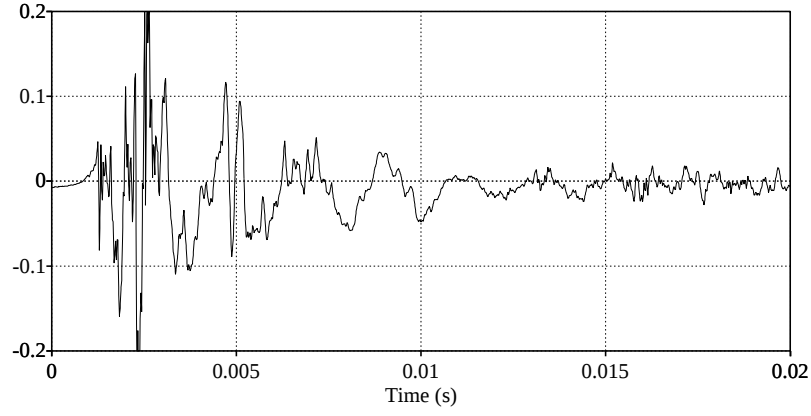
3 Physical analysis of the different sounds

3.1 Hand clapping

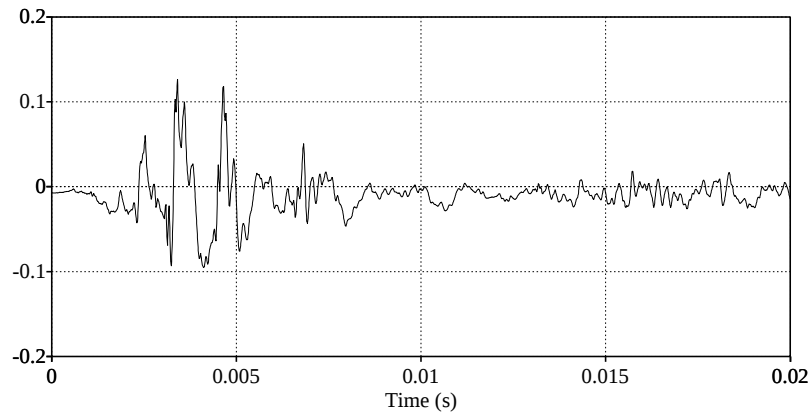
Hand clapping is one of the most intuitive and commonly produced body sounds. The detailed physical properties of the sound vary greatly among individuals. Common properties are fairly loud sound, sharp pulses in most cases and easy recognition.

Our results show that the complete duration of this kind of pulse is 15 ± 5 ms for most individuals, although pulse reverberation inside a room can be several times longer. This numerical value is the result of analyzing three different pulses from every participant, averaging a total of 30 different pulses. The estimated uncertainty is the standard deviation of the final result. Every numerical result is presented as an average value calculated from at least 10 different measurements and the uncertainty is the standard deviation of the sample.

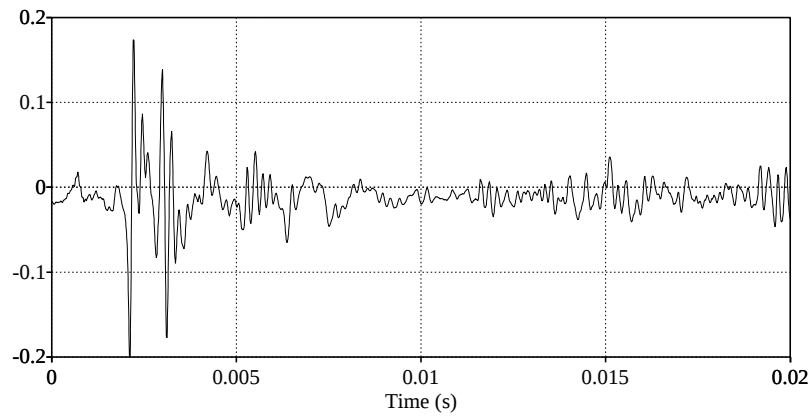
The intensity of the sound made can be made fairly high. However, for these experiments, hand clap loudness was kept as low as possible to prevent distortion of the recorded sounds. The oscillations inside the pulse have a typical separation of 0.25 ± 0.03 ms between them. This is roughly the same as the Full Width Half Maximum (FWHM) duration of each oscillation. These minor oscillations vary in intensity over the whole pulse and they do not present a clear decaying pattern as palatal clicks do.



(a) Hand clap waveform from a distance of 40 cm.

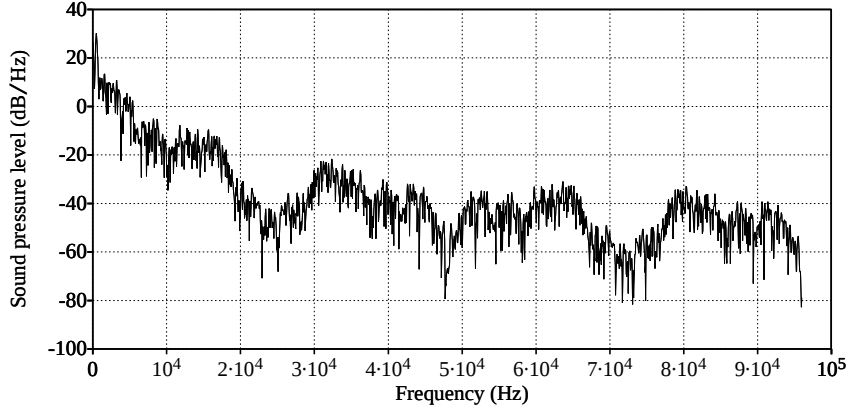


(b) Hand clap waveform from a distance of 20 cm.

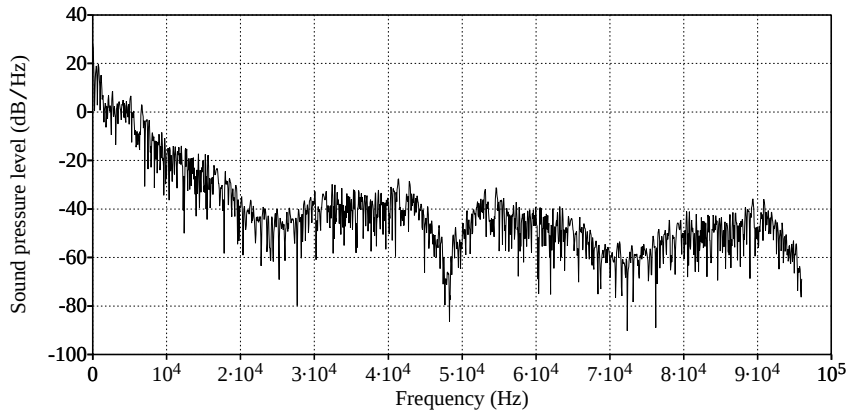


(c) Hand clap waveform from a distance of 5 cm.

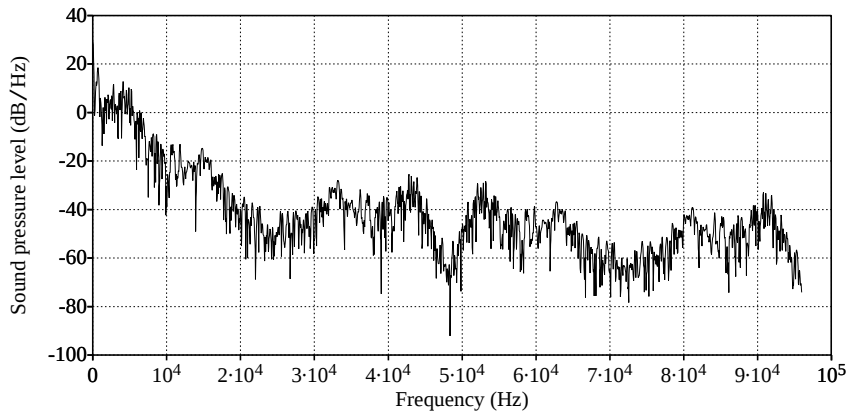
Figure 2: Waveforms of a sequence of hand clap pulses approaching a flat computer monitor from distances of 40, 20 and 5 cm.



(a) Hand clap spectrum from a distance of 40 cm.



(b) Hand clap spectrum from a distance of 20 cm.



(c) Hand clap spectrum from a distance of 5 cm.

Figure 3: Frequency spectra of a sequence of hand clap pulses approaching a flat computer monitor from distances of 40, 20 and 5 cm.

As can be seen in figures 2 and 4, the sound waveforms are more complex than palatal clicks when we are approaching an obstacle. Some remarkable differences among the approaching claps, however, are present, so distance cues can be extracted in time domain. The oscillations are shorter and cleaner when the obstacle is very near. The physical interpretation of this pulse evolution in the time domain is very complex. A relatively simple pattern, similar to palatal clicks, cannot be found.

Spectral analysis, figure 3, shows that band gaps are more noticeable and deeper, the nearer the obstacle is. Frequency spectra have been calculated by Fast Fourier Transform (FFT) of the data with a Hamming window and 1024 points of resolution. The differences in their audible spectral bands are not as clear as those that palatal pulses produce. The spectral content of hand claps is rich in almost all the audible range and ultrasonic contributions are also present. There is a clear bandgap between the limit of the audible range and the beginning of the first ultrasonic band. Ultrasonic bands tend to be symmetrical with respect to a central bandgap around 45 kHz. The maximum of highest frequency peak, near 90 kHz, seems to be correlated with the distance from the object. There is some frequency shift from the central bands towards higher regions of the spectrum when we approach a flat surface.

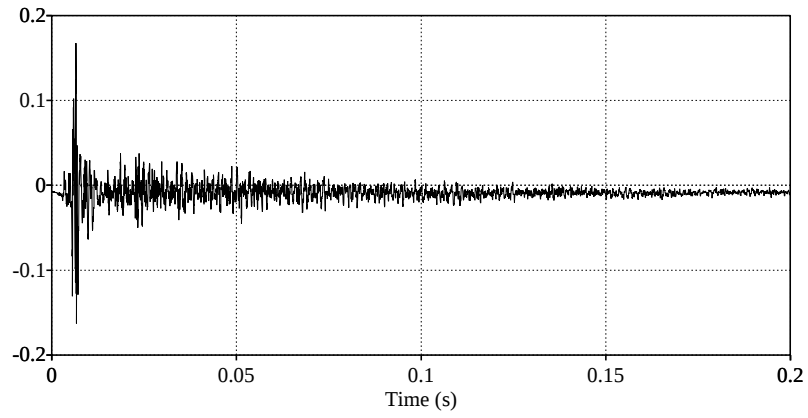
Hand claps can be made very quickly. However, most individuals report difficulties interpreting the perceived echoes if the duration between two consecutive claps is less than 0.4 or 0.5 seconds. Hand claps are louder and longer than palatal clicks, so their reverberation decays more slowly, due to the actual level of noise. This advantage of palatal clicks over hand claps can be clearly seen in figure 4. Both sounds were recorded in the same conditions.

This sound is very easy to perform and the quality of the sound is not affected by progressive dryness, unlike palatal clicks. However, except for very skilled hand clappers, it is an almost impossible task to reproduce the same sound for every pulse, because the relative position of both hands changes between performances. The palatal click waveform is more stable in this regard. Additionally, it is much more difficult to locate the echoes from a small object using sound made by the hands instead of using head based sounds. The hand-echolocation coordination is much more complex in this case. This limits the quality of hand claps for accurate human echolocation. A consequence of the irregular performance of hand claps is the large variation in the recorded amplitudes, as can be seen in figure 2. In this case the sound from 40 cm is louder than from 20 cm due to this fact.

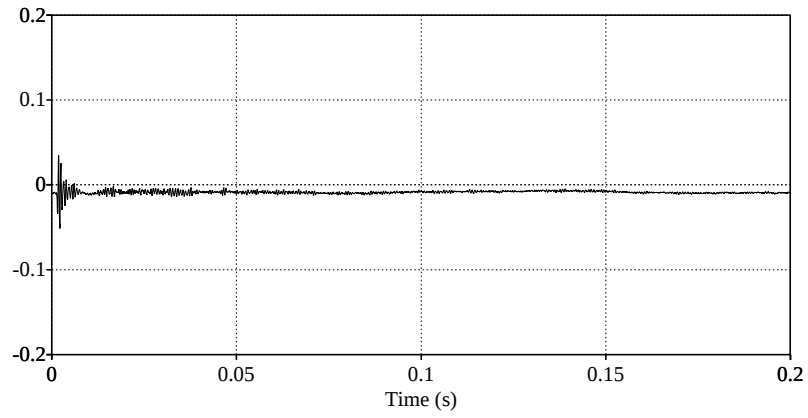
In spite of this, some people find hand claps very useful for long distance, low accuracy, echolocation. This is logical, because in such circumstances, hand position can be negligible compared to the distance from the object and most people can make hand claps louder than palatal clicks.

The subjective quality of the hand clap sounds can be characterized as follows:

- Intensity: Excellent.
- Reproducibility: Good.
- Duration: Very good.
- Time interval between pulses: Good.



(a) Hand clap waveform with reverberation.



(b) Palatal click waveform with reverberation.

Figure 4: Hand clap and palatal click reverberation times recorded inside the same room. The reverberation produced by the palatal pulse decays faster.

- Spectral content: Very good.
- Usability: Good.
- Adaptability: Poor.
- Noise immunity: Very good.

It should be noted that most individuals find much more difficult to recognize their own produced hand claps than their own palatal clicks when several sounds are present. Palatal clicks are, then, a much better personal identification than hand claps.

3.2 Finger snapping

Finger snaps are also typically human produced sounds. Performance is very different among individuals. Some people find it very difficult to produce a clear snap or are even unable to produce any sound by this method due to their hand anatomy. By contrast, some gifted individuals can use finger snaps like natural castanets and their performances are considered a form of musical art.

If properly done, finger snaps can be considered high quality sounds for human echolocation. The analysis of their waveforms and spectra reveals many physical properties similar to palatal clicks, as can be seen in figures 5 and 6. They also share some of the advantages of hand claps, as well as their limitations. Finger snaps cannot be made with a repetition rate as high as palatal clicks. Their performance can be severely compromised if a high speed is required. Sometimes, a few repetitions are necessary in order to obtain a clear echo. The time interval between consecutive finger snaps varies generally from 0.5 s to 1 s or more.

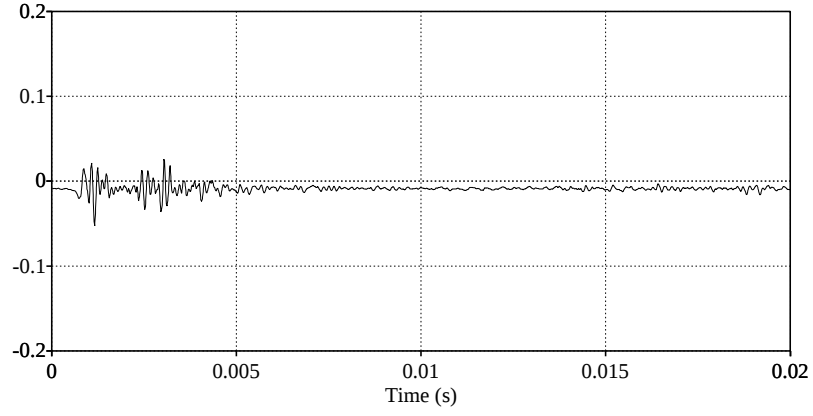
Finger snaps have a pulse duration of approximately 9 ± 1 ms, very similar to palatal clicks in the same conditions. The pulses are formed by minor oscillations of 0.1 ms or 0.2 ms FWHM. These oscillations decrease in intensity with time, but in a less regular form than palatal clicks. Inside the oscillations, especially the first ones, some shorter ripples of only 0.06 ms FWHM can be seen. In general, finger snap waveforms are more regular than hand clap ones and less ideal than palatal clicks. The complete waveform of finger snaps, close to an object, resembles that of alveolar clicks, studied in [1].

The spectra of finger snaps contains some ultrasonic bands, but they do not exhibit a frequency shift as clear as hand claps. Bandgaps are much deeper and clearer in this case and the ultrasonic contribution is not as important.

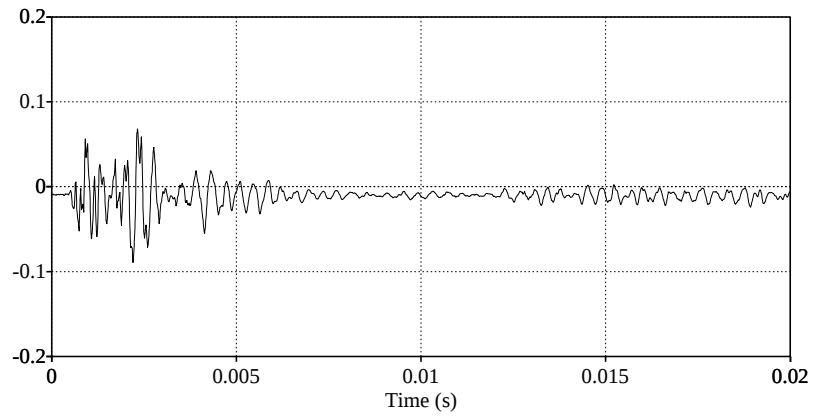
The reverberation of finger snaps decays faster than palatal clicks, but faster than hand claps in most cases.

The subjective quality of the finger snap sounds can be characterized as follows:

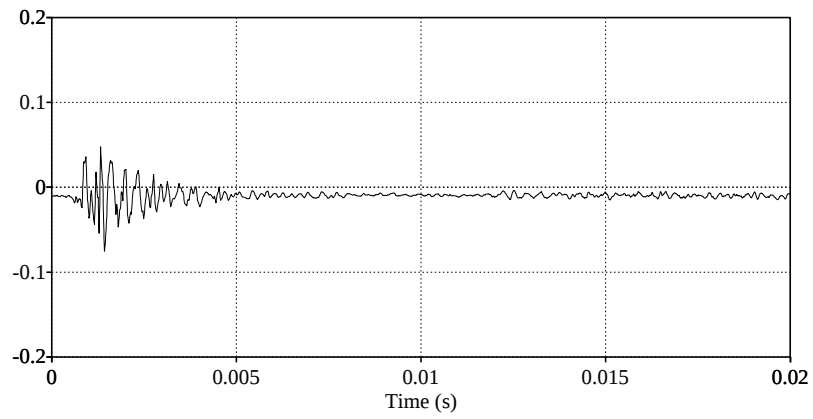
- Intensity: Very good.
- Reproducibility: Good.
- Duration: Very good.
- Time interval between pulses: Poor.



(a) Finger snap waveform from a distance of 40 cm.

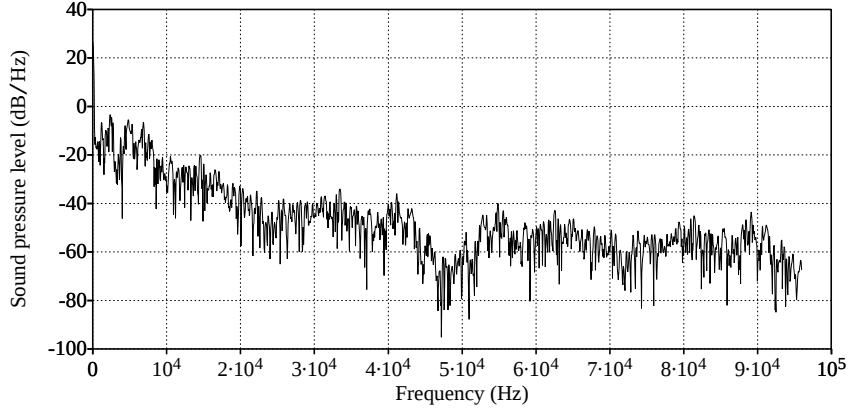


(b) Finger snap waveform from a distance of 20 cm.

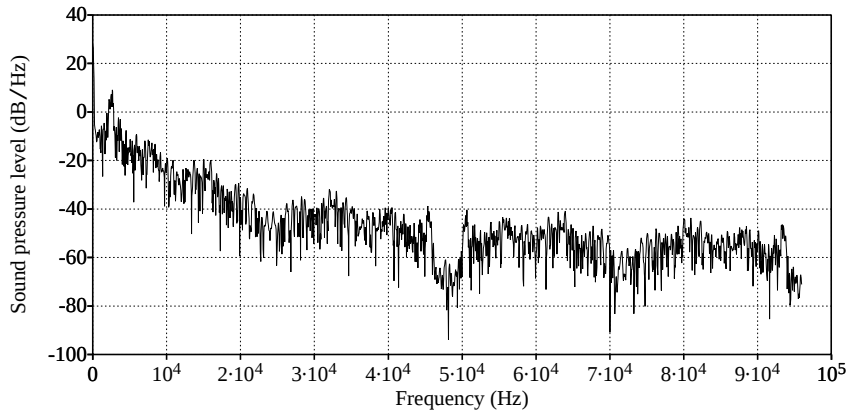


(c) Finger snap waveform from a distance of 5 cm.

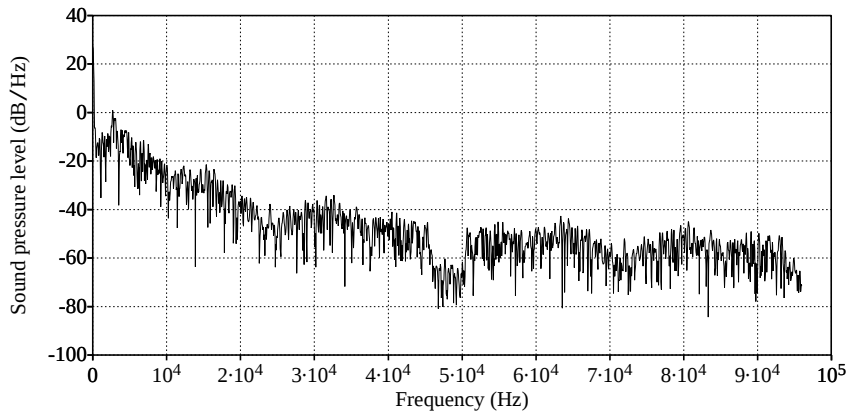
Figure 5: Waveforms of a sequence of finger snap pulses approaching a flat computer monitor from distances of 40, 20 and 5 cm.



(a) Finger snap spectrum from a distance of 40 cm.



(b) Finger snap spectrum from a distance of 20 cm.



(c) Finger snap spectrum from a distance of 5 cm.

Figure 6: Frequency spectra of a sequence of finger snap pulses approaching a flat computer monitor from distances of 40, 20 and 5 cm.

- Spectral content: Very good.
- Usability: Good.
- Adaptability: Poor.
- Noise immunity: Very good.

In a previous informal survey among 12 students, we discovered that many individuals were able to recognize their own produced finger snaps, when noise or other echolocating sounds were heard. In this regard, finger snaps would be better than hand claps, but worse than palatal clicks. In the final experiments, 8 of 10 participants were able to recognize their own finger produced sounds immediately. The other two participants were able to distinguish them after 30 min of practice.

3.3 Knuckle vacuum pulse

The knuckle vacuum pulse is a less common human produced sound. It is performed by clapping one finger against the vacuum space between two fingers just below the knuckle. An example of how to generate this kind of sound can be seen in figure 7.

The physical properties of the knuckle vacuum make it an excellent sound for human echolocation. The intensity of the generated pulses can be several times the intensity of palatal clicks. Curiously, palatal clicks can be seen as a low resolution version of knuckle vacua. In other words, the waveforms of both kinds of sounds are very similar, with knuckle vacua being an almost perfect downsampled copy, by a factor of 2, of the corresponding palatal click emitted in the same conditions. This similarity can be clearly seen in figure 9. A comparison of their frequency spectra is shown in figure 10. Their performance is very stable compared with hand claps or finger snaps. In figure 8, three different knuckle pulses with a distance of 20 cm from a flat obstacle can be seen for comparison purposes.

As can be observed in figure 11, knuckle vacuum pulses are formed by a set of decaying oscillations of approximately 0.20 ± 0.05 ms FWHM. The temporal separation between consecutive maxima is almost the same. The analysis of the sounds when the hands approach a flat surface, made of plastic, shows that no shorter ripples are present. The information of the echoes is present in the intensity variation of the pulse oscillations themselves. This is due to the shorter width and greater amplitude of such oscillations compared with palatal pulses.

The repetition rate of knuckle vacuum pulses can be as high as 4 per second without serious deterioration of the ideal waveform. This makes them comparable to palatal pulses in this point. However, the performance of such fast finger motions produces muscle fatigue in a few minutes. A more sustainable and realistic repetition rate would be 2 pulses per second.

Knuckle vacuum pulses exhibit a very interesting spectral behavior. When the pulse source is approaching a flat surface, the sound contribution increases in the 1000 Hz - 5000 Hz region. Frequency bands are wider and there are less bandgaps in the audible region when the obstacle is very near. On the contrary, the corresponding ultrasonic bands decrease the nearer the object is, as figure 12 shows.

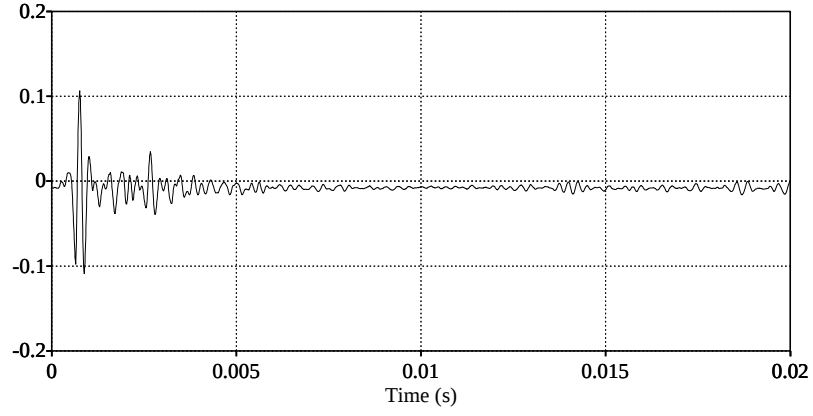


(a) Finger and hand position before impact.

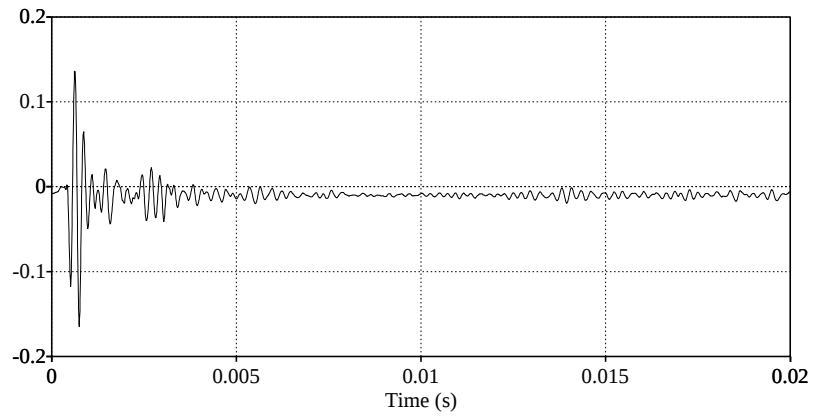


(b) Finger - hand impact.

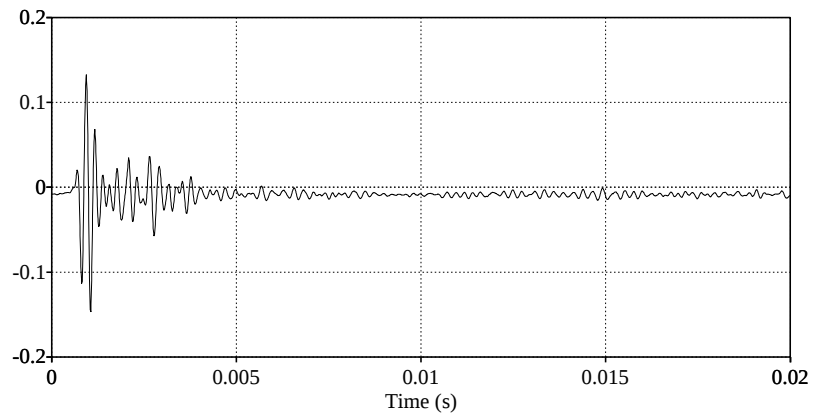
Figure 7: Performance of a knuckle vacuum pulse.



(a) First example of knuckle vacuum sound.



(b) Second example of knuckle vacuum sound.



(c) Third example of knuckle vacuum sound.

Figure 8: Different knuckle vacuum pulses with a distance of 20 cm from a flat obstacle for comparison purposes.

In spite of their very high quality as echolocating sounds, there are two main limitations of knuckle vacua which make them inferior to palatal clicks in general. The first one is the need to use both hands in order to produce the sound. You can freely use your hands while echolocating with palatal clicks. The second serious limitation is a more complex hand - echolocation coordination.

A very important property shared by palatal clicks and knuckle vacua is a strong haptic feedback from the perceived echoes. Palatal clicks are sensed as complex vibrations on the tongue, teeth, jaws and skull bones. In a similar form, knuckle vacua are perceived both as sound and as complex vibrations on the skin, fingers, hand and forearm bones. These haptic cues are crucial to fully understand the phenomenon of human echolocation. We shall devote more detailed studies to the haptic properties of human echolocation in future works.

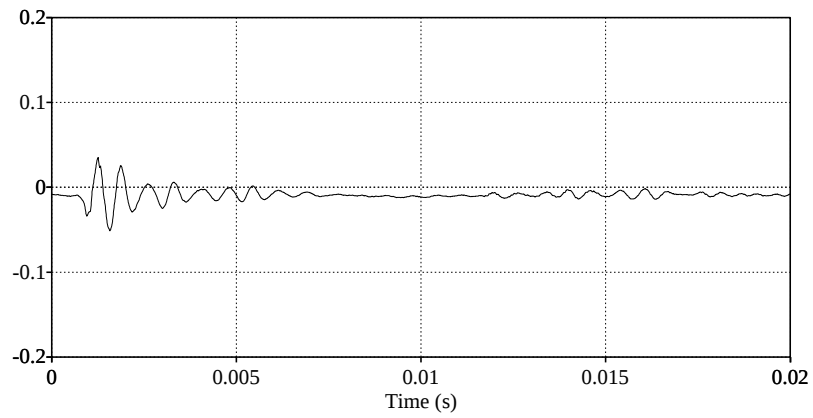
The subjective quality of knuckle vacuum sounds can be characterized as follows:

- Intensity: Excellent.
- Reproducibility: Very good.
- Duration: Excellent.
- Time interval between pulses: Very good.
- Spectral content: Excellent.
- Usability: Good.
- Adaptability: Poor (fundamental frequency of the pulses cannot be varied, palatal pulses are much more flexible).
- Noise immunity: Very good.

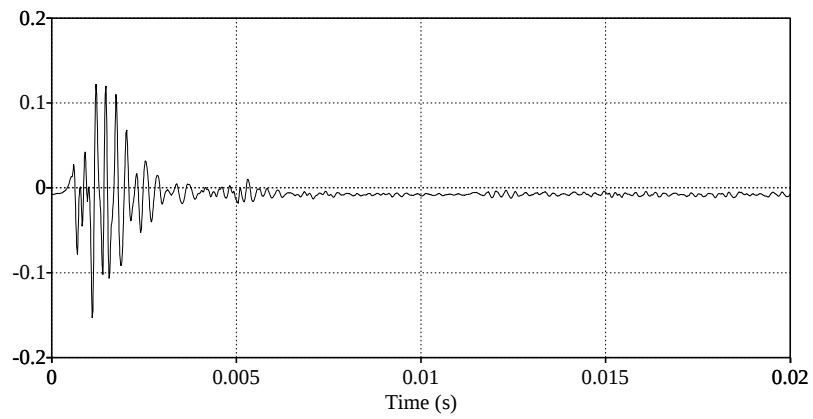
The performance of knuckle vacua is very limited without proper hand anatomy. This implies that relatively few people are able to produce the correct sounds, so the psychoacoustical tests in this case were seriously reduced. Only two of the ten participants were able to perform the sound correctly.

4 Conclusions

Following our work devoted to the physical study of some natural sounds suitable for human echolocation, we have analyzed the properties of the most common finger and hand produced pulses. Hand claps, finger snaps and knuckle vacua are compared with palatal clicks and among themselves. The results show that, from a purely acoustical perspective, knuckle vacua represent the best echolocating sound. However, in practice, few people are able to perform them correctly. Hand claps are usually used as a low accuracy alternative for detecting distant obstacles. Finally, finger snaps, when properly produced, have better sound characteristics than hand claps and can be used for similar purposes. A summary of the most important studied physical and psychoacoustical parameters of every sound, including palatal clicks for comparison, can be seen in tables 1 and 2.

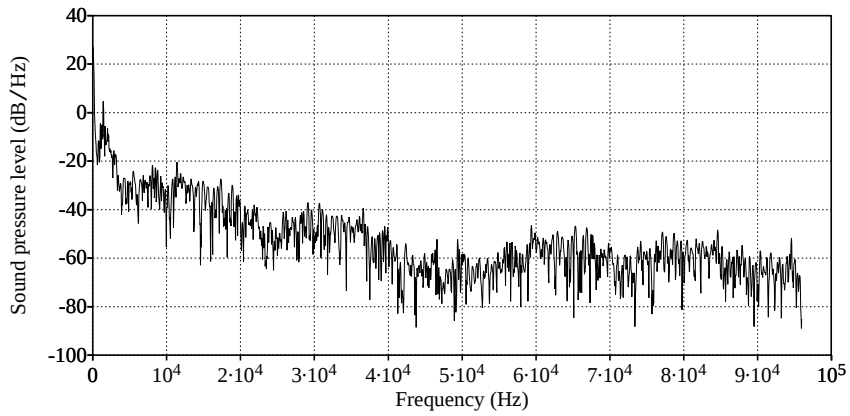


(a) Palatal click waveform.

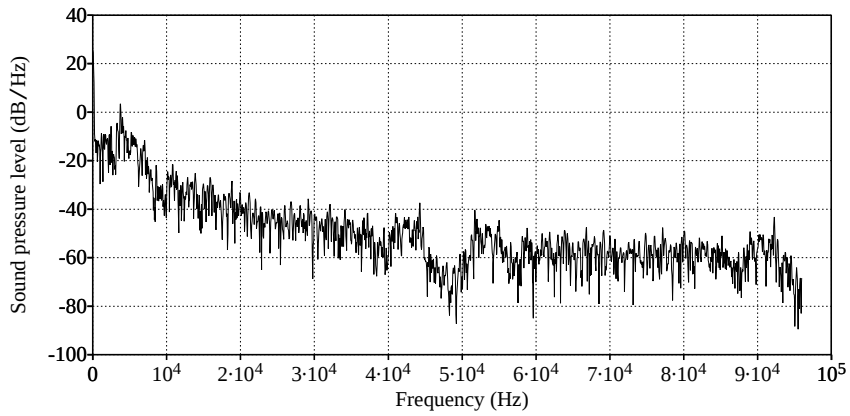


(b) Knuckle vacuum waveform.

Figure 9: Waveforms of a palatal click and a knuckle vacuum recorded in the same conditions.

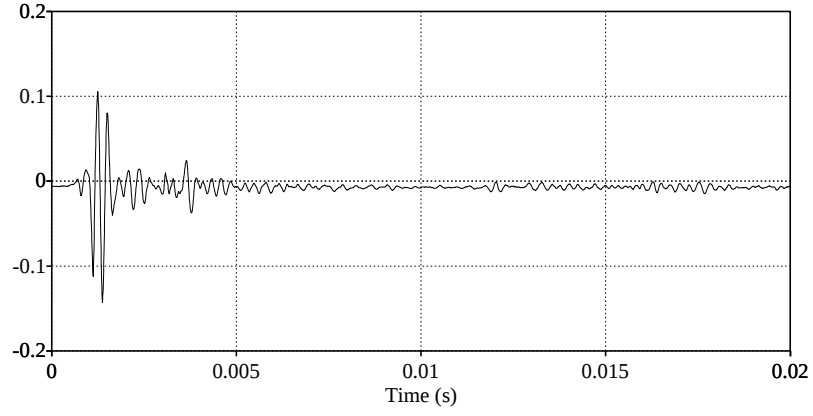


(a) Palatal click spectrum.

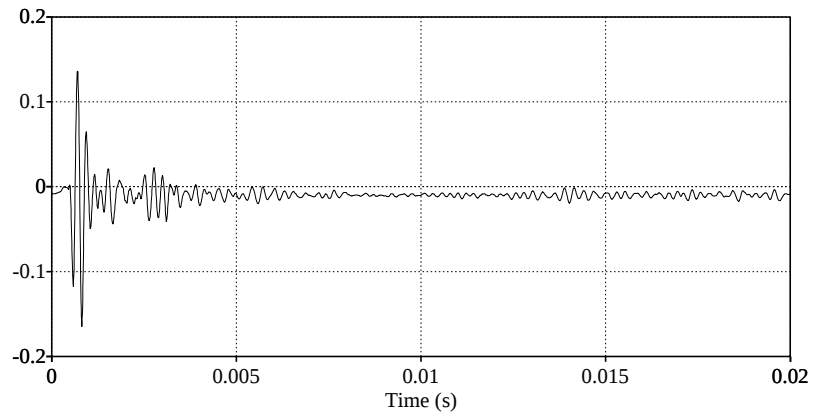


(b) Knuckle vacuum spectrum.

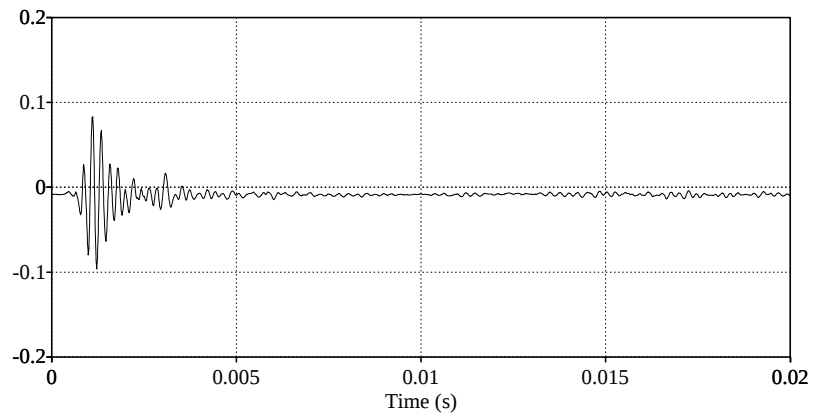
Figure 10: Frequency spectra of a palatal click and a knuckle vacuum recorded in the same conditions. The nearly symmetrical high frequency (ultrasound) components of the knuckle vacuum are clearly seen.



(a) Knuckle vacuum waveform from a distance of 40 cm.

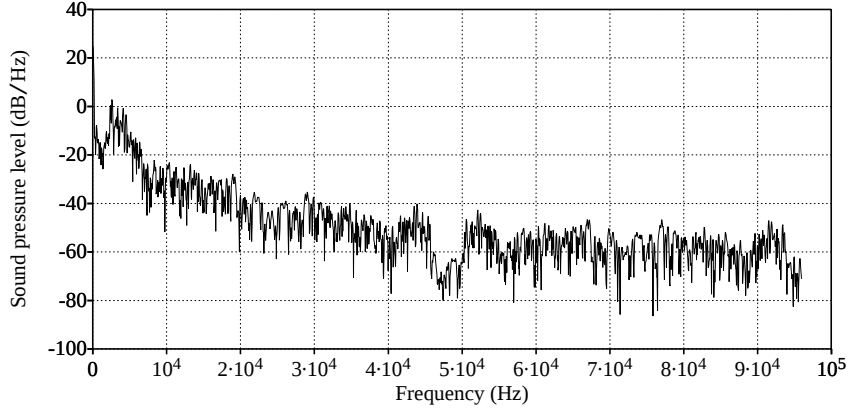


(b) Knuckle vacuum waveform from a distance of 20 cm.

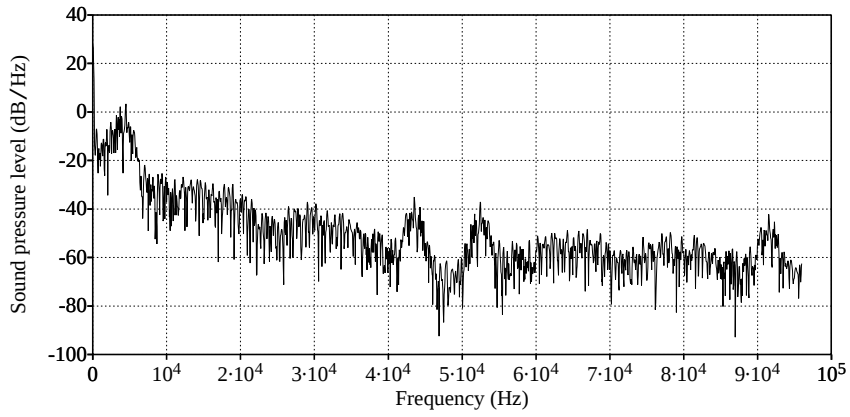


(c) Knuckle vacuum waveform from a distance of 5 cm.

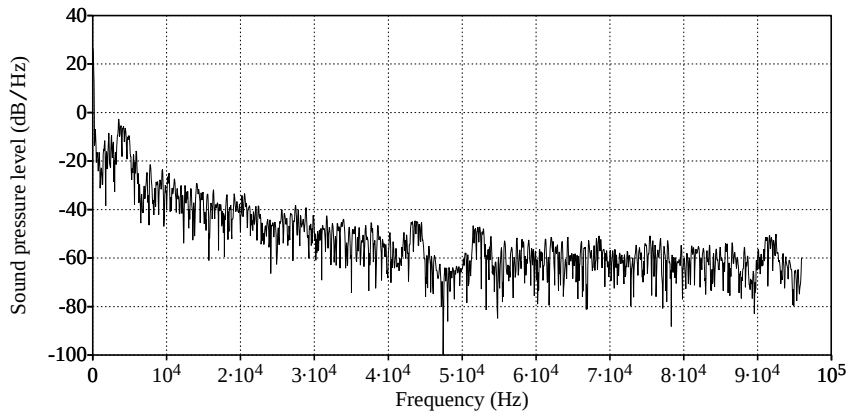
Figure 11: Waveforms of a sequence of knuckle vacuum pulses approaching a flat computer monitor from distances of 40, 20 and 5 cm.



(a) Knuckle vacuum spectrum from a distance of 40 cm.



(b) Knuckle vacuum spectrum from a distance of 20 cm.



(c) Knuckle vacuum spectrum from a distance of 5 cm.

Figure 12: Frequency spectra of a sequence of knuckle vacuum pulses approaching a flat computer monitor from distances of 40, 20 and 5 cm.

Physical parameter	Echolocating sounds			
	PC	HC	FS	KV
Duration (ms)	10 ± 4	15 ± 5	9 ± 1	5 ± 1
FWHM (ms)	0.90 ± 0.10	0.25 ± 0.03	0.20 ± 0.10	0.20 ± 0.05
Rate (sounds / s)	3	4	2	4

Table 1: Summary of physical parameters of the studied echolocating sounds. PC: Palatal click, HC: Hand clap, FS: Finger snap, KV: Knuckle vacuum.

Sound	Psychoacoustical parameters							
	I	R	D	TI	S	U	A	NI
Palatal click	4	4	5	4	3	5	4	5
Hand clap	5	3	4	3	4	3	2	4
Finger snap	4	3	4	2	4	3	2	4
Knuckle vac	5	4	5	4	5	3	2	4

Table 2: Summary of psychoacoustical parameters of the studied echolocating sounds. I: Intensity, R: Reproducibility, D: Duration, TI: Time Interval, S: Spectrum, U: Usability, A: Adaptability, NI: Noise Immunity.

However, the main limitation of finger and hand produced sounds is the almost continuous use of our hands for many other tasks. Palatal clicks do not have this problem. In theory, our hands could be used for echolocation instead of palatal clicks if we need to talk, but in practice the produced sounds could be annoying for many people. In such cases, the spoken sounds should be used as echolocating clues instead. We shall study this possibility in future works.

The present study used only sighted people. Future studies will have to show if similar results are found in blind and myopic people. Careful separate studies of each group will be necessary, including experimental adaptations to their specific needs. However, our results show that practical teaching of basic echolocation skills in sighted people are possible in a few hours using naturally produced sounds.

This kind of training would be also very useful for blind people, even without specific optimizations. Although our analysis shows that hand and finger produced sounds have enough quality for practical echolocation, they would be less convenient for blind people in general, due to their use of canes for increased safe mobility. Our results strongly suggest that echolocation teaching in blind people, using natural sounds, should focus mainly on palatal clicks in order to allow a free use of other mobility aids.

5 Acknowledgements

We dedicate this work to Ben Underwood (1992 - 2009), with our most sincere admiration. He has been one of the best exponents of human echolocation and a true inspiration for us.

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