Horizontal sound localization in adults with unilateral or bilateral cochlear implants

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Abstract

Introduction: Individuals with deafness or severe hearing loss may enhance their hearing sense by receiving cochlear implants (CIs). Bilateral CI (BCI) shows a greater improvement in horizontal sound localization ability (SLA) compared to a unilateral CI (UCI). Most previous studies on this topic included only children, which motivated the aim of the present study, namely, extending the knowledge concerning SLA in adult CI users.

Objectives: SLA in adults with BCI and UCI were tested and the results were compared and analyzed.

Material and Methods: SLA of 10 BCI and 13 UCI subjects were tested in a semi-anechoic room (reflection-free room, except for floor) with 12 speakers, which were placed in a circle around the participants and played three different sound stimuli. Normal hearing (NH) subjects and BCI subjects were tested under both binaural and monaural conditions. An error index (EI) was used as a measure of SLA. 11 NH subjects were also included to serve as reference.

Results: NH subjects had an EI-mean between 0.04 and 0.14 during binaural conditions, hence a better SLA than during monaural conditions where EI-mean was between 0.49 and 0.77. BCI subjects had a better SLA during binaural conditions (EI-mean between 0.53 and 0.64) compared to monaural conditions (EI-mean between 0.80 and 0.90). UCI subjects had an EI-mean between 0.82 and 0.97.

Conclusion: BCI subjects had a better SLA than UCI subjects, however, not compared to NH subjects. The main finding in the present study was that BCI subjects under monaural conditions had a better SLA than permanent UCI subjects. If this can be shown in a study with a larger sample size and statistical analysis, it can provide further reason for clinicians to consider BCI over UCI.

Key words: Sound localization, cochlear implants, adults, deafness, hearing loss
Abbreviations

BB - Bicycle bell sample
BCI - Bilateral cochlear implant
BCI-L - BCI, monaural conditions with hearing on left side
BCI-R - BCI, monaural conditions with hearing on right side
CI - Cochlear implant
CH - Car horn sample
dB HL - Decibels hearing level
EI - Error index
ILD - Interaural level difference
ITD - Interaural time difference
NH - Normal hearing
NH-L - NH, monaural conditions with hearing on left side
NH-R - NH, monaural conditions with hearing on right side
PN - Pink noise
SLA - Sound localization ability (horizontal)
UCI - Unilateral cochlear implant
UCI-L - UCI in left ear
UCI-R - UCI in right ear
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1. Introduction

1.1 Ear anatomy and physiology

The auditory system can grossly be divided into four parts: the outer ear, the middle ear, the inner ear, and the central auditory nervous system [1].

The outer ear is composed of the pinna, the visible part of the ear, and the external auditory canal, the canal that leads to the tympanic membrane (eardrum) [1].

The middle ear is a cavity where the most lateral part, the medial part of the tympanic membrane, is connected with the three ossicles (bones of the middle ear): malleus, incus and the stapes [1]. In the most medial part of the middle ear the ossicles connect with the oval window [1]. The ossicles work like levers where vibration increases with each consecutive bone [2].

The inner ear consists of three semicircular canals, a part of the vestibular system, the vestibule, a small cavity in the inner ear which laterally connects to the oval window and contains other components of the vestibular system (utricle and saccule), and the shell-shaped cochlea [1]. Within the cochlea there are two membranes: the vestibular membrane and the basilar membrane. These membranes create three fluid-filled sections: the scala vestibuli, the scala media and the scala tympani [2]. Inside the scala media and on top of the basilar membrane lies the organ of Corti which contains hair cells and the tectorial membrane [2]. The fluid in the scala vestibuli and the scala tympani is called perilymph. The fluid in the scala media is called the endolymph and contains a high potassium ion concentration and low sodium ion concentration. The electric potential in the endolymph in relation to the perilymph is +80 mV and is called the endocochlear potential [2].

When the stapes vibrates toward the oval window waves are created in the scala vestibuli. These waves create pressure on the vestibular membrane, which in turn causes the endolymph to press against the tectorial membrane which will bend the stereocilia (hair-like projections) on hair cells. Depending on which direction the stereocilia are bent, mechanically gated potassium channels at the tip of the stereocilia will either open or close. The hair cells stereocilia are circled by endolymph and the rest of the hair cell is circled by perilymph. The hair cells have a membrane potential of roughly -70 mV. The endocochlear potential and the rich potassium concentration in the endolymph creates an electrochemical gradient causing potassium ions to move into the hair cell. If enough potassium ions enter a hair cell it will depolarize and lead to the release of transmitter that will bind to receptors [2] and generate an increased amount of action potentials in afferent neurons [3].
The auditory nerve consists of approximately 30 000 afferent neurons in a bundle. Each hair cell is connected to the dendrites of about 20 neurons. Depending on where in the cochlea the basilar membrane vibrates, due to the frequency of a sound, specific fixed hair cells in that area will depolarize and neurons connected to these hair cells will increase their firing rate [3]. Close to the oval window is the base of the cochlea which is sensitive to high frequencies, while in the apex there is instead a low frequency sensitivity [3]. The volume of sound also determines the neurons firing rate, the higher the volume the higher the firing rate [3].

The auditory nerve transports sound information, received from the hair cells, to the cochlear nucleus in the brainstem. From the cochlear nucleus, the information is transported via synapses to the superior olivary complex on the same side (ipsilateral) and the opposite side (contralateral). From the superior olivary complex various connections in the brainstem take place before reaching the medial geniculate body in the thalamus. From the medial geniculate body neurons lead to the auditory cortex in the temporal lobe eventually leading to the sensation of hearing [3].

1.2 Sound and sound localization

A vibrating object can change the density of air molecules surrounding it. When the object moves toward the air molecules it presses them together and creates areas of high density and when moving away from the molecules it creates areas of low density. These pressure variations are known as sound waves [3].

There are three fundamental physical properties of sound: time, volume and frequency [1]. The speed of sound in air at atmospheric pressure is approximately 330 meters per second [3], implying that, the time it takes for a sound to reach a listener depends on how far the listener is situated from the sound source. The volume of sound is determined by the difference in density between the areas of high density and areas of low density, the bigger the difference the stronger the volume of the sound. The volume of sound is expressed in decibels (dB) [2]. In conversational speech the volume of sound is approximately 50 to 60 dB [2]. The frequency of sound is determined by the amount of sound waves generated per second and is expressed in hertz (Hz). The more waves per second the higher the frequency [2]. Humans, in general, are able to hear sound waves with frequencies between 20 to 20 000 Hz [2].

The physical properties of sound allow one to locate it and the ability to hear the nuances that these properties create is what determines one’s sound localization ability (SLA)
Interaural time difference (ITD) and interaural level difference (ILD) are suggested as main cues for left-right localization of sound in the horizontal plane [5]. For frequencies below 1500 Hz the ITD is said to be the most important cue, whereas for frequencies above 1500 Hz it is the ILD [5]. The pinna of the ears contributes to front-back [5, 6] and up-down localization [6].

Previous studies have shown that SLA is affected in individuals with hearing impairment and that there is a correlation between the degree of hearing impairment and SLA [4, 7].

1.3 Cochlear implants

Children and adults with deafness or severe hearing loss, due to damage in the inner ear, may improve their sense of hearing by receiving cochlear implants (CIs) [8].

The CI consists of three external parts, a microphone, a speech processor and a transmitter, and two internal parts, a receiver/stimulator and an electrode array [9].

The microphone registers sounds from the environment and sends them to the speech processor which will arrange the received sound information [8]. After the transmitter receives the acoustic sound signals from the speech processor it will convert the signals into electric signals and send them to the receiver/stimulator [9]. From there the electric signals are sent to electrodes implanted in the cochlea [8], where each electrode codes a specific frequency area of the incoming sound [10]. The electrodes will stimulate afferent nerve fibers, leading to the sensation of hearing [8].

1.4 Horizontal sound localization with cochlear implants

Previous studies done in children with CI have shown a better SLA with bilateral CI (BCI) when compared to unilateral CI (UCI) [11, 12, 13]. There is, to our knowledge, only one study done in adults with CI that compares SLA between BCI and UCI, this study also showed a better SLA with BCI [14].

When compared to NH subjects, previous studies show that CI users do not quite reach the same level of SLA [12, 13, 14].

1.5 Aim and objectives

The aim of this study was to verify if adult BCI users had a better SLA than adult UCI users, and if adult NH subjects had a better SLA compared to adult CI users. In order to
achieve this aim following was done: (1) SLA in three groups were tested, a) adult NH subjects, b) adult BCI users and c) adult UCI users; and (2) the results of the three groups were compared and analyzed.

2. Material and Methods

This study was a prospective comparative study and all data was provided by the Audiological Research Center at Örebro University Hospital. To be a subject in this study one had to meet the following inclusion criteria: (1) be an adult (≥ 18 years); and (2) have bilateral profound deafness with either BCI or UCI. Normal hearing (NH) subjects were included in the study as a control group.

2.1 Setup

The tests were performed by different members of the staff at the Audiological Research Center at Örebro University Hospital. Testing took place in a semi-anechoic room, where 12 speakers (Genelec 8030B) in a horizontal plane were placed in a circle, around a chair where the subjects were seated, each speaker having an equal distance from the subjects’ position (1.45 m) and each other (30°).

An in-house developed software, installed on a PC with Windows 7, was used for presenting sound stimuli and registering the subjects’ answers. A hand control, which the subjects used to signal from which speaker they heard the sound stimuli, was also developed in-house.

RME FireFace 800 with RME ADI-8 DS was used as sound interface to generate sounds from the computer to the speakers.

2.2 Procedure

Subjects performed the test once. During the test, the subjects were told to face the speaker placed straight in front (0° angle) and keep the head in a fixed position throughout the testing. Three sound stimuli were used in the test: (1) A car horn sample (CH) with a duration of 750 milliseconds (ms) and highest dB levels between 400 and 1000 Hz; (2) a bicycle bell sample (BB) with a duration of 1002 ms and highest dB levels between 1550 and 7500 Hz; and (3) pink noise (PN) with a duration of 1000 ms. Pink noise is a noise where there is a 3 dB decrease for every doubling in frequency, it contained frequencies between 100 and 20
000 Hz in the present study. The three sound stimuli were tested separately. Each sound stimulus was played three times from each of the 12 speakers with a volume of 65 (± 5) dB, played in a random order and was never played twice or three times consecutively from the same speaker.

When a sound stimulus was played, the subjects, using a hand control pressed a button corresponding to the speaker they thought was playing the stimulus. The hand control was designed in a way so that when the subjects, during testing, were seated accordingly, each of the 12 buttons pointed in the direction of its corresponding speaker.

NH and BCI subjects were tested under binaural and monaural conditions. For NH subjects, monaural conditions were achieved by plugging one ear with an earplug and further covering it with an earmuff. For BCI subjects the same conditions were achieved by having one implant switched off during testing.

2.3 Error index

An error index (EI) was used in the present study to evaluate and determine SLA. EI 0.00 was a test result with no errors. EI 1.00 was equal to the subject guessing each time a sound stimulus was presented. The scale 0 to 1 is the same as used in studies on SLA in children with CI done by Asp et al [11, 15, 16].

EI was calculated by adding the sum of errors during one performance (one subject, one stimulus and one condition) divided by average random error. Average random error was calculated by adding all possible errors for all speakers, multiply it with the number of presentations per speaker, divided by the number of speakers). One error was equal to perceiving sound as coming from one speaker away from the speaker actually presenting the sound, two errors was equal to perceiving sound as coming two speakers away from the actual speaker etc. Average random error in the present study was 108 (All possible errors with all speakers, 36 x 12 = 432 multiplied with number of presentations per speaker, 432 x 3 = 1296, divided by the number of speakers, 1296 / 12 = 108). EI and average random error was explained to me by one of the research engineers at the research center [17].

More detailed information regarding EI in the context of sound localization can be found in the previously mentioned studies by Asp et al. [11, 15, 16] and in a study done by Gardner and Gardner [18].

2.4 Ethics
Informed consent was received from all subjects which participated in the study. The study was approved by the regional Ethical review board in Uppsala.

3. Results

3.1 Subjects

*Adults with normal hearing*

To be classified as NH and be a part of the control group one had to: (1) be an adult (≥ 18 years); (2) have two functional ears; and (3) score ≤ 20 decibels hearing level (dB HL) on an audiometric test with pure tones ranging from 0.25 to 8 kHz (0.25, 0.5, 1, 2, 4 and 8).

Audiometric testing is a method to test a person’s subjective ability to hear tones with different frequencies. 0 dB HL is the lowest volume that the average young and healthy individual can hear for a certain frequency. This means that when testing a subject’s dB HL, it is relative to the average young and healthy individuals’ dB HL. An increased dB HL means a decreased ability to hear a certain frequency at a certain volume [6].

Table 1. presents NH subjects’ study ID, age at test date and gender. 13 subjects were tested, two were excluded for having >20 dB HL on at least one of the tested frequencies. 11 subjects were finally included. Their mean age was 33.5 years (26 - 50 years).

*Adults with bilateral CI or unilateral CI*

Table 1. presents BCI and UCI subjects’ study ID, age at test date, gender, type of CI (BCI, UCI-L or UCI-R) as well as duration of first and second implant in years (at test date).

10 adult BCI users were tested and included in this study. The BCI groups mean age, was 49 years (33 - 66 years).

16 adult UCI users were tested in this study. Three subjects were excluded for one of the following reasons: (1) one subject held the hand-control used in the test the wrong way, resulting in opposite answers; and (2) two subjects pressed the same button throughout the test giving unreliable results. 13 adult UCI users were finally included. Their mean age was 63 years (23 - 85 years). Three subjects, one female and two males, had an implant on the left side (UCI-L) and 10 subjects, seven females and three males, had implants on the right side (UCI-R).
Table 1. *Subjects study ID, age, gender, type of CI, duration of first implant and second implant in years. F = female. M = male. L = left. R = right.*

<table>
<thead>
<tr>
<th>Study ID</th>
<th>Age</th>
<th>Gender</th>
<th>Type of CI</th>
<th>Implant 1 duration</th>
<th>Implant 2 duration</th>
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<tbody>
<tr>
<td>NH002</td>
<td>36</td>
<td>F</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
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<td>NH008</td>
<td>42</td>
<td>F</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>M</td>
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</tr>
<tr>
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<td>26</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH011</td>
<td>29</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>NH013</td>
<td>27</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH014</td>
<td>43</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FP002</td>
<td>48</td>
<td>F</td>
<td>BCI</td>
<td>2 (R)</td>
<td>1 (L)</td>
</tr>
<tr>
<td>FP003</td>
<td>46</td>
<td>F</td>
<td>BCI</td>
<td>8.5 (R)</td>
<td>0.5 (L)</td>
</tr>
<tr>
<td>FP013</td>
<td>66</td>
<td>M</td>
<td>BCI</td>
<td>17 (R)</td>
<td>2.5 (L)</td>
</tr>
<tr>
<td>FP016</td>
<td>43</td>
<td>M</td>
<td>BCI</td>
<td>6 (L)</td>
<td>0.5 (R)</td>
</tr>
<tr>
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<td>62</td>
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<td>BCI</td>
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<td>1.5 (L)</td>
</tr>
<tr>
<td>FP031</td>
<td>55</td>
<td>M</td>
<td>BCI</td>
<td>2.5 (L)</td>
<td>1.5 (R)</td>
</tr>
<tr>
<td>FP037</td>
<td>33</td>
<td>F</td>
<td>BCI</td>
<td>6.5 (R)</td>
<td>2.5 (L)</td>
</tr>
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<td>FP041</td>
<td>45</td>
<td>F</td>
<td>BCI</td>
<td>2*</td>
<td></td>
</tr>
<tr>
<td>FP043</td>
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<td>BCI</td>
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</tr>
<tr>
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<td>BCI</td>
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<td>M</td>
<td>UCI-L</td>
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<tr>
<td>FP012</td>
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<td>F</td>
<td>UCI-L</td>
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<td></td>
</tr>
<tr>
<td>FP024</td>
<td>66</td>
<td>F</td>
<td>UCI-L</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>
3.2 Normal hearing subjects

**Binaural conditions**

For all sound stimuli, the majority of errors, for NH subjects under binaural conditions, were found when stimuli were presented from the back speakers ($\pm 120^\circ$, $\pm 150^\circ$, $+180^\circ$, $-150^\circ$, $-120^\circ$). A few subjects perceived the CH and the BB, when presented at $0^\circ$ or $180^\circ$, as coming from the opposite direction. The BB had a higher EI (0.14) compared to CH (0.07) and PN (0.04). Possible significant differences were not calculated in the present study. However, to facilitate in the discussion of the results, an EI-difference of at least 0.05 was referred to as notable.

**Monaural conditions**

For all sound stimuli, NH subjects under monaural conditions perceived the majority of sounds as coming from the center ($0^\circ$), center back ($180^\circ$) or the side with ones “functional” ear. There were no notable differences in EI between hearing only on the left (NH-L) or the right side (NH-R) for the CH and the BB. PN, however, had a difference in 0.09 EI-units ($0.58 - 0.49$). PN had a lower EI (0.58 and 0.49) compared to the CH (0.74 and 0.71) and the BB (0.75 and 0.77)

**Summary**

NH subjects had a better SLA under binaural conditions compared to monaural. EI-
mean during binaural conditions was between 0.04 and 0.14 and monaural between 0.49 and 0.77. PN had the lowest EI under binaural and monaural conditions.

3.3 Bilateral CI subjects

_Binaural conditions_

In general, BCI subjects under binaural conditions could identify if sound stimulus came from the left (-30° to -150°) or the right (+30° to +150°), but they had a harder time pinpointing from what speaker the sound was presented. When sound stimuli were presented at 0° or 180°, subjects in general, for all sound stimuli, had difficulty pinpointing from which speaker each sound stimulus was presented. The BB had a lower EI (0.53) compared to the CH (0.59) and PN (0.64).

_Monaural conditions_

BCI subjects under monaural conditions perceived the majority of sounds as coming from the side with ones “functional” ear. There were no notable differences in EI between hearing only on the left (BCI-L) or the right (BCI-R). A tendency to perceive sound stimuli as coming from the speakers at +180°, +150° and +120° when they were presented from the right during BCI-L conditions, and +180°, -150° and -120° when presented from the left during BCI-R conditions, was seen. The BB had a lower EI (0.81 and 0.80) compared to the CH (0.88 and 0.90) and PN (0.84 and 0.89)

Summary

BCI subjects had a better SLA under binaural conditions compared to monaural. EI-mean during binaural conditions was between 0.53 and 0.64 and monaural between 0.80 and 0.90. The BB had the lowest EI under both binaural and monaural conditions.

3.4 Unilateral CI subjects

_UCI-L subjects_

The CH and PN were most of the times perceived as coming from the center (0°), center back (180°) and left side (-30° to -150°). For the BB, sound perception was more scattered, however, most of the times it was perceived as coming from the left side (-30° to -150°).

_UCI-R subjects_
All sound stimuli for UCI-R subjects were most of the times perceived as coming from the right side. Sound stimuli presented from right side was most often perceived as coming from the speaker at 90°.

Summary

EI-mean was between 0.82 and 0.97 for UCI subjects. A notable difference in EI, between UCI-L and UCI-R subjects, was seen with the CH (0.93 – 0.82 = 0.11) and the BB (0.97 – 0.88 = 0.09)

3.5 Summary

NH subjects had a lower EI compared to the subjects with CI under both monaural (see figure 1) and binaural conditions. BCI subjects had a lower EI compared to UCI subjects under both monaural (see figure 1) and binaural conditions.

![EI: Monaural conditions](image)

Figure 1. Presents EI-mean for NH-L, BCI-L and UCI-L for each sound stimulus.

4. Discussion

The aim of this study was to extend the knowledge concerning SLA of adult CI users. This study showed that there was an advantage to have BCI compared to UCI for an adult with bilateral profound deafness.
4.1 Bilateral CI subjects versus unilateral CI subjects

Subjects with BCI had a better SLA under binaural conditions, compared to UCI subjects for all sound stimuli. An approximate 0.4 difference and close to 1.0 in EI indicates a clear disadvantage for UCI users.

Asp et al. [11], Lovett et al. [12] and Grieco-Calub & Litvosky [13] found that BCI in children was beneficial for SLA when compared to UCI. Verschuur et al. [14] made the same observations on adult subjects. The results of these studies were in parity with the present study, there were, however, some differences that distinguished the present study from the previous ones. One obvious difference was the fact that the present study was tested on adult subjects while most of the previous studies were done in children (< 18 years). One cannot ignore the thought, what the outcome would be if the two groups were tested under equal conditions. In one of the studies by Asp et al. [16] it was shown that SLA was slightly better in BCI users who received their second implant before the age of four. This could imply that the EI-difference would be even higher if children who received both their implants before the age of 4 were included in the present study. However, it would only be fair to compare these subjects to children with UCI who have been implanted before the age of four, and in this case we should not neglect the possible relative benefit of receiving ones first and only implant before the age of four, which has not, to my knowledge, yet been presented.

In the present study permanent UCI users were also included, while the previously mentioned studies only tested permanent BCI users where one implant was temporarily switched off to achieve monaural conditions. This study was, to the best of my knowledge, the first to compare SLA of BCI users under monaural conditions with UCI users, regardless of age group. The results of this comparison showed that BCI-L had a better SLA for all sound stimulus compared to UCI-L. Despite not knowing if there was a significant difference or not it was still an interesting finding, and if later proven to be of significance could provide further reason for clinicians to consider BCI over UCI. One reason for better SLA under monaural conditions for BCI users could be that the auditory system, which has both ipsi- and contralateral connections, builds a stronger pathway with binaural hearing, making a BCI user, temporarily under monaural conditions, better equipped for localizing sound than a permanent UCI user. Another reason could be the fact that BCI subjects had a lower mean age (49 years) than UCI subjects (63 years), implying that a younger adult age would given an enhanced SLA for CI users. In a study by Noble et al. [19] it was found that adult BCI and UCI users younger than 60 years had a slightly better SLA than BCI and UCI users older than 60. The difference was found not to be of significance, however a trend was shown [19],
which perhaps could explain the difference seen in the present study.

4.2 Bilateral CI subjects versus normal hearing subjects

Under binaural conditions, BCI subjects did not achieve the same level of SLA as NH subjects. The reason for this, according to Grieco-Calub & Litvosky [13], could be that the speech processors of CIs work in isolation of one another, which would mean an inadequate coordination and communication of ITD to the central auditory system for BCI users compared to NH subjects. However, a previous study has shown that ITD is of little importance for BCI subjects SLA, instead they rely mostly on ILD to localize a sound [20]. By having fewer cues to rely on, one can assume that SLA of BCI users would be poorer compared to NH subjects, which the present study has clearly demonstrated.

NH subjects, under monaural conditions, performed better than BCI subjects under the same conditions. The main reason for this was probably the fact that despite plugging one ear with an earplug and covering it with an earmuff, complete deafness was not achieved, this meant that NH subjects had some help from their “deaf” ear during the SLA tests.

4.3 Error index depending on sound stimuli

The reason why NH subjects, under binaural conditions, had the lowest EI for PN could perhaps be explained by applying the knowledge from the study of Kuk et al. [5], which showed that ILD and ITD are of most importance in different frequency regions. PN, with a wide frequency span, gives NH subjects the advantage of relying on ITD and ILD in their most important frequency regions, while CH, with highest dB levels below 1500 Hz, has the most important region only for ITD, and BB, with highest dB levels above 1500 Hz, only for ILD. Note however, that EI-difference between PN and CH was only 0.03 units.

PN had also the lowest EI for NH-L subjects under monaural conditions. When considering the fact that NH subjects were not tested under strict monaural conditions, perhaps the same reason that explained why PN had the lowest EI under binaural conditions can be applied here.

For BCI subjects, BB had the lowest EI under binaural and monaural conditions (BCI-L subjects). This could perhaps be understood by applying the findings of Kuk et al. [5] and Seeber et al. [20], which suggested that ILDs most important frequency region is above 1500 Hz and that BCI subjects (at least under binaural conditions) mostly rely on ILD to localize a sound. UCI-L subjects, however, did not have their lowest EI for BB, which contradicts the
latest proposal. However, EI-difference between the sound stimuli, under monaural conditions for UCI-L subjects, was only 0.04 units.

4.4 Study limitations

Two main limitations of the present study have been identified: (1) The practical implications of a certain EI are not understood. There is no debate that it is better to have an EI closer to 0.00 than 1.00, however, there is currently no understanding of what a difference of, for example, 0.10 EI units means in the context of everyday life. This issue should be examined in future studies; (2) No statistical calculations were done. Hence, the credibility of the present study was poorer than what would have been the case if statistics were used. For example, the minimum amount of subjects that would have been adequate for a statistical sample was not determined.

Other limitations that may have had an effect on the present study’s credibility: (1) Difference in mean age between test groups. It is difficult to determine whether this had an effect on the outcome, however, there is one study that has shown that sound localization deteriorates with increased age [21], which could imply that SLA differences would have been less if subjects had similar ages giving a different analysis; and (2) subjects had different instructors. There was always an instructor present during testing, however, all subjects did not have the same instructor. Having different instructors could mean different ways of explaining instructions giving subjects different premises.

5. Conclusion

The present study showed that adult BCI users had a better sound localization ability compared to adult UCI users. Adult NH subjects had a better SLA compared to adult CI users. This study will be expanded with more subjects and statistical analysis.

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