Objective assessment of auditory Spatial Change Complex perception using single-channel electroencephalography

Master Speech and Language Pathology
Faculty of Arts

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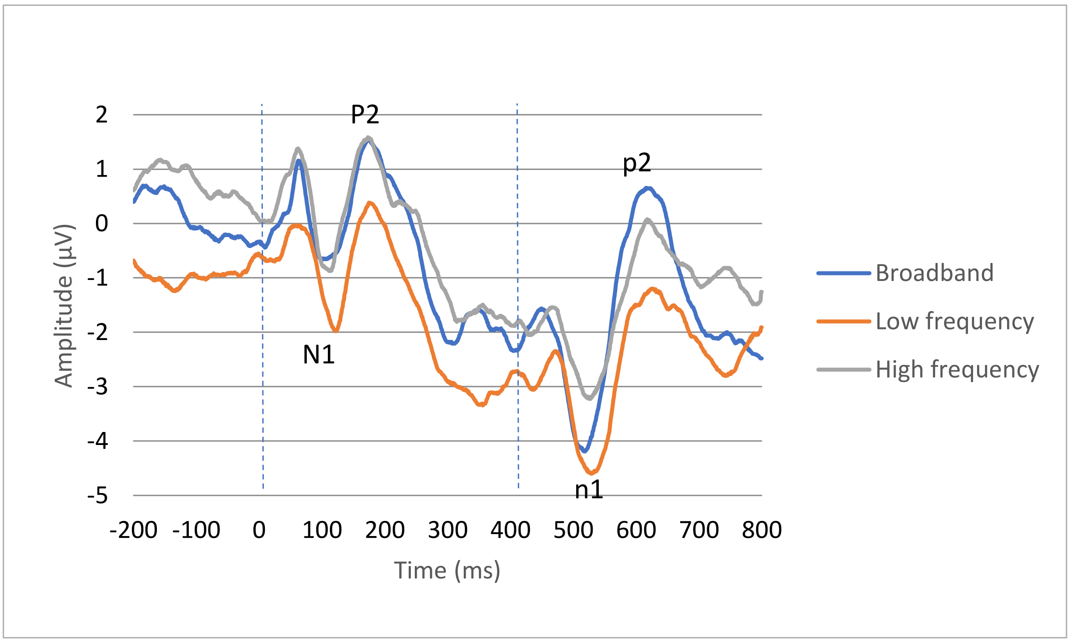

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Preface

After graduation as a speech language therapist last year, I felt the need to expand my knowledge. So, I started the master in linguistics. After six months, attending courses specifically about language it was time to get out of my comfort zone. Nine months ago, I started my internship at the Radboudumc at the department of otorhinolaryngology. I've always been always interested in brain measurements e.g. electro-encephalography, so it was a great opportunity for me to focus on cortical brain activity and sound localization. I have experienced the whole project as interesting and educational, with some setbacks. But the conquest of these setbacks felt fantastic.

Firstly, I want to thank my supervisor dr. Andy Beynon for his guidance and enthusiasm during the project. He gave me new insights and inspired me. He made it possible to attend symposia and presentations of research experts.

In addition, there are the employees of the Radboudumc that I would like to thank. Whether for a fun chat, questions about how the research progresses, for cooperation for patient recruitment or for assistance when the equipment let me down. Thank you very much!

I would like to thank my participants who willingly gave their time and company. Without their cooperation, this investigation had not been established.

I want to thank my friends for all the coffees, proof-reading, and support. More than thanks as always to my family for their unconditional support.

Now that I have finalized the thesis, I am proud to say: enjoy reading.

Abstract

Objectives
This study aimed to (1) investigate the effect of spectral content of stimuli on the P-P amplitude and latency of the Spatial Change Complex (SCC); and (2) examine the sensitivity, specificity, and accuracy of SCC as an objective measurement for sound localization. In addition, the SCC P-P amplitude of subjects with unilateral perceptive hearing loss is compared to those of normal hearing subjects.

Design
In the first experiment, the SCC was recorded from Cz using three formats: broadband white noise (0.5-20 kHz), low frequency white noise (.5-1.5 kHz) and high frequency white noise (3.5-4.5 kHz). In these formats, three conditions are measured, namely 0º-90º left, 0º-90º right and the 0º-0º control condition. In the second experiment, the SCC was recorded from Cz using broadband white noise measured in five conditions: 0º-90º left, 0º-30º left, 0º-30º right, 0º-90º right and the 0º-0º control condition.

Study Sample
In the first experiment, ten adults with normal hearing (≤20 dB), ranging between 21 and 53 years were included. In the second experiment, 25 adults with normal hearing (≤20 dB), ranging between 18 and 53 years and 14 adults with unilateral sensorineural hearing loss, ranging between 27 and 73 years were included. All patients with hearing loss experienced localization problems in daily life.

Results
The study showed that a significant difference was present between the 0º-0º control condition and 0º-90º lateral condition for broadband white noise low frequency white noise ($p < .001$). and high frequency white noise. The broadband condition was significantly higher than the low frequency condition and was also significant higher than the high frequency condition. However, no significant difference was present between the high frequency condition and the low frequency condition. In the second experiment, a significant difference was present between the 0º-30º and 0º -90º condition in the normal hearing group. No significant difference between these two conditions in SCC n1 and p2 latency was present. A significant difference was found in the 0º-30º left condition between normal hearing group and patient group. The other conditions did not turn out to differ significantly. The sensitivity was .78, the specificity is .72 and the accuracy has a value of .74.

Conclusion
Broadband white noise generates a larger SCC P-P amplitude compared to high-frequency and low-frequency narrowband white noise. The investigation did not result in a difference in latency of the SCC n1 and p2 between the different stimuli. The size of the SCC amplitude may depend on the size of the angle change, in other words, there might be a larger SCC amplitude at a larger angle condition. The SCC can be used as an objective index of auditory discrimination in localization.

Keywords: Spatial Change Complex (SCC), auditory late cortical potentials, auditory event-related potentials (AERP), auditory discrimination, unilateral sensorineural deafness

Content

1. Introduction

The ability to localize sound sources in space is of considerable importance to the human safety- and survival-system (Paulus, 2003). Selective attention, sensitivity and localization accuracy provide a realistic acoustic representation of the environment and go beyond visual perception. Obtaining this auditory information is of great importance for communicative interaction and safety (Goverts, 2004). The examination of sound localization has so far only been subjective. This means that it cannot be investigated in young children and persons with intellectual disabilities. Therefore, to obtain an objective measurement of sound localization is of interest.

Noordeloos (2017) has taken the first steps in investigating sound localization through electroencephalography (EEG). This study has shown a spatial change complex (SCC) could be raised in 71% of normal hearing people. In the group of normal hearing persons with simulated unilateral conductive hearing loss, 21% appeared to elicit an SCC. However, it is not known if these persons were able to correctly sense the sounds because they had a residual hearing since the earplugs may not completely block the hearing. There has been a subjective localization measurement, but this was obtained performed under different conditions, so that objective measurement could not be correlated.

As a follow-up, SCC research can be obtained in patients with sensorineural unilateral hearing loss performed under different conditions. To determine if any SCC is generated in accordance with subjective localization, it is important to determine any correlation between these two components. There is also little known about the effect of different types of bandwidth of the stimulus on the SCC.

1.1 Anatomy and physiology of the ear

The ear can be divided into three parts: the outer ear, the middle ear, and the inner ear (see figure 1). These parts are also called the 'peripheral' hearing system (McFarland, 2009).

Figure 1. The human ear.

1.1.1 The outer ear

The outer ear consists of the pinna and the ear canal. The pinna is a kind of flap that transmits sound waves to the ear canal and supports sound localization (Seikel, King & Drumright, 2010). The pinna consists of fibrocartilage which is covered by skin and attaches itself to the temporal bone. The ear canal is an oval S-shaped tube of about 25-35 m long and has a diameter of about 7 mm. The resonance frequency sensitivity is amplified at sounds between 1 and 6 kHz. In this frequency range, the speech area is the most effective for communication. At the end of the ear canal lies the tympanic membrane. This is a thin but strong membrane that is vibrated due to acoustic energy. The tympanic membrane has an oval shape with a diameter of approximately 10 mm (McFarland, 2009).

1.1.2 The middle ear

The middle ear consists of the tympanic cavity and the middle ear ossicles. The middle ear ossicles are the malleus, incus and stapes (see figure 2). The malleus, or “hammer”, is the largest and most lateral located ossicle. The malleus is connected to the incus, or “anvil”. The incus, in turn, contacts the stapes again (Seikel, King & Drumright, 2010). The stapes, or “stirrup”, is the smallest bone of the human body. The stapes attaches to the oval window of the cochlea. These ossicles have a leverage effect that enhances vibratory vibration (McFarland, 2009). Another important feature is the impedance adjustment required to transfer vibrations into air in vibration in fluid. This effect is much greater than that of the leverage effect (Beer et al., 1999).

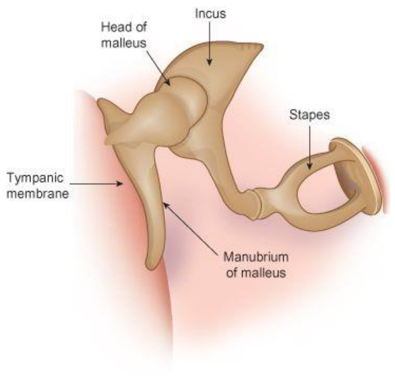


Figure 2. The ossicles.

1.1.3 The inner ear

The inner ear consists of two labyrinth systems: the bony labyrinth and the membrane maze. On the side of the bony labyrinth the semicircular canals are located. These channels are involved in balance and body orientation. The bony labyrinth is filled with perilymph containing the membrane labyrinth. The membrane labyrinth is filled with endolymph (Rietveld & Van Heuven, 2009).

The vestibule is located between the cochlea and the semicircular canals. The cochlea is the middle part of the bony maze. The oval window is the entrance of the cochlea. The oval window is the entrance of the cochlea and the round window is the exit. The cochlea is divided into two parts by the scala media. The scala media is narrow and rigid at the beginning and at the end of the cochlea increasingly broader and more flexible. This is important for frequency response characteristics: high frequencies stimulate the onset of the basilar membrane (thick and rigid base), while low frequencies stimulate the end of the basilar membrane (thin and flexible base). In addition, higher intensity noise stimulation leads to a greater range of stimulation (Rietveld & Van Heuven, 2009). The scala media has a sensory end organ: the organ of Corti, where the sensory hair cells are located which transmit signals to the auditory nerve (McFarland, 2009). The upper part of the cochlea, the scala vestibuli, is in direct contact with the oval window. At the end is an opening which connects the scala vestibuli and the scala tympani (Seikel, King & Drumright, 2010).

1.1.4 Hearing problems

Causes of hearing loss can be divided into conductive hearing loss and sensorineural hearing loss. Conductive hearing loss indicates that sound is not efficiently transmitted through the ear canal to the esophagus and the auditory bones. Possible causes of conductive hearing loss are ear infections, poor function of Eustachius tube, perforated tympanic membrane and benign tumors (American Speech-Language-Hearing Association (ASHA), 2017a). In sensorineural hearing loss, the lesion is located in the cochlea, the auditory nerve or the further auditory system. Sensorineural hearing loss can be caused by diseases, head trauma, aging and exposure to loud noises, but can be also genetically determined. Of all early onset of sensorineural hearing loss, about half is due to inherited factors (Morton & Nance, 2006). In most cases, sensorineural hearing loss cannot be treated medically or surgically (ASHA, 2017b).

Unilateral conductive hearing loss (UCHL) and single-sided deafness (SSD) in patients with a contralateral normal hearing ear can lead to typical problems associated with unilateral hearing such as poor localization and poor speech recognition in noise (Agterberg et al., 2011). In situations without ambient noise, there are also problems with speech recognition and localization, with distance being the most common factor (Giolas & Wark, 1967).

Problems with detecting spatial resolution may affect the functioning of daily life. Reduced binaural processing can lead to problems in social environments. Individuals with unilateral hearing loss often have the feeling of being disadvantaged in these social communication situations (Giolas & Wark, 1967; Wie, Pripp & Tvete, 2010). In addition to these social problems, a reduced localization ability also has an impact on learning performance. It appears that children learn less with unilateral hearing loss than children with normal hearing (Lieu, 2013). Also, a reduced hearing function is associated with a higher fall risk (Viljanen et al., 2009) and a greater chance of death for the elderly (Appollonio, Carabellese, Magni, Frattola & Trabucchi, 1995).

1.2 Spatial resolution

Human beings and animals are able to detect spatial resolution. Selective attention, sensitivity and localization accuracy provide a realistic acoustic representation of the environment and go beyond visual perception. Sound localization refers to two dimensions, namely azimuth and elevation. Azimuth can be defined as "the angle given by the sound source, the center of the listener's head and the median plane; this is the angle in the 'horizontal dimension'. Elevation is defined as "the angle given by the sound source, the center of the listener's head and the vertical plane" (Middlebrooks & Green, 1991). Additionally, spectral and binaural cues play a role in spatial listening (Goverts, 2004).

1.2.1 Spectral cues

Using spectral cues makes it possible to judge vertical sources (19.6° localization error of the normative angle) and front / back localization to determine the position. These cues are produced by broadband signals by the ear, head and space positions (Roffler & Butler, 1967; Gardner & Gardner, 1973). The result of these cues is an amplification or attenuation of the energy of a signal, depending on the direction of the signal. Spectral cues are better in estimating elevation angles of noise sources as compared to binaural cues. Although binaural cues are better (3° localization error), spectral cues can contribute to estimate azimuth angles (11° localization error). The ability to estimate front / back localization is equal for both spectral cues and binaural cues (Rodemann, Ince, Joublin & Goerick, 2008).

1.2.2 Binaural cues

The assessment of sound sources in the horizontal plane appeals to binaural cues (3° localization error). In addition, these cues contribute to accurate estimation at about 40% of the audio files. Most audio files were short speech phrases but also other types of sound e.g. white noise were used. Looking at front-back observation, in more than 85% of all audio files the angles are correct located through binaural hearing cues (Rodemann et al., 2008). Three effects of binaural hearing can be attributed to improved performance in background disorders: binaural summation (SU), head shadow effect (HSE), and binaural squelch (SQ). Summation of hearing means that, with two hearing ears, the brain receives signals louder as opposed to one hearing ear (Pyschny et al., 2014).

A century ago, Rayleigh (1907) observed that when a sound was presented from the side, the listener's head would interrupt the path from the source to the far ear. This interruption is also called 'head shadow effect' (HSE). This HSE provides an interaural difference in sound level (ILD). Relative to the size of the head, the wavelength contributes to the size of the HSE. At high frequencies, there is a smaller wavelength, which reflects the signal by the head. At these high frequencies, the shadow is a difference of about 35 dB between two ears for a source located on the side (Middlebrooks, Makous, & Green, 1989). Conversely, the wavelength is smaller for low frequencies. If the wavelength is equal to or greater than the diameter of the head, the signal may bend around the head. In this case, the signal also reaches the far ear, with the result that the sound source cannot be located based on ILD (figure 3). Where ILDs affect localization at high tones (>3 kHz), ITDs are most commonly encoded by low frequency signals (<1.5 kHz). When a low frequency pure tone is recognized as coming from the right or left side, it can be presumed that this decision is based on the difference in phases between two ears. As mentioned above, in low sounds there is a great distance between the wavelengths. Because the noise can bend over the head, the sound is also heard in the distant ear. However, the signal will be delayed, resulting in a phase difference (figure 3). This relative timing is related to the location of a sound source (Middlebrooks and Green, 1991; Firszt, Meeder, Dwyer, Burton, & Holder, 2015). The assumption that spatial resolution information is obtained by high frequencies of ILDs and low frequency of ITDs is often referred to as the "duplex" theory of sound localization (Middlebrooks & Green, 1991).

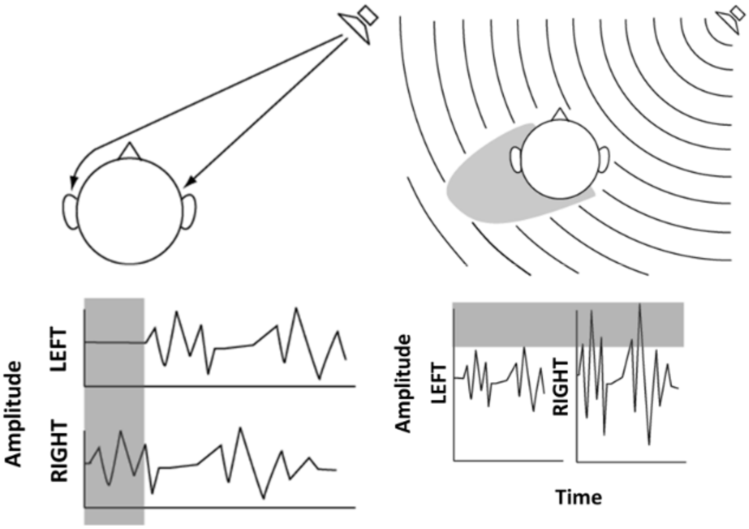


Figure 3. Interaural Time Difference (ITD) and Interaural Level Difference (ILD). The head shadow effect is visible because the waveforms of the high frequencies do not bend over the head. Taken from: Zhong, Yust & Sun, 2015.

The squelch effect, or cocktail party effect, is the ability to filter a signal from background noise. This ability can be attributed to the suppression of noise by the central auditory system, by using the difference in ITD and ILD. Binaural hearing is required to facilitate it and makes it easier to focus on the desired signal (Pyschny et al., 2014).

1.3 The effect of hearing problems on spatial hearing

1.3.1 Patients with unilateral hearing loss

Much research has been done with respect to the effects of spatial and binaural hearing on hearing problems. Overall, most studies have shown that the performance of persons with hearing problems is worse than that of normal hearing. However, a large variation has been found between the hearing-impaired persons ranging from almost normal to severely different (Goverts, 2004).

Some individuals with unilateral hearing loss have learned to use spectral cues from their intact ear to locate sound sources. But in a real monaural situation, the observed intensity of a sound source also relates to the azimuth localization, due to the head shadow effect (HSE) (Slattery & Middlebrooks, 1994). Agterberg et al. (2011) have investigated the extent to which unilateral deaf patients rely on this head shadow effect in horizontal localization. This study showed that unilateral deaf persons use the head shadow effect in the localization of sound sources when their bone conductor device (BCD) was turned off. Probably, the patients have learned that under certain conditions the HSE may be beneficial for localization, for example in well-known acoustic environments. The observations showed that the azimuth rapidly improves localization in unilateral deaf participants when they explicitly were told that the sound level is fixed and when visual feedback was given. In this situation, the HSE served as a valid azimuth cue. It must be considered that sound sources in daily life are often unknown and vary widely in sound levels, which makes the HSE ambiguous for localization and hence unusable (Van Wanrooij & Van Opstal, 2004).

In the study of Wazen, Ghossaini, Spitzer & Kuller (2005) narrow band stimuli were used at twelve patients with unilateral severe to profound sensorineural hearing loss. Nine of these patients subsequently received a bone anchored hearing aid (BAHA) on the worst hearing ear. In addition, ten participants with normal hearing in both ears were included as control group. This study showed that persons with unilateral sensorineural hearing loss perform worse on localization tasks compared to the control group at 500 and 3000 Hz. Remarkably, no difference in localization ability was present between the unaided condition and the condition when the BAHA was turned on.

In contrast to the studies mentioned above, the study of Slattery and Middlebrooks (1994) showed that three out of five patients with unilateral deafness did as well as the normal hearing control group. However, the other two patients did show problems with localization. The authors did not give a conclusive explanation for the great variation in performance among the five monaural patients in this study. One point that is worthy of note is that one of the two patients who did show problems with localization had residual hearing at low frequencies in the impaired ear.

The study from Rothpletz, Wightman and Kristler (2012) showed that patients with unilateral hearing loss performed as well as the control group. Twelve patients with unilateral hearing loss and twelve normal hearing controls completed a horizontal localization task using broadband stimuli.

This result was also found by Agterberg, Snik, Hol, Van Wanrooij and Van Opstal (2012) using broadband noise. In this study, patients with unilateral conductive hearing loss were examined. The patients were tested in two conditions: one condition without headphones on the affected ear and one condition with headphones on the affected ear. Horizontal localization became worse after patients had headphones on the affected ear, indicating that they use spectral cues (pinna) to locate sounds at broadband noise.

In addition to investigating patients with unilateral hearing problems, normal hearing participants with imitated hearing loss have also been investigated. Irving and Moore (2011) presented broadband noise to normal hearing participants. These persons were tested in two conditions, means without an ear plug and with an ear plug. A deterioration was found when the ear was plugged. The individuals were trained to locate sound, which showed that an improvement appeared after the fourth day.

A possible explanation for the great variation of localization abilities in patients with unilateral hearing loss between the studies mentioned above is the variation used in the stimulus spectrum. Variation in the spectrum of a stimulus, mainly in the middle frequency of a bandpass filter, may affect the horizontal localization when an ear is blocked (Butler & Flannery, 1980; Butler, 1986). Butler (1986) showed that localization improves with an increasing bandwidth. In narrowband noise, only an ITD cue or ILD cue is present, while broadband noise contains both cues. This suggests that locating broadband noise is easier than locating narrowband noise (Agterberg et al., 2012). In addition, the severity of hearing problems may have affected the results. In the study of Wazen et al. (2005) patients with severe hearing loss were included. The result of this study was that patients with unilateral hearing loss performed worse on the localization task compared to normal hearing participants.

Finally, in a few studies, some of the participants have used the HSE. In the studies mentioned above, there has been little variation in intensity, which results in HSE (Agterberg et al. 2011). For example, in the study of Wazen et al. (2005), one of the two patients who showed large errors in localization response had residual hearing at the low frequencies of the impaired ear. It might be the case that, like plugged participants, the patient expected a certain balance of levels at the two ears. One of the three patients who performed well in the monaural condition noticed that she knew that a stimulus came from the affected side because the sound was ‘muted’. The use of HSE contributes to the ability to localize sound sources (Van Wanrooij & Van Opstal, 2004).

1.3.2 Bilateral sensorineural hearing loss

There is some confusion in the field of sound localization in persons with bilateral sensorineural hearing loss. According to some studies, persons with severe bilateral perceptive hearing loss with a unilateral cochlear implant are unable to locate sounds due to a difference in balance between the sound inputs from both ears. The reason for this is that they have one cochlear implant that makes them unable to apply interaural level differences (Johnstone, Nábelek & Robertson, 2010; Nopp, Schleich & D’Haese, 2004).

A bilateral gain is potentially important to obtain binaural information. Binaural hearing can be provided by bilateral cochlear implantation or bimodal stimulation (Heo, Lee & Lee, 2013). Bimodal hearing, in contrast to bilateral stimuli, means that a person's hearing is stimulated in two different ways, for example by electrical stimulation in one ear and acoustic stimulation in the other ear (Raj, Saini & Mishra, 2017). A growing number of people use a contralateral hearing aid after a CI transplantation (Keilmann, Bohnert, Gosepath & Mann, 2009). Bilateral hearing, in turn, means that both ears are stimulated in the same way. This means, for example, that a person has a cochlear implant in both ears (Ching, Van Wanrooy & Dillon, 2007).

The main benefit of the added information is the bilateral auditory input that allows the patient to use binaural processing to improve speech perception and sound localization (Keilmann et al., 2009; Offeciers et al., 2005). In bimodal stimulation, both the hearing aid provides the patient with fine time information through the low frequency tones as well as the cochlear implant through the high frequency tones. These interaural time differences help to locate sound (Wightman & Kistler, 1992). However, a problem with bimodal stimulation is an atypical interaural time difference due to two different stimuli that results in asymmetric hearing. Because the processing times of the bilateral devices differ from each other, shifts occur that affect the interpretation information of interaural time differences. If this shift is small and constant, listeners can adapt to these cues and are thus able to locate sound (Shinn-Cunningham, 2001). However, if this shift is large and not constant, the information between them is too distorted to be useful (Ching et al., 2007). Although this problem is present in bimodal hearing, directional hearing in a bimodal hearing condition is better compared to a single cochlear implant condition (Litovsky, Johnstone & Godar, 2006). Bilateral implants offer a significant advantage in locating sound. Users of bilateral implants can benefit from the effects that are known from persons with a normal-hearing, specifically, head shadow effect, summation effect and the squelch effect. (Nopp et al., 2004). A second implant allows bilateral CI listeners to scan the frontal region on both sides from the center line by one implant, independent of both sides. Like persons with normal hearing, bilateral CI listeners can use a combination of monaural and binaural cues to locate sound (Murphy, Summerfield, O'Donoghue & Moore, 2011). In bilateral stimulation, the patient uses interaural level differences through the high frequencies. Because of most implant speech coding strategies do not process fine-structured information, which is present in speech signals, a cochlear implant does not provide the patient with interaural time differences, which makes the localization more difficult. However, in some cases, it has been found that persons with bilateral CIs are able to apply these interaural time differences: the study of Schoen, Mueller, Helms and Nopp (2005) in postlingual late-deafened patients show a significant advantage in sound localization. In contrast, prelingual deaf patients who are implanted at a later age, may not benefit from bilateral implants with respect to sound localization. However, early implantation in this population might cause better spatial hearing, and therefore better sound localization (Nopp et al., 2004).

1.4 Objective assessments of sound discrimination

To test the effect of a hearing adjustment, two types of methods can be applied: behavioral measurements and objective measurements. Contrary to objective measurement, active participation of the patient is required in a behavioral measurement. Behavioral measurements include threshold determination by audiometry, assessments of speech recognition and self-assessment questionnaires. In order to investigate the capability to localize, the minimum audible angle (MAA) can be used. The MAA is a relative measure to measure the localization ability and the just-noticable difference (JND) in sound angles. This is the smallest difference between the azimuth between two sources of sound (Smith & Price, 2014). The MAA is the angle formed at the center of the head by lines projecting two sound sources whose difference in position is noticeable when they sound in succession (see figure 4) (Mills, 1958). In a MAA assessment, the subject will hear two tones, of which one (reference) comes from a central localization point (S). The second tone is either from the left, either from the right side from the central point. The subject must then indicate where the sound is coming from. The stimuli are constant, with the angles being fixed during the experiment. The MAA is determined by 75% correct responses. This method can be used to compare results in localization within different conditions, such as at different positions of the central localization point and for different bandwidths of stimuli (Hartmann & Rakers, 1989). Harris & Sergeant (1971) have determined the MAA of listeners in monaural and binaural condition. They found that the monaural MAA was as large (about 2.5°) as the binaural MAA in white noise (complex signal), but the monaural MAA was at least twice as large in tones (about 7°).

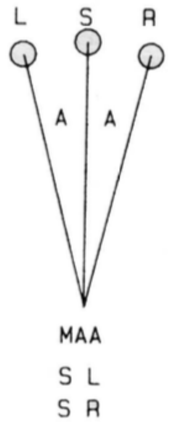


Figure 4. Setup of the MAA, where (S) is the central localization point, (L) the stimulus left and (R) the stimulus on the right (adapted taken from: Hartmann & Rakers, 1989).

In contrast, objective electrophysiological measurements use e.g. auditory evoked brain potentials. Conducting behavioral measurements is well applicable in adults, but not always in younger children, therefore it is recommended to test the latter objectively (Bagatto, Moodie, Seewald, Bartlett & Scollie, 2011). Electrical changes in the peripheral and central nervous system can be measured with surface electrodes from the skull by obtaining an electroencephalogram (EEG). An evoked potential (EP) refers to a series of electrical changes that occur and consists of a series of positive and negative peaks (Näätänen & Picton, 1987). These neural changes are usually related to sensory pathways. Depending on which sensory system is stimulated, the EP is referred to the system. Thus, in a stimulated auditory system, the EP is referred to as auditory evoked potential (AEP) (Jacobson, 1994). Some AEPs are smaller than the EEG and are therefore not visible in the raw EEG signal. The most widely used method of improving the S/N-ratio is by averaging the responses of multiple identical stimuli with the AEP remaining constant with each stimulus, while the background noise varies. By averaging the EEG responses, the variation of the background noise decreases, according to the root-mean-square (RMS) of the noise (Plourde, 2006).

The AEPs can be divided into four different ways: latency (the time that they occur in the nervous system), supposed generator (where they occur in the nervous system), temporal characteristics (how they react to acoustic stimulation and subject factors (endogenous or exogenous). Based on latency, AEPs can be classified as brainstem response (ABR), middle latency response (MLR) and long latency response (LLR).

The long latency auditory evoked potentials (P1, N1, P2, N2, P300), are visible between 50 and 500 milliseconds after presenting the stimulus (see figure 5). These potentials are predominantly registered with the vertex (Cz) (Picton et al., 1974). These evoked potentials are of an exogenous nature, which means that responses are more related to external factors, therefore, they are also called event-related potentials (ERP) (Jacobson, 1994). Long latency AEPs are mainly used in studies related to higher brain functions due to perceptual and cognitive processes (Regan, 1989). If a person collects information about objects and events around him, then this is called ‘perception’. The internalization of these objects and events can be seen as 'cognition' (Gibson, 1969 in McPherson, 1996).

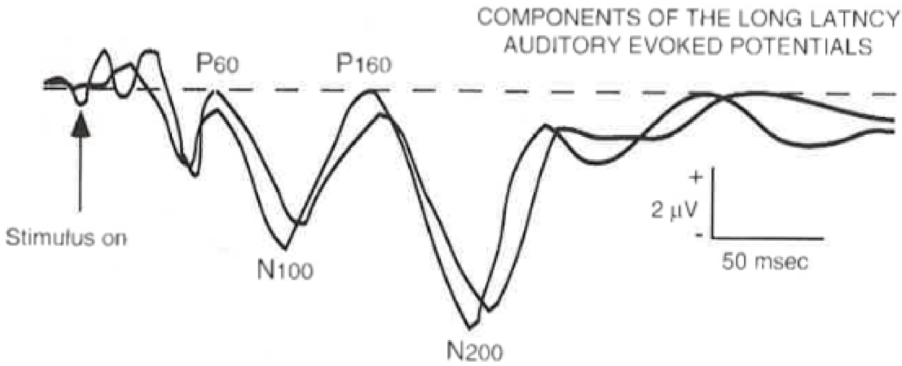


Figure 5. P1 (P60), N1 (N100), P2 (P160) and N2 (N200) components of the long latency AEPs (from: McPherson, 1996).

The P1 is the first positive peak following a middle late AEP and occurs approximately 55 to 80 milliseconds after offering a stimulus. The N1 follows the P1, about 80 to 150 milliseconds after offering the stimulus. The P2 is a robust response that appears 150 to 230 milliseconds after the stimulus (McPherson, 1996). The N2 appears approximately 180 to 250 milliseconds after a physical discrimination task requiring passive attention (Ritter, Simson & Vaughan, 1983). The P2-N2 complex is best obtained from the vertex on the center mid-line of the scalp, with most of the ipsilateral mastoid or earlobe as a reference point. This complex is also called the "slow vertex potential". Both the N1 and P2 and N2 are characteristic of acoustic properties of the ability of hearing. (McPherson, 1996).

1.4.1 The Acoustic Change Complex

The Acoustic Change Complex (ACC) is a cortical AEP, which may occur due to acoustic change within a sound, consisting of a positive- negative-positive complex (P1-N2-P2)

(Martin & Boothroyd, 2000). Tremblay, Friesen, Martin & Wright (2003) used four naturally-produced stimuli (/bi/, /pi/, /ʃi/ and /si/) and reported different ACC responses for different acoustic changes, based on the different acoustic features. In addition, it has been found that there is a good agreement between the ACC and behavioral measure of discrimination of intensity (Martin & Boothroyd, 2000) and frequency (Martin, 2007), suggesting that ACC may be a useful measure for the clinical assessment of speech perception.

With respect to the pediatric population, Small and Werker (2012) has shown that the ACC can even be obtained in children of four months old.

Martinez, Eisenberg and Boothroyd (2013) have investigated the ACC in five normal-hearing children and five children with bilateral perceptive hearing loss with bilateral hearing aids. Results showed that the ACC could be measured reliably in children of three years old, both with normal hearing and hearing aids, which is in line with Martin (2007), reporting that ACC can be obtained in bilaterally implanted CI children.

1.4.2 Mismatch negativity

The mismatch negativity (MMN) is an AEP that is produced in response to the brain on violations of rules, drawn up by a sequence of sensory stimuli, for example in presenting frequent and infrequent signals. These infrequent signals are known as 'deviants'. The frequent consecutive sounds are called the 'default' or 'standard' sounds. Two intracranial generators for the MMN are assumed: one in the auditory cortex and one in the frontal brain region (Sams, Paavilainen, Alho & Näätänen, 1985). The MMN can be associated with pre-alert activities of hearing and it is therefore suggested that the MMN reflects the primitive intelligence of the auditory cortex and may be useful in identifying central hearing problems of newborns and prelingual children (Näätänen, Tervaniemi, Sussman, Paavilainen & Winkler, 2001). This early identification is important, because results of behavioral tests are usually obtained too late to prevent a delay in language and speech development (Kurtzberg, Vaughan, Kreuzer & Fliegler, 1995).

1.4.3 Relationship between Mismatch Negativity and other Event-Related Potentials

The MMN can be separated from other ERP waveforms in different ways. The N1, like the MMN, often increases in amplitude if a change in the stimulus occurs. The differentiation of the MMN and the N1 depends on several findings.

First, the amplitude of the N1 becomes smaller at decreasing intensity between the standard and the deviant, whereas this is not the case with the MMN (Picton, Alain, Otten, Ritter & Achim, 2000). Secondly, there is no difference in the amplitude of the N1 with a change in pattern time duration, in contrast to the MMN (Czigler, Csibra & Csontos, 1992). In addition, the amplitude of the N1 is influenced by the interstimulus interval (ISI), which does not affect the MMN (Näätänen, Gaillard & Mäntysalo, 1987). Regarding latency, the difference between the standard and the deviant affects MMN on latency, but not on the latency of the N1 (Picton et al., 2000). Finally, the N1 is influenced by difference in pitch, regardless of the stimulus duration. In addition, there is only effect of pitch if the stimulus is long enough to perceptually distinguish pitches (Sams et al., 1985).

The MMN is also distinctive from subsequent different waveforms occurring in the ERP, such as the P2 wave. This distinction is based on the fact that the MMN is relatively unaffected by both the relevance of the stimulus to each task the subject performs and the amount of attention the person gives to the stimulus. When attention is paid to the stimuli, the P2 wave often appears on top of the MMN (Näätänen, Simpson & Loveless, 1982).

The MMN is similar to the ACC, however, the ACC has a better signal to noise ratio. Because each ACC stimulus contributes to a response, less stimuli are required which results in a significantly shorter measurement time. These may be reasons for choosing ACC measurements instead of MMN measurements (Martin & Boothroyd, 2000).

1.4.4 Influence of Side of Hearing on Cortical Organization

In normal hearing subjects, the cortical activation pattern is characterized by shorter and greater neurophysiological responses in the hemisphere contralateral to the stimulated ear in response to monaural stimulation, because the contralateral auditory pathway contains a greater number of nerve fibers than the ipsilateral pathway (Hanss et al., 2009).

In mammals, a cortical reorganization has been a result of severe unilateral deafness. After removal of one cochlea during the neonatal period in cats, neurophysiological responses showed a reduced activation threshold in the auditory cortex contralateral to the intact ear (Reale, Brugge & Chan, 1987).

In human adults, studies have shown that auditory plasticity mechanisms also occur in the first week after the onset of unilateral deafness and continues for several years. The main change in the auditory cortex ipsilateral to the healthy ear of subjects with unilateral deafness is the use of long latency evoked potentials. The study of Ponton et al. (2001) showed that a more synchronous and equal activation in hemispheres was present due to increased activation in the hemisphere ipsilateral to the healthy ear.

Khosla et al. (2003) investigated the influence of the side of deafness on cortical reorganization using monaural click stimulation in eight normal hearing subjects and nineteen subjects with unilateral deafness. The subjects with lefts-sided deafness (right ear stimulation) showed similar N1-P2 amplitudes in both hemispheres, whereas subjects with right-sided deafness (left ear stimulation) showed an asymmetry in hemispheres. In both normal and unilateral deaf subjects the N1-P2 amplitude was greater in the contralateral hemisphere than the ipsilateral hemisphere of the stimulated ear. Regarding peak latency, normal hearing subjects have former N1 compared to the P2. For the patient group, no difference in latency of both the N1 and P2 in both hemispheres was found. Finally, no difference was visible between stimulation in the left ear and right ear for both groups.

1.4.5. The Spatial Change Complex

From the ACC, the idea has come about to investigate whether a spatial change complex can be generated. The SCC could be defined as an AEP consisting of a negative waveform (n1) which occurs around 100 milliseconds followed by a positive waveform (p2) which occurs around 160 milliseconds after changing the spatial resolution within a stimulus.

The study conducted by Noordeloos (2017) showed that 71% of the normal participants (N = 36) could generate a SCC. The patient group consisted of the same persons as that of the control group, but in this condition an ear plug was placed in the left or right ear, to simulate a conductive hearing loss. These results showed that still 21% of the patient group could generate a SCC. Because some participants were still able to localize the sounds correctly, it was not clear what the underlying reason was.

1.5 Aim of the study

The aim of the study is to determine the sensitivity, specificity and accuracy of electroencephalography as clinical tool for the ability of sound localization. The study objectives include:

Experiment 1

1. How does spectral content of the noise (broadband, low frequency and high frequency) affect the P-P amplitude and latency of the SCC?

2*. Is there a difference in the P-P amplitude and latency of the SCC between sounds presented from the left side and sounds presented from the right side?*

Experiment 2

1. *What is the sensitivity, specificity and accuracy of the SCC determined by electroencephalography as an objective measure of sound localization?*

2*. How does angle changes affect the P-P amplitude and the latency of the SCC?*

3*. Is there a difference in the P-P amplitude and latency of the SCC between persons with a normal hearing and persons with unilateral sensorineural hearing loss?*

4. *Is there a difference in SCC P-P amplitude and latency of the SCC between sounds presented from the left side and sounds presented from the right side in patients with unilateral sensorineural hearing loss in the left ear and patients with unilateral sensorineural hearing loss in the right ear?*

Experiment 1

2. Method

2.1 Participants

The group consisted of ten normal hearing subjects (one male) in the age of 21;2 through 53;7 years with a mean age of 29.5 years (*SD* =12.2). Pure-tone air conduction thresholds of octave frequencies from 250 to 4000 Hz were obtained using a tone audiometer [Interacoustics AD629]). All included participants show hearing threshold ≤20 dB HL and have signed an informed consent prior to the investigation.

2.2 Stimuli

In this experiment, broadband noise stimuli (0.5-20 kHz), high frequency noise stimuli (1/3 octave band white noise, centered around 4 kHz with a cutoff frequency of 3.5-4.5 kHz) and low frequency noise stimuli (1/3 octave band white noise centered around 600 Hz with a cutoff frequency of .5-1.5 kHz) were used. The spectra are shown in appendix II, figure 30 - 32. The stimuli have been developed with an audio frequency signal generator (Pigeon, 2012). On all stimuli, 10th order Butterworth bandpass filter is applied (Hyde, 1994a). The stimuli were all presented at an intensity level of 65 dBA (A-weighted, to measure the noise level that matches the perception in the field). Before the experiment, all speakers were calibrated with a Brüel & Kjaer Investigator 2260. The stimuli were controlled by a computer at 1 meter distance from the subject. The experiment consisted of a control condition (0°) and two lateral conditions (-90° and +90°, indicating negative (-) as left and positive (+) to the right). During the control condition, broadband stimuli, high frequency stimuli and low frequency stimuli were presented for 790 milliseconds. The rise-fall time was 10 milliseconds (see Figure 6).

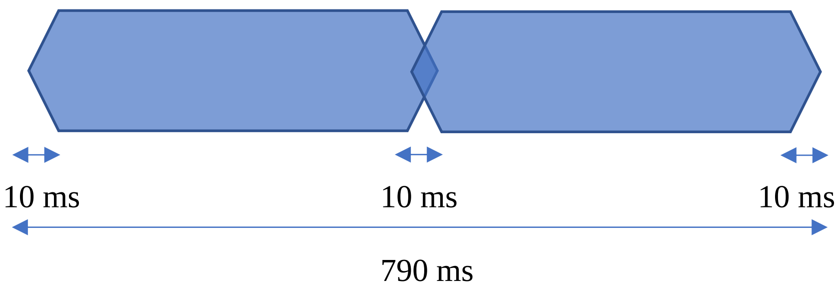


Figure 6. The stimulus for the control condition with a total stimulus duration of 790 ms and a rise-fall time of 10 ms from the 0º-0º control condition. The two signals have a rise-fall time of 10 ms, where the rise time of the second lateral signal starts when the fall time of the first signal from the speaker begins frontally. A partial overlap of 10 ms is visible in the middle of the stimulus.

During the lateral conditions, it was examined whether an effect of bandwidth in the EEG would result in a different SCC. A 790 ms stimulus was presented, consisting of a 400 ms frontal presentation (0°) followed directly by a 400 ms lateral stimulus (90°). Both signals had a rise time of 10 ms, with the rise time of the second lateral signal starting as soon as the fall time of the first signal began, resulting in 10 milliseconds overlap (see figure 7). This transition provided a continuous signal without the transition being observed (see pilot study, appendix I). Interstimulus interval (ISI) was 1.6 seconds for both the control condition and the lateral condition, which means the time between the end of one stimulus and the beginning of the next stimulus (Hyde, 1994a).

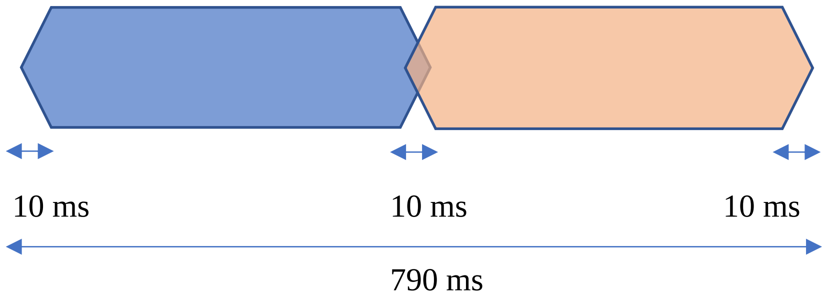


Figure 7. The stimulus for the lateral conditions with a total stimulus duration of 790 ms and a rise-fall time of 10 ms. The two signals have a rise-fall time of 10 ms, where the rise time of the second signal from one of the corners (±30º and ±90º) starts when the fall time of the first signal from the speaker begins frontally (0º). A partial overlap of 10 ms is visible in the middle of the stimulus. The stimulus is used for all three conditions, where the entire stimulus contains high frequency, low frequency or broadband noise. The stimulus is therefore never divided into a combination of these three.

2.3 Measurement setup

In a soundproof room, a stimulation PC and an EEG device were placed behind the subject. The participant sat on a chair surrounded by five custom made Vifa ball speakers (Falcon Acoustics, appendix IV) in a free field setup. On the stimulation PC, a customized interface (Labview) has been built to enter desired stimuli to manipulate the stimulus.

The stimuli were presented via an audio amplifier (Ecler MPA4-80R) through free field loudspeakers. At the same time, a trigger pulse (+ 5V sync pulse) was transferred to the EEG recording system (Medelec Synergy, Oxfords Instruments, UK) to ensure exact time-locking during data acquisition. The speaers were located one meter away from the center of the head of the participant at the height of the ears. The positions of the speakers used were -90° (left), 0 and +90° (right). To minimize artifacts by generating head movement, the participant placed his chin on a head support (Hyde, 1994a). In addition, the kin support contributed to the reliability of the measurements, because the head of each subject was throughout the experiment at the same distance from the speakers, without any movement (see appendix III, figure 33).

2.4 Data acquisition

A one-channel EEG measurement was performed to measure the SCC in an analysis window of 1000 milliseconds, which included 200 ms prior to stimulus onset. The active electrode was placed on the vertex (Cz) because at this point the AEP's are more robust (Hyde, 1994a). The reference electrode was placed on the nose and the ground electrode was placed below the hairline laterally on the forehead (Fp2). The impedance of the electrodes had to be <8000 Ohm in all subjects (Hyde, 1994a). The cortical brain activity was measured in microvolt (μV) with an automatic artefact rejection level set to 50 μV. Through the pre-amplifier, the measured brain activity was strengthened, and then averaged. The data was acquired at a sampling rate of 25 kHz, a bandpass filter of 0.1 to 30 Hz and a 50 Hz notch filter (Hyde, 1994b). The number of averages consisted of at least 45 responses. To check reproducibility, the data was averaged within subjects based on the same condition (Hyde, 1994a), defined as 'Grand Average' or 'GA'.

2.5 Procedure

The participant took place in a chair with a head support. The subjects were asked to move as little as possible and to relax as much as possible. Also, clamping of the jaw was not allowed,

since this generates artefacts (Hyde, 1994a). To keep the attention as focused as possible, the subjects were instructed to count the number of stimuli from a particular speaker.
The participants were presented the stimuli in three conditions: frontal (0°), frontal (0°) and immediately followed by a +90° angle and frontal (0°) immediately followed by a -90° angle. These three corner conditions, as well as the three bandwidth conditions, were randomly presented to the subject.

During the experiment, a subjective localization measurement was also performed to verify that the subject could locate the sounds. After the first measurement of each condition, persons were asked where both sounds came from.

2.6 Data analysis

Of each grand average (GA), the SVP and the SCC were determined. For the SVP, the latency of the N1 is defined as a negative potential that occurs between 80 and 150 ms followed by the P2, which is defined as a positive potential that occurs between 150 and 230 ms. The SCC consists of the n1 defined as negative potential which occurs between 80 and 150 ms after an angle change within a sound stimulus followed by the p2 defined as positive potential occurring between 150 and 230 ms after an angle change within a sound stimulus. The P-P amplitudes of all SVPs (N1-P2) and SCCs (n1-p2) were calculated and were indicated in microvolt (μV).

To determine if the SVP and SCC were present, the peaks were compared to the standard deviation of the 200 ms pre-stimulus noise. Since the SCC in the control condition (0°) should be absent, the n1 and p2 were determined by placing them on the same latencies as in lateral ERP responses. When the amplitude exceeds the standard deviation of the pre-stimulus noise, it was accepted that an SVP or SCC was present. The condition of an existing SCC was the presence of a SVP was obligatory.

The experiment consisted of a within subject design with two dependent variables: amplitude in microvolt (μV) and latency time in milliseconds (ms), measured under different conditions. Statistical analyses were performed using Repeated Measures ANOVAs and Paired Samples T-Tests (SPSS, version 24.0) with a p value of $<.05$ considered as significant. Repeated Measures ANOVAs have been conducted to investigate whether the average P-P amplitude of the SCC and latency times of the n1 and p2 differ significantly in the lateral conditions in the broadband condition, the high frequency condition and the low frequency condition (question 1a and 1b). If a significant effect was present, post-hoc pairwise comparisons were reported, where the p-values from the ANOVAs were corrected according to Bonferoni. Before performing the Repeated Measures ANOVAs, the assumptions of normality and sphericity have first been tested. For the assumption of normality, the Kolmogorov-Smirnov test was performed and for the assumption of sphericity, the Mauchly's test was performed. If Mauchly's test had a significant value, the Greenhouse-Geisser or Huynh-Feldt test was applied (Field, 2013).

Paired Samples T-tests were performed per bandwidth condition to determine whether a significant difference was found in both P-P amplitude and latency between stimuli presented from 0-90° left and stimuli presented from 0-90° right (question 2a and 2b). Before the Paired Samples T-tests were performed, the assumption of normality was first tested using the Kolmogorov-Smirnov test. If the assumption of normality was violated, the Paired-Samples T-tests were performed by Bootstrap. Due to a lack of normality, the shape of the sample distribution remains unknown. Bootstrap is a technique that avoids this problem, with the sample distribution being estimated by taking multiple small samples from the sample data. Because the average of these small samples is calculated, the distribution of the overall sample is estimated (Field, 2013). For all Paired Samples T-tests, the effect strength was calculated using Cohen's d. This indicates whether it was a weak effect (d = .0 - .5), an average effect (d = .5 - .8), a strong effect (.8 - 1.3) or a very strong effect (> 1.3) (Field, 2013). The data was at interval level.

3. Results

3.1 SCC P-P amplitude of the control conditions

The Kolmogorov-Smirnov test has shown that the P-P amplitude of the SCC of the control conditions was normally distributed for broadband stimuli ($D(10) = .16$, $p = .20$), low frequency ($D(8) = .16$, $p = .20$) and high frequency ($D(9) = .19$, $p = .20$. No outliers in the control condition were visible. For the control condition, the assumption of sphericity was assumed, $\chi^2(2) = .81$, $p = .48$. No significant main effect of frequency of spectral content on the amplitude of the SCC of the control conditions was found, $F(2, 16) = .25$, $p = .78$, $\eta^2 = .03$ (see figure 8).

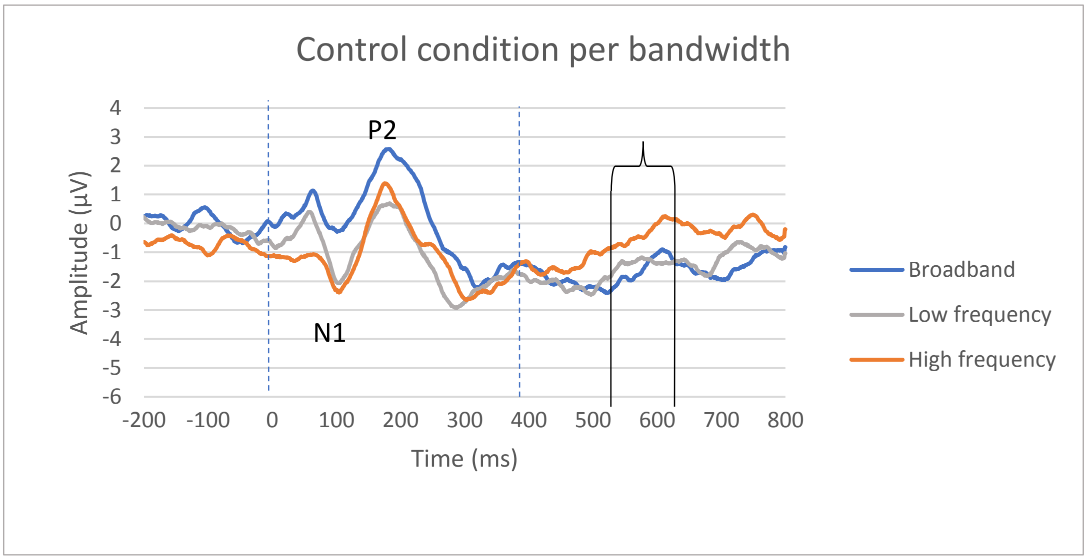


Figure 8. Grand mean averaged ERP signal of all participants for the control condition (0°) per bandwidth, with the accolade indicating the period where normally the n1 and p2 of the SCC are located. The blue dotted lines indicate the onset of stimulus.

3.2 The P-P amplitude and latency of the SCC in the control conditions versus the lateral conditions

SCC P-P amplitude

The P-P amplitude of all control conditions were found to be normally distributed, see §3.1. The P-P amplitude of the lateral broadband condition ($D(10) = .19$, $p = .20$), the lateral low frequency condition ($D(8) = .14$, $p = .97$ and the high frequency condition ($D(9) = .16$, $p = .20$) was normally distributed with no outliers present.

The paired samples t-test has shown that the SCC of the broadband control condition ($M = .69$, $SD = .42$) significantly differs from the SCC from the broadband lateral condition ($M = 5.48$, $SD = 1.57$), 95% CI [-5.78, -3.80], $t(8) = -10.91$, $p < .001$.

The paired samples t-test has shown that the SCC of the low frequency control condition ($M = .57$, $SD = .42$) significantly differs from the SCC from the low frequency lateral condition ($M = 4.28$, $SD = 1.55$), 95% CI [-4.81 -2.61], $t(9) = -7.63$, $p < .001$.

The paired samples t-test has shown that the SCC of the high frequency control condition ($M = .53$, $SD = 3.29$) significantly differs from the SCC from the high frequency lateral condition ($M = 3.29$, $SD = 1.46$), 95% CI [-3.85, -1.66], $t(9) = -5.81$, $p < .001$ (see figure 9).

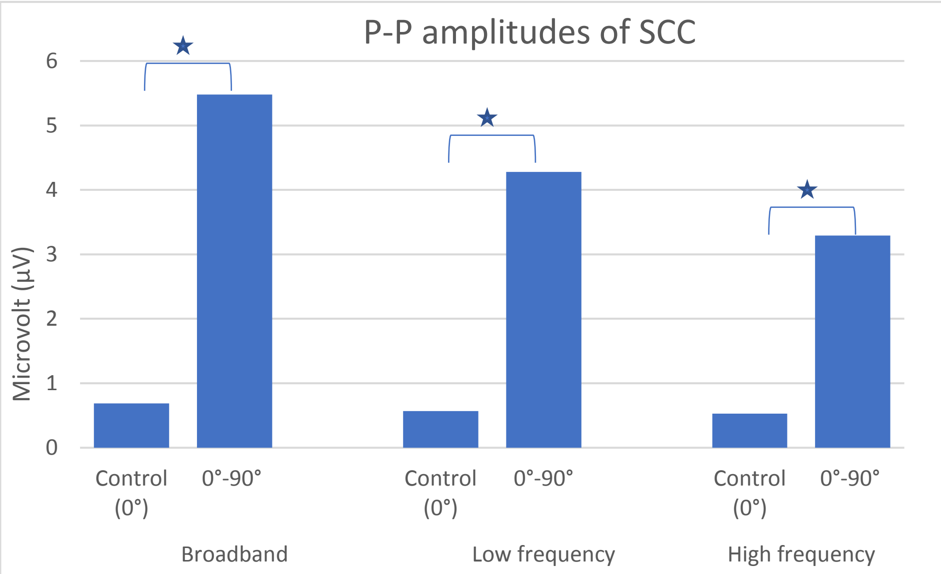


Figure 9. Bar charts showing the SCC P-P amplitudes of the control condition (0º) and lateral condition (0º - ±90º) for broadband, low frequency and high frequency. The asterisk indicates whether it is a significant difference ($p < .05$).

SCC n1 and p2 latency

The latency of the n1 of the broadband control condition (0º) (M = 514.60, SD = 19.60) did not differ significantly with the latency of the n1 of the broadband condition 0°-90° lateral (M = 523.75, SD = 8.62) 95% CI [-4.67, 22.96], $t(9)$ = 1.50, p = .17, and represented a X effect, d =.60. The latency of the p2 of the broadband condition control condition (0º) (M = 600.10, SD = 23.87) did not differ significantly with the latency of the p2 of the broadband condition 0°-90° lateral (M = 614.60, SD = 16.38) 95% CI [-33.46, 4.46], $t(9)$ = -1.73, p = .12, and represented an average effect, d =.71.

The latency of the n1 of the low frequency control condition (0º) (M = 526.83, SD = 15.55) did not differ significantly with the latency of the n1 of the low frequency condition 0°-90° lateral (M = 516.22, SD = 14.36), 95% CI [-.47, 21.69], $t(8)$ = 2.21, p = .06, and represented an averaged effect, d = 0.71. The latency of the p2 of the low frequency control condition (0º) (M = 594.11, SD = 44.16) did not differ significantly with the latency of the p2 of the low frequency condition 0°-90° lateral (M = 592.89, SD = 29.00), 95% CI [-45.72, 47.72], $t(8)$ = -.061, p = .953, and represented a weak effect, d = .03.

The latency of the n1 of the high frequency control condition (0º) (M = 527.40, SD = 12.99) did not differ significantly with the latency of the n1 of the high frequency condition 0°-90° lateral (M = 525.40, SD = 18.66), 95% CI [-9.08, 12.88], $t(8)$ = -.56, p = .70, and represented a weak effect, d = .12. The latency of the p2 of the high frequency control condition (0º) (M = 610.80, SD = 17.35) of the high frequency condition control condition (0º) did not differ significantly with the latency of the p2 of the high frequency condition 0°-90° lateral (M = 611.00, SD = 15.69), 95% CI [-9.23, 8.83], $t(9)$ = -.05, p = .96, and represented a weak effect, d = .01.

3.3 Effect of spectral content on P-P amplitude of the SCC

The Kolmogorov-Smirnov test has shown that all the lateral conditions were normally distributed, see §3.2. The assumption of sphericity was assumed, $\chi^2(2)$ = .54, p = .08. A significant main effect of frequency on the amplitude of the SCC was found, $F(2,18) = 14.01$, $p = .001$, $\eta^2 = .55$.

Bonferroni post hoc tests revealed that broadband noise condition (*M* = 5.48, *SD* = 1.57) reveal significantly higher amplitudes than using the low frequency noise condition (*M* = 4.28, *SD* = 1.55), $F(1,9) = 14.28$, $p = .01$, $\eta^2 = .60$, and was also significant higher than the high frequency noise condition (*M* = 3.35, *SD* = 1.39), $F(1, 9) = 23.68$, $p = .001$, $\eta^2 = .73$. However, no significant difference was found between the high frequency condition (*M* = 3.35, *SD* = 1.33) and the low frequency condition (*M* = 4.28, *SD* = 1.55), $F(1, 9) = 2.37$, $p = .16$, $\eta^2 = .21$ (see figure 10).

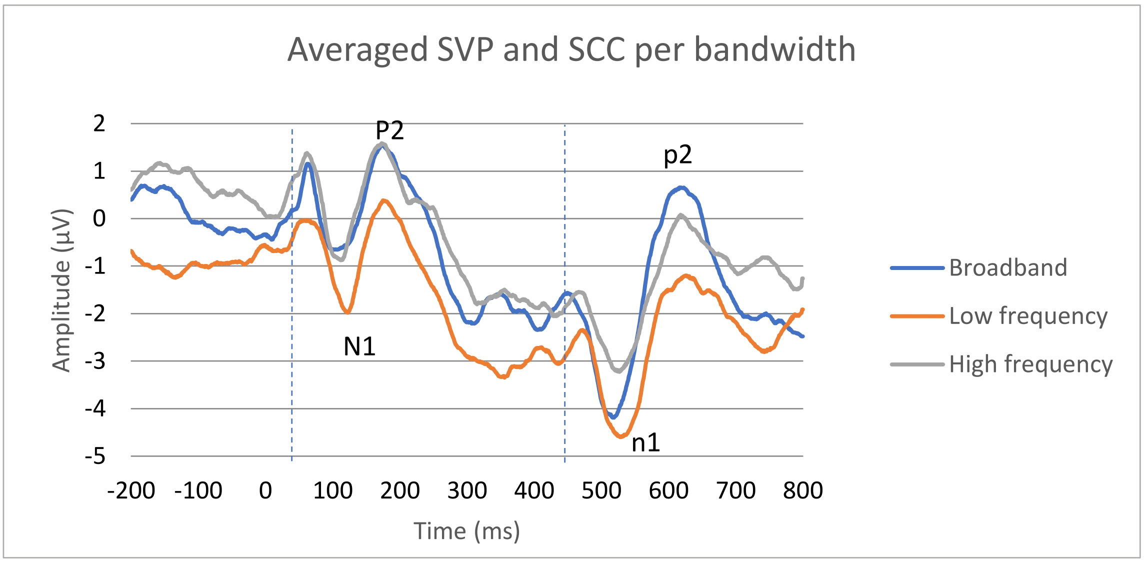


Figure 10. Grand mean averaged ERP signals of all participants for the lateral condition 0° - ±90° per bandwidth. The blue dotted lines indicate the onset of stimulus.

3.4 SCC P-P amplitude versus SVP P-P amplitude

A significant difference was found between SCC P-P amplitude of the broadband lateral condition (*M* = 5.48, *SD* = 1.57) and the SVP P-P amplitude of the broadband lateral condition (*M* = 3.17, *SD* = .84), 95% CI [-3.27, -1.34], $t(9) = -5.380$, $p < .001$.

No significant difference was found between SCC P-P amplitude of the low frequency lateral condition (*M* = 4.28, *SD* = 1.55) and SVP P-P low frequency lateral condition (*M* = 3.36, *SD* = .93), 95% CI [-1.90, .06], $t(10) = -2.12$, $p = .06$. It represented an average effect, $d = .72$.

The SCC P-P amplitude of the high frequency lateral condition (*M* = 3.35, *SD* = 1.39) did not differ significantly from the SVP P-P of the high frequency lateral condition (*M* = 2.76, *SD* = .83), 95% CI [-1.56, .37], $t(9) = -1.40$, $p = .20$. It represented an average effect, $d = .52$ (see figure 11).

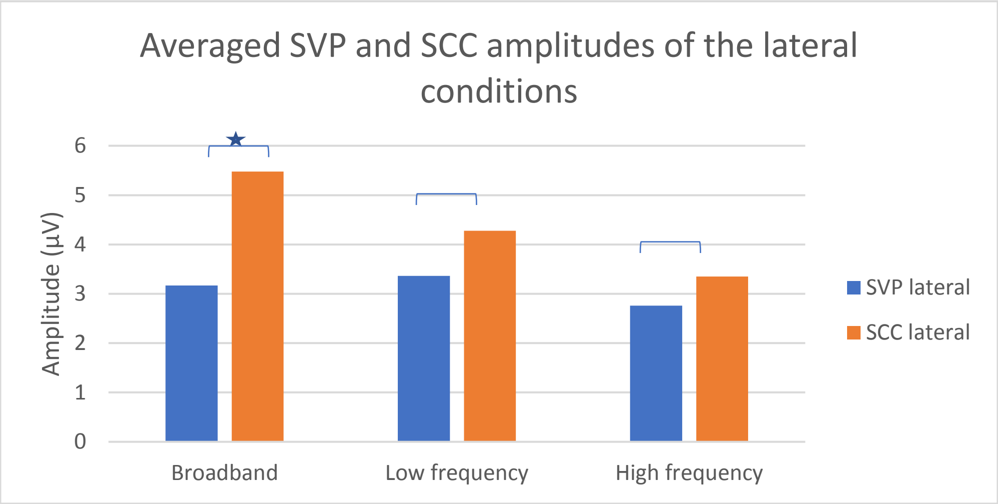
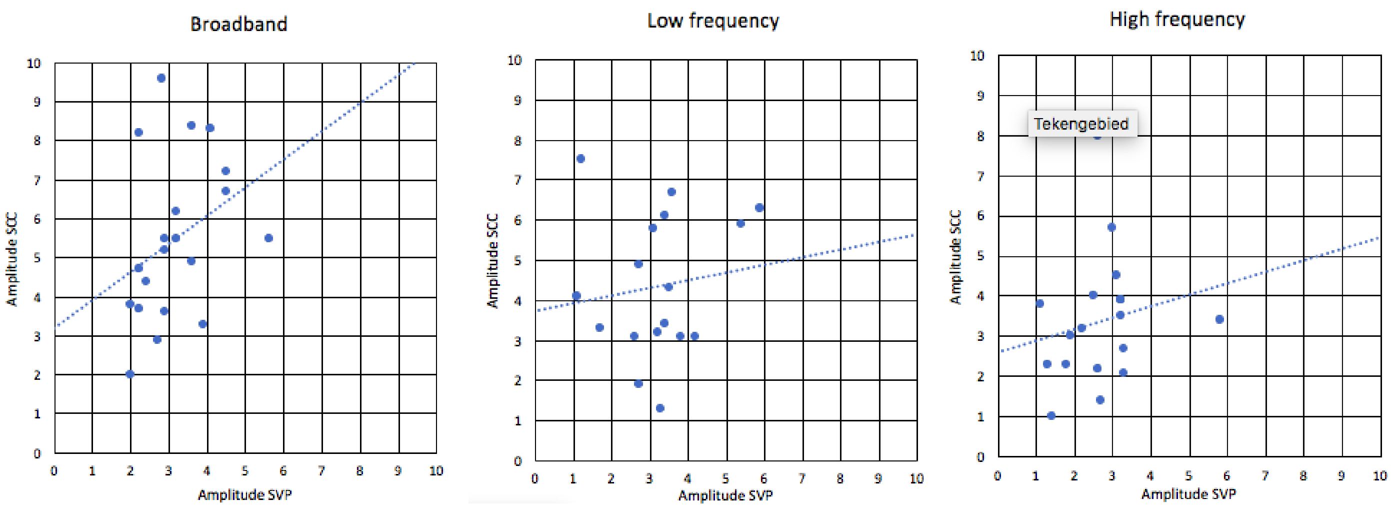


Figure 11. Bar charts showing the SVP P-P amplitudes and SCC P-P amplitudes of the lateral condition (0º-±90º) for broadband, low frequency and high frequency. Asterisk indicates a significant difference ($p < .05$).

A regression analysis has been performed. For the broadband condition, the analysis showed that no significant causality was found between the SVP P-P amplitude and the SCC P-P amplitude, $R^2 = .12$, $F(1,18) = 2.37$, $p = .14$.

For the low frequency condition, the analysis showed that no significant causality between the SVP P-P amplitude and the SCC P-P amplitude was found, $R^2 = .02$, $F(1,16) = .26$, $p = .62$.

For the high frequency condition, the analysis showed that no significant causality was found between the SVP P-P amplitude and the SCC P-P amplitude, $R^2 = .03$, $F(1,16) = .46$, $p = .46$ (see figure 12.)



$R^2 = .12$ $R^2 = .02$ $R^2 = .03$

Figure 12. Scatter plots with SVP amplitude on the x-axis and SCC amplitude on the y-axis for broadband, low frequency and high frequency.

The ratios are determined per bandwidth and indicate how much larger the SCC amplitude was than the SVP amplitude. The range for broadband was 1.04 to 2.86 (M = 1.75). The range for low frequency was .53 to 2.25 (M = 1.35) and for high frequency .59 to 2.17 (M = 1.27).

3.5 Effect of spectral content on latency of the SCC

Effect of spectral content on the n1 of the SCC

The Kolmogorov-Smirnov test has shown that the 0-90 left condition ($D(10) = .18$, $p = .20$) and 0-90 right condition ($D(10) = .16$, $p = .20$) of the broadband condition, the 0-90 left condition ($D(9) = .17$, $p = .20$) and the 0-90 right condition ($D(9) = .17$, $p = .20$) of the low frequency condition, and the 0-90 left ($D(9) = .17$, $p = .20$) and ($D(9) = .21$, $p = .20$) of the high frequency condition as regards the latency time of the n1 were normally distributed. The assumption of sphericity was assumed, $\chi^2(2) = .80$, $p = .41$. No significant effect of frequency on the latency of the n1 was found, $F(2,18) = .36$, $p = .70$, $\eta^2 = .04$.

Table 1. Mean values and standard deviations for latency of the SCC n1 for the broadband, low frequency and high frequency conditions.

	M	***SD***
Broadband n1	523.75	8.62
Low frequency n1	527.45	9.77
High frequency n1	527.30	12.96

Effect of spectral content on the p2 of the SCC

The Kolmogorov-Smirnov test has shown that the 0-90 left condition ($D(10) = .20$, $p = .20$) and 0-90 right condition ($D(10) = .13$, $p = .20$) of the broadband condition, the 0-90 left condition ($D(9) = .16$, $p = .20$) and the 0-90 right condition ($D(9) = .19$, $p = .20$) of the low frequency condition, and the 0-90 left of low frequency condition ($D(9) = .19$, $p = .20$) and 0-90 right condition ($D(9) = .16$, $p = .20$) of the high frequency condition as regards the latency time of the p2 were normally distributed. The assumption of sphericity was not assumed, $\chi^2(2) = .41$, $p = .03$. Greenhouse-Geisser indicated that no significant effect of frequency on the latency of the n1 was present, $F(1.256,18) = .18$, $p = .191$, $\eta^2 = .18$.

Table 2. Mean values and standard deviations for latency of the SCC p2 for the broadband, low frequency and high frequency conditions.

	M	***SD***
Broadband p2	614.60	16.38
Low frequency p2	595.60	28.66
High frequency p2	611.00	15.69

3.6 Lateralization preference

SCC P-P amplitude

The Kolmogorov-Smirnov test has shown that the lateral conditions of the broadband, low frequency and high frequency conditions as regards latency time of the n1 and p2 were normally distributed (see §3.4).

The P-P amplitude of the SCC of the broadband condition 0°-90° left (M = 6.01, SD = 2.07) did not differ significantly with the SCC amplitude of the broadband signal 0°-90° right (M = 4.95, SD = 2.03), 95% CI [-.83, 2.93], $t(9) = 1.29$, $p = .23$, and represented an average effect, $d = .52$

The P-P amplitude of the SCC of the low frequency condition 0°-90° left (M = 4.58, SD = 1.83) did not differ significantly from the P-P amplitude of the SCC of the low frequency condition 0°-90° right (*M* = 4.23, *SD* = 1.91), 95% CI [-.91, 1.61], *t*(7) = .66, *p* = .53, and represented a weak effect, *d* = .19.

The P-P amplitude of the SCC of the high frequency condition 0°-90° left (*M* = 3.62, *SD* = 2.14) did not differ significantly from the P-P amplitude of the SCC of the high frequency condition 0°-90° right (*M* = 2.96, *SD* = .93), 95% CI [-.51, 1.84], *t*(8)= 1.31, *p* = .23, and represented a weak effect, *d* = .40.

Table 3. Mean values and standard deviations for SCC P-P amplitude for the broadband, low frequency and high frequency conditions.

		M	***SD***
Broadband P-P amplitude	Left	6.01	2.07
	Right	4.95	2.03
Low frequency P-P amplitude	Left	4.58	1.83
	Right	4.23	1.91
High frequency P-P amplitude	Left	3.62	2.14
	Right	2.96	.93

SCC n1 and p2 latency

The latency of the n1 of the broadband condition 0°-90° left (*M* = 523.40, *SD* = 9.55) did not differ significantly with the latency of the n1 of the broadband condition 0°-90° right (*M* = 524.10, *SD* = 12.40), 95% CI [-10.22, 9.22], *t*(9) = -.16, *p* = .88, and represented a weak effect, *d* = .06. The latency of the p2 (*M* = 617.20, *SD* = 14.26) of the broadband condition 0°-90° left did not differ significantly with the latency of the p2 of the broadband condition 0°-90° right (*M* = 609.00, *SD* = 19.29), 95% CI [-2.71, 19.11], *t*(9) = 1.70, *p* = .12, and represented a weak effect, *d* = .48.

The latency of the n1 of the low frequency condition 0°-90° left (*M* = 523.56, *SD* = 7.55) did not differ significantly with the latency of the n1 of the low frequency condition 0°-90° right (*M* = 530.22, *SD* = 14.34), 95% CI [-14.51, 1.17], *t*(8) = -1.96, *p* = .09, and represented an averaged effect, *d* = .58. The latency of the p2 of the low frequency condition 0°-90° left (*M* = 603.89, *SD* = 13.90) did not differ significantly with the latency of the p2 of the low frequency condition 0°-90° right (*M* = 604.11, *SD* = 15.10), 95% CI [-10.32, 9.87], *t*(8) = -.051, *p* = .961, and represented a weak effect, *d* = .02.

The latency of the n1 of the high frequency condition 0°-90° left (*M* = 524.44, *SD* = 17.64) did not differ significantly with the latency of the n1 of the high frequency condition 0°-90° right (*M* = 527.33, *SD* = 9.59), 95% CI [-14.84, 9.07], *t*(8) = -.557, *p* = .593, and represented an X effect, *d* = . 20. The latency of the p2 (*M* = 613.89, *SD* = 19.58) of the high frequency condition 0°-90° left did not differ significantly with the latency of the p2 of the high frequency condition 0°-90° right (*M* = 614.11, *SD* = 13.82), 95% CI [-16.45, 16.17, *t*(9) = -.03, *p* = .98, and represented a weak effect, *d* = .01.

Table 4. Mean values and standard deviations for latency of the SCC n1 and p2 for the broadband, low frequency and high frequency conditions.

		M	***SD***
Broadband SCC n1	Left	523.40	9.55
	Right	524.10	12.40
Broadband SCC p2	Left	617.20	14.26
	Right	609.00	19.29
Low frequency SCC n1	Left	523.56	7.55
	Right	530.22	14.34

Low frequency SCC p2	Left	603.89	13.90
	Right	604.11	15.10
High frequency SCC n1	Left	524.44	17.64
	Right	527.33	9.59
High frequency SCC p2	Left	613.89	19.58
	Right	614.11	13.82

4. Discussion and conclusion

4.1 SCC P-P of the control conditions versus SCC P-P amplitude of the lateral conditions

No significant differences between spatial change complex (SCC) P-P amplitude of the broadband, low frequency and high frequency control conditions were found. This was as expected, as no change of angle was present in these conditions. As the SCC should be absent in this condition, the n1 and p2 were determined by placing them on the same latencies as in lateral ERP responses by determining the interval distance of the lateral condition. The t-tests in section 3.2 showed that no differences in both n1 latencies and p2 latencies between the lateral conditions and the control conditions were present. It can be said that the n1 and p2 are not in a decisive position as where normally the n1 and p2 of the SCC would be present.

For all bandwidths, the SCC P-P amplitudes of the lateral conditions were significantly larger compared to the control condition. This was expected because no change in angle in the control condition was visible, in contrast to the lateral condition that generates a SCC. The P1 is the first positive peak that occurs approximately 100 milliseconds after offering a stimulus. The P2 is a robust response that appears approximately 200 milliseconds after the stimulus (Hyde, 1994a). The acoustic change complex is a cortical auditory evoked potential, which may occur due to acoustic change within a sound, consisting of a positive-negative-positive complex (N1-P2-N2) (Martin & Boothroyd, 2000). The SCC is like the ACC, except that it is a response to change of location of a stimulus.

4.2 Effect of spectral content on the SCC P-P amplitude and latency

This research has shown that broadband white noise generates a significantly larger P-P amplitude of the SCC compared to low frequency white noise and high frequency white noise.

One possible reason for this larger P-P amplitude of the SCC in broadband white noise stimulus is that these stimuli contain both interaural time differences and interaural level differences. With high frequency noise, there is only an ILD cue present and with low frequency noise, there is only an ITD cue present. This finding suggests that locating broadband noise is easier than locating narrowband noise and is in line with previous investigations (Agterberg, 2012; Middlebrooks & Green, 1991; Van Wanrooij & Van Opstal, 2007).

No significant difference was present in latency of the SCC n1 and p2 between broadband noise, high frequency noise and low frequency noise, which is in line with scientific literature. Picton, Alain, Otten, Ritter & Achim (2000) did not detect any significant change in latency of the N1 when investigating different stimuli.

Because only normal hearing individuals were included in this study, the results may not match those with subjects with hearing impairments. Because a cochlear implant processes all frequencies and, conversely, a hearing aid mainly processes the lower tones Schoen, Mueller, Helms & Nopp (2005), the P-P amplitude of the SCC might be increased with high frequency signals measured by cochlear implanted persons, and there might be a larger P-P amplitude of the SCC at low frequency signals measured in persons who carries a hearing aid.

4.3 SVP P-P amplitude and SCC P-P amplitude

The SCC P-P amplitude was found to be significantly larger than the SVP P-P amplitude in the lateral broadband condition. This is in line with the study of Martin, Boothroyd, Ali and

Leach-Berth (2010). The purpose of their study was to compare four strategies for stimulus presentation in terms of their efficiency when generating a speech-evoked cortical acoustic change complex (ACC). This was measured in adults and children. They found that some subjects raised a larger ACC compared to the SVP. Any variability in latency, amplitude and waveform of the SVP is normal between and within people (Hyde, 1994b).

A possible cause for a higher SCC P-P amplitude in the broadband condition is a relatively large SCC of one or more individuals that greatly affects the average of the group. However, from the ratios were found that at broadband all persons had a larger SCC amplitude relative to the SVP. Unlike narrowband noise, not all participant's ratios were higher than 1.0. In the low frequency stimuli, eight out of ten people had a larger SCC amplitude than SVP amplitude. The high frequency stimuli showed that six out of ten people had a larger SCC amplitude than SVP amplitude. However, the difference between SCC and SVP was not significant in these conditions.

Another explanation may be that this broadband stimulus is better processed because it contains both ILD and ITD cues (Agterberg, 2012; Middlebrooks & Green, 1991; Van Wanrooij & Van Opstal, 2007). When this stimulus is presented frontally, it is heard by both ears at about the same loudness level and contains the same time difference. But when the stimulus is offered laterally, it is heard louder on one side because of the ILD cue. Also, the sound is heard later in time in one ear compared to the other, because of the ITD cue. Due to the angular shift in this stimulus, a response may result that leads to a larger P-P amplitude.

In addition to the fact that binaural cues are present in broadband condition (ILD and ITD), this stimulus also contains spectral cues. These cues are produced by broadband signals by the ear, head and space positions (Roffler & Butler, 1967; Gardner & Gardner, 1973). It might be that, because the broadband stimuli containing these spectral cues, the brain gives a greater response to the change of angle in a stimulus as compared to narrow-band noise, where no spectral cues are present.

Despite a significant larger SCC amplitude than SVP amplitude for broadband noise, the amplitude of the SCC cannot be predicted based on the amplitude of the SVP. This is also the case for low frequency and high frequency white noise.

4.4 Difference between left and right offered stimuli

No difference in both the SCC amplitude and latency time of the n1 as the p2 between left and right offered stimuli was present. However, a strong effect between left and right stimuli for the broadband noise stimuli was found (d = 1.40), which may result in a significant difference if the study would have been conducted in a larger group. Because speech signals are better processed in the left hemisphere and the nervous tracts run down the cortex contralaterally, stimuli presented to left-handed subjects may be heard better in the left ear, evoking larger P-P amplitude left (Gu, Zhang, Hu & Zhao, 2013). From the study of Hanss et al. (2009) it appeared that in normal hearing subjects, the cortical activation patterns are characterized by shorter and larger neurophysiological responses in the hemisphere contralateral to the stimulated ear in response to monaural stimulation. These activation patterns are believed to be based on contralateral dominance in the auditory pathway, because the contralateral auditory pathway contains a greater number of nerve fibers than the ipsilateral pathway. The contralateral pathway contributes to a more direct activation of the contralateral auditory cortex. Because current research has been using single-channel EEG measurement, several electrodes can be used to investigate whether there is a difference between the left and right hemispheres, contralateral and ipsilateral to the sound.

4.5 Conclusion

Current research has shown that a broadband white noise stimulus significantly generates the largest SCC P-P amplitude compared to high frequency white noise stimulus and low frequency white noise stimulus. The investigation did not result in a difference in latency of the SCC n1 and p2 between the different stimuli. In the objective examination of spatial resolution by means of electroencephalography, broadband white noise stimulus is most recommended.

Experiment 2
5. Method

In experiment 2, the same measurement set up and data acquisition was used as in experiment 1. Therefore, these are not mentioned in this section, but can be read in section 2.3 and 2.4.

5.1 Participants

The group consisted of fourteen participants (ten male) in the age of 27;6 through 73;2 years (M = 53.48, SD = 11.12) with unilateral sensorineural hearing loss. Seven persons were wearing a hearing aid, whose shortest duration was one month and the longest duration of wearing a hearing aid was 24 months. The mean Fletcher Index of the bone conduction was 63.5 dB with a range of 45.0 through 80.0 dB. The range of the duration of hearing problems was 1.5 through 56.0 years (M = 18.8, SD = 20.2) (see table 5). Because tinnitus may influence the EEG results, in this study, only patients without tinnitus were included. Due to the unilateral hearing, all patients experienced localization problems in daily life.

The control group consisted of 25 normal hearing participants with pure-tone air conduction thresholds from 250 through 4000 Hz of ≤20 dBHL [Interacoustics AD629]) in the age of 18;0 through 53;0 years (M = 28.0, SD = 10.5). All participants have signed an informed consent prior to the investigation.

Table 5. Subject description (N = 14). N.a.= not applicable, patient in question do not wear any hearing aid.

Subject	**Affected side**	**Cause**	**Age (years)**	**Gender**	**Duration of hearing problems**	**Duration of wearing hearing aid**	**Flecher Index[1] impaired ear**	**High Flecher Index[2] impaired ear**
S1	Left	Vestibular schwannoma	63	F	1.5 years	6 months	68	77
S2	Left	Infection	56	M	5 years	N.a.	45	57
S3	Right	Vestibular schwannoma	56	M	4 years	24 months	65	70
S4	Left	Meningioma	60	F	15 years	N.a.	53	73
S5	Left	Ototoxic	73	F	4 years	N.a	70	75
S6	Left	Congenital	54	M	54 years	N.a.	55	80
S7	Right	Infection	36	M	1.5 years	1 month	65	75
S8	Left	Congenital	51	M	51 years	24 months	67	73
S9	Left	Congenital	56	M	56 years	N.a.	52	60
S10	Left	Infection	57	M	24 years	N.a.	63	83
S11	Right	Meningitis	48	M	14 years	1 month	68	75
S12	Left	DFNA9	57	F	10 years	3 months	68	80
S13	Right	Medical	27	M	3.5 years	N.a.	70	70
S14	Left	Medical	53	M	20 years	3 months	80	80

1 Average loss in dBHL at 500 Hz, 1000 Hz and 2000 Hz.

2 Average loss in dBHL at 1000 Hz, 2000 Hz and 4000 Hz.

5.2 Stimuli

In this experiment, the broadband noise stimuli (0.5-20 kHz) of experiment 1 was used (see section 2.2). The current experiment consisted of a control condition (0°-0°) and four lateral conditions (-90°, -30°, +30° and +90°, indicating negative (-) as left and positive (+) as right.

5.3 Procedure

The participant took place in a chair with a head support. The subjects were asked to move as little as possible and to relax as much as possible. Also, clamping of the jaw was not allowed, since this generates artefacts (Hyde, 1994a). To keep the attention as focused as possible, the subjects were instructed to count the number of stimuli from a particular speaker. An attention-oriented task has a positive effect on the EEG measurement (Bagatto et al., 2011). The participants were presented the stimuli in five conditions: frontal (0°), frontal (0°) and immediately followed by a 30° or 90° speaker on the left and frontal (0°) immediately followed by a 30° or 90° speaker on the right. These five conditions were randomly presented to the subject.

During the experiment, a subjective localization measurement was also performed to verify that the subject could locate the sounds. After the first measurement of each condition were asked whether the person could identify where both sounds came from. In all participants from the control condition, a measurement of pure-tone air conduction [Interacoustics Diagnostic Audiometer, AD629] has been taken to determine the hearing threshold. A person was "normal hearing" if the hearing threshold was ≤20 dB at all octave frequencies.

5.4 Data analysis

Of each grand average (GA), the SVP and the SCC is determined. For the SVP, the latency of the N1 is defined as a negative potential that occurs between 80 and 150 ms followed by the P2, which is defined as a positive potential that occurs between 150 and 230 ms. The SCC consists of the n1 defined as negative potential which occurs between 80 and 150 ms after a change of angle within a sound stimulus followed by the p2 defined as positive potential occurring between 150 and 230 ms after a change of angle within a sound stimulus. The P-P amplitudes of all SVPs (N1-P2) and SCCs (n1-p2) will be calculated and were indicated in microvolt (μV).

To determine if the SVP and SCC were present, the peaks were compared to the standard deviation of the 200 ms pre-stimulus noise. Since the SCC in the control condition (0°-0°) should be absent, the n1 and p2 were determined by placing them on the same latencies as in lateral ERP responses. When the amplitude exceeds the standard deviation of the pre-stimulus noise, it was accepted that an SVP or SCC was present. The condition of an existing SCC was the presence of a SVP was obligatory.

The experiment consisted of a within subject design and a between subject design with two dependent variables: amplitude in microvolt (μV) and latency time in milliseconds (ms), measured under different conditions. Statistical analyses were performed using Repeated Measures ANOVAs, Paired-Samples T-tests and Independent-Samples T-Tests (SPSS, version 24.0) with a p value of <.05 considered as significant. Repeated Measures ANOVA have been conducted to investigate whether the average P-P amplitude of the SCC and latency times of the n1 and p2 differ significantly in the lateral conditions (0º-±90º) versus (0º-0º) (question 2). Also, the condition 0º-90º left was compared with the 0º-90º right condition (question 4). A Repeated Measured ANOVA have been conducted for the comparison of (0º-±30º) versus (0º-0º) (question 2) and the condition 0º-30º left was compared with the 0º-30º right condition (question 4). If a significant effect was present, post-hoc pairwise comparisons were reported, where the p-values from the ANOVAs were corrected according to Bonferonni. Before performing the Repeated Measures ANOVAs, the assumptions of normality and sphericity have first been tested. For the assumption of normality, the Kolmogorov-Smirnov test was performed and for the assumption of sphericity, the Mauchly's test was performed. If Mauchly's test had a significant value, the Greenhouse-Geisser or Huynh-Feldt test was applied (Field, 2013).

For the comparison of the 0º-±90º and the 0º-±30º conditions, the 0º-90º left and 0º-90º right conditions were averaged, so were the 0º-30º left and 0º-30º right. Then they were compared with a Paired-Sampes T-test. Before the Paired Samples T-tests were performed, the assumption of normality was first tested performed with the Kolmogorov-Smirnov test. If the assumption of normality was violated, the Paired-Samples T-tests were performed by Bootstrap. Due to a lack of normality, the shape of the sample distribution remains unknown. Bootstrap is a technique that avoids this problem, with the sample distribution being estimated by taking multiple small samples from the sample data. Because the average of these small samples is calculated, the distribution of the overall sample is estimated (Field, 2013). For all Paired Samples T-tests, the effect strength was calculated using Cohen's d. This indicates whether it was a weak effect (d = .0 - .5), an average effect (d = .5 - .8), a strong effect (.8 - 1.3) or a very strong effect (> 1.3) (Field, 2013).

Subsequently, it was checked whether a difference between the 0º-0º, 0º-90º and 0º-30º condition between the normal group and the patient group (question 3) was present. This was executed by the Independent-Samples T-test. Before performing the Independent-Samples T-test, the assumptions of normality and homogeneity of variance have first been tested. For the assumption of normality, the Kolmogorov-Smirnov test was performed and for homogeneity of variance the Levene's Test was executed. The data was at interval level.

The specificity, sensitivity and accuracy are measured by the number of hits, misses, false alarms and correct rejections. A 'hit' was present when a person locates the sound source incorrectly and no SCC occurs. When a person was unable to locate the sound subjectively, but the SCC was visible, a 'miss' was present. Otherwise, if a person could correctly locate the sound source and a SCC occurred, this was seen as a 'true negative'. A 'false alarm' occurs when the person can locate the source, but no SCC occurs (see figure 15).

Subjective Measurement / EEG measurement Abnormal (+) Normal (-)	Change of angle: incorrect	Change of angle: correct
+ (SCC absent)	**Hit (true positive)**	**False alarm (false positive)**
- (SCC present)	**Miss (false negative)**	**True negative (correct rejected)**

Figure 15. Relationship between subjective measurement and EEG measurement. Adapted taken from: Altman & Bland, 1994.

The sensitivity was calculated by dividing the number of Hits by the number of Hits plus the number of Misses (see figure 16). The specificity was calculated by dividing the number of true negatives by the number of true negatives plus the number of false alarms. The accuracy was determined by dividing the number of hits plus the number of true negatives by the number of hits, misses, false alarms and true negatives. The terms 'sensitivity' and 'specificity' indicate how well a test is capable of measuring what it should measure. In the normal hearing group, the subjective measurement is linked to the GA of the objective measurement, because this group was subjectively able to locate all the sounds correctly. In the patient group, the subjective measurement linked to individual measurements, which took place twice a condition. The reason for this is that the patient possibly cannot locate the first objective measurement of a particular condition subjectively, while the patient is able to correctly indicate this in the second objective measurement.

Sensitivity = hit / (hit + miss)
Specificity = true negative / (true negative + false alarm)
Accuracy = (hit + true negative) / (hit + false alarm + miss + true negative)

Figure 16. Formulas to calculate the sensitivity, specificity and accuracy.

6. Results

6.1 Spatial change complex in normal hearing subjects

6.1.1 SCC P-P amplitude

Effect of ±90º condition on the P-P amplitude of the SCC

The Kolmogorov-Smirnov test has shown that the P-P amplitude of the SCC of the 0˚ -90˚ left condition (*D*(20) = .10, *p* = .20), the 0˚-0˚ control condition (*D*(23) = .18, *p* =.06) and the 0˚ -90˚ right condition (*D*(19) = .16, *p* = .19) were normal distributed. The assumption of sphericity was assumed, $\chi^2(2) = .89$, *p* = .43. The 0˚-0˚ control condition and 0˚-90˚ right had one or two outliers. The analyzes were performed with these outliers, since the outliers are reliable data and no difference in the level of statistical significance (*p* < .05) was found.

A significant main effect of ±90º condition on the amplitude of the SCC was present, *F*(2,32) = 48.52, *p* < .001, η^2 = .75. Bonferroni post hoc tests revealed that a significant difference was found between the 0˚-90˚ left condition (*M* = 6.02, *SD* = 2.72) and the 0˚-0˚ control condition (M = .60, *SD* = .55), *F*(1,16) = 80,47, *p* < .001, η^2 = 83. Also, there a significant difference between the 0˚-90˚ right condition (*M* = 5.72, *SD* = 3.05) and the 0˚-0˚ control condition (M = .60, *SD* = .55) was present, *F(*1,16) = 52.62, *p* < .001, η^2 = .77 (see figure 17 and 18). The raw data is visible in the appendix VI, table 15.

Effect of ±30º condition on the P-P amplitude of the SCC

The Kolmogorov-Smirnov test has shown that the P-P amplitude of the SCC of the 0˚-30˚ left condition (*D*(19) = .13, *p* =.20), the 0˚-0˚ control condition (*D*(23) = .18, *p* =.06) and the 0˚-30˚ right condition (*D*(18) = .14, *p* = .20) were normal distributed. The assumption of sphericity was assumed, $\chi^2(2) = .98$, *p* = .92. The conditions 0˚ -30˚ left, the 0˚-0˚ control condition and the 0˚-30˚ right had one or two outliers. The analyzes were performed with these outliers, since the outliers are reliable data and no difference in the level of statistical significance (*p* < .05) was found.

A significant main effect was found of ±30º condition on the amplitude of the SCC, *F*(2,22) = 18.81, *p* < .001, η^2 = .63. Bonferroni post hoc tests revealed that a significant difference between the 0˚-30˚ left condition (*M* = 5.54, *SD* = .73) and the 0˚-0˚ control condition (M = .73, *SD* = .57) was present, *F*(1,16) = 80,47, *p* < .001, η^2 = .83. Also, there a significant difference between the 0˚-30˚ right condition was present (*M* = 4.90, *SD* = 2.76) and the 0˚-0˚ control condition (M = .73, *SD* = .57), *F(*1,11) = 26.34, *p* < .001, η^2 = .71 (see figure 17 and 18). The raw data is visible in the appendix VI, table 15.

Difference of SCC P-P amplitude between ±90º and ±30º

A larger SCC P-P amplitude was visible in the 0-±90 condition (*M* = 6.41, *SD* = 2.99) compared to the 0-±30 condition (*M* = 4.92, *SD* = 2.34). This difference, 1.49, was significant, 95% CI [-2.57, -.42], *t*(20) = -2.91, *p* = .01; an average effect was represented, *d* = .55 (see figure 17 and 18).

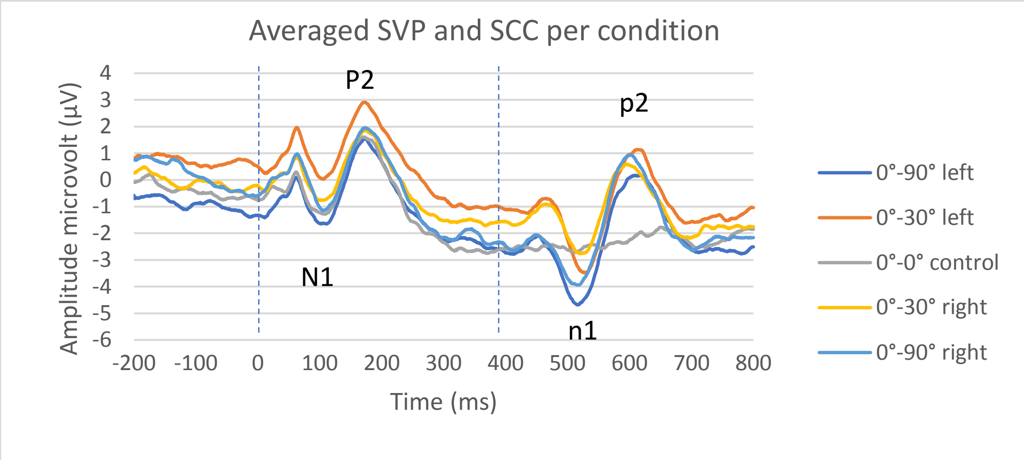


Figure 17. Grand mean averaged ERP signals of all normal hearing participants for the five conditions. The blue dotted lines indicate the onset of stimulus.

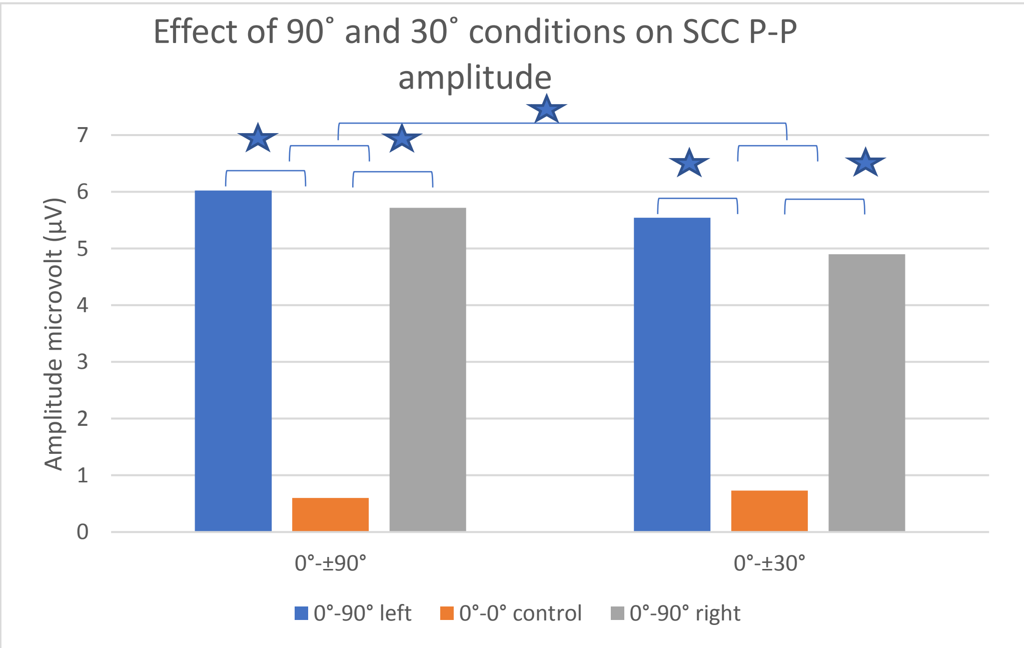


Figure 18. Bar charts showing the mean P-P amplitudes in μV of the SCC's in the control condition and lateral conditions for the normal hearing subjects. The asterisk indicates whether it is a significant difference ($p < .05$).

Figure 19 shows a typical example of large, clear cortical responses in a normal hearing subject (no. 20) on the five conditions. In contrast, Figure 20 shows a typical example of small, less clear cortical responses in a normal hearing subject (no. 24) on the five conditions. The SCC of 0-90 right condition was considered as a missing value.

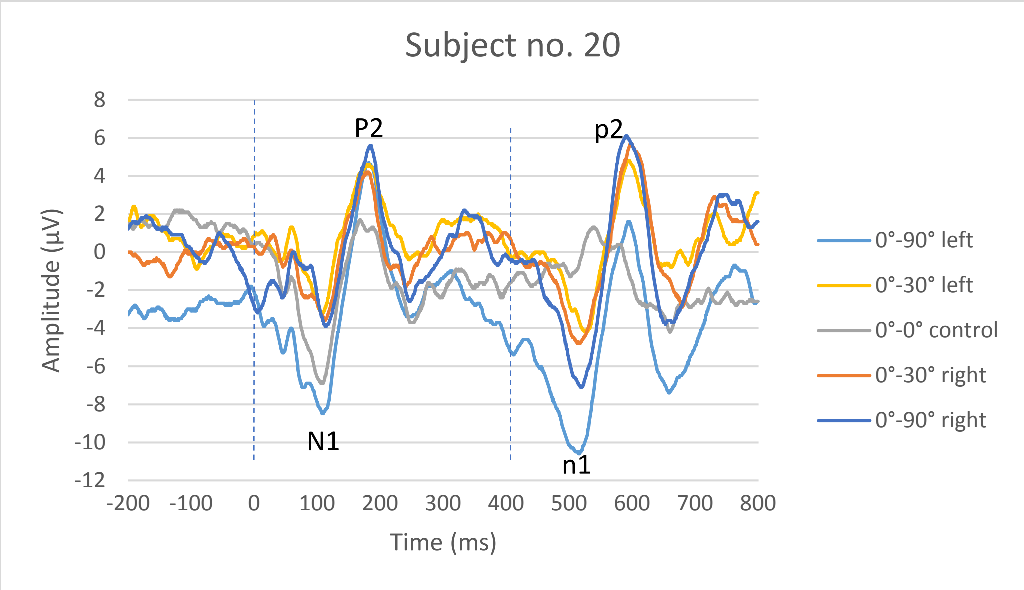


Figure 19. Example of large, clear cortical responses of a normal hearing subject (number 20) on broadband noise to the five conditions. The blue dotted lines indicate the onset of stimulus.

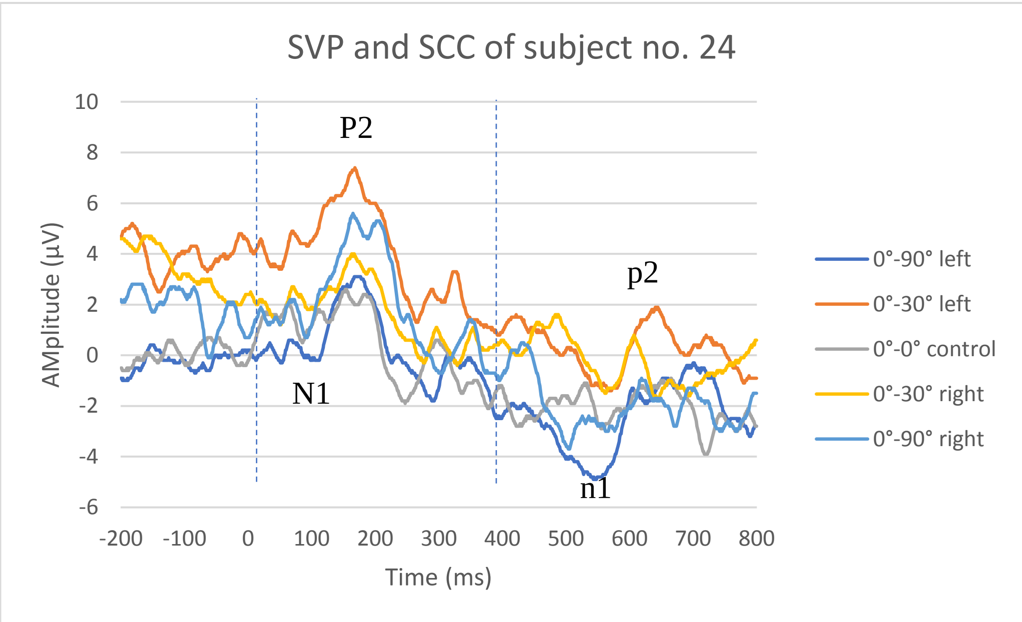


Figure 20. Example of small, less clear cortical responses of a normal hearing subject (number 20) on broadband noise to the five conditions. The blue dotted lines indicate the onset of stimulus.

Difference between left and right presented stimuli.

A significant main effect of ±90º on the amplitude of the SCC was found, $F(2,32) = 48.52$, $p < .001$, $\eta^2 = .75$ (see 6.1.1). Bonferroni post hoc tests revealed that no significant difference was found between the 0˚-90˚ left condition ($M = 6.02$, $SD = 2.72$) and the 0˚-90˚ right condition (M = 5.72, $SD = 3.05$), $F(1,16) = .32$, $p < .59$, and represented a weak effect $d = 02$.

A significant main effect of ±30º condition on the amplitude of the SCC was found, $F(2,22) = 18.81$, $p < .001$, $\eta^2 = .631$ (see 6.1.1). Bonferroni post hoc tests revealed that no significant difference between the 0˚-30˚ left condition (*M* = 5.54, *SD* = .73) and the 0˚-30˚ right condition (M = 4.90, *SD* = 2.76) was visible, *F*(1,16) = ,59, *p* = .46, and represented a weak effect *d* = .05.

6.1.2 SCC latencies

Latency of the SCC n1

The Kolmogorov-Smirnov test has shown that the latency of the SCC n1of the 0˚-90˚ left condition (*D*(21) = .12, *p* = .20), the 0˚-30˚ left condition (*D*(21) = .13, *p* =.20), the 0˚-0˚ control condition (*D*(24) = .11, *p* =.20), the 0˚-30˚ right condition (*D*(18) = .09, *p* = .20) and the 0˚ -90˚ right condition (*D*(21) = .15, *p* = .20) were normal distributed. The assumption of sphericity for ±90º condition, $\chi^2(2) = .99$, *p* = .95 and ±30º condition, $\chi^2(2) = .92$, *p* = .57 was assumed. One outlier was present in the 0˚-90˚ right condition. The analyzes were performed with this outlier, since the outlier is reliable data and no difference in the level of statistical significance (*p* < .05) was present.

No significant main effect of ±90º condition on the n1 latency of the SCC was found, *F*(2,36) = 1.21, *p* = .31, η^2 = .06. Also no significant main effect of ±30º condition on the n1 latency of the SCC was present, *F*(2,28) = .15, *p* = .86, η^2 = .01. See table 6 for mean value and standard deviation of the SCC n1 for the five conditions.

Difference of SCC n1 latency between ±90º and ±30º

The latency of the SCC n1 of the 0-±90º condition appeared earlier (*M* = 521.16, *SD* =12.30) compared to the latency of the n1 of the 0-±30º condition (*M* = 526.07, *SD* = 12.55). This difference, 4.91, was not significant, 95% CI [-1.16, 10.98], *t*(21) = 1.68, *p* = .11; and represented a weak effect, *d* = .40.

	M	***SD***
SCC n1 0˚-90˚ left	522.95	10.83
SCC n1 0˚-30˚ left	525.73	11.38
SCC n1 0˚-0˚ control	526.68	12.62
SCC n1 0˚-30˚ right	526.40	18.33
SCC n1 0˚-90˚ right	522.89	11.66

Table 6. Mean and standard deviation per condition for the latency of the SCC n1.

Latency of the SCC p2

The Kolmogorov-Smirnov test has shown that the latency of the SCC p2 of the 0˚-90˚ left condition (*D*(20) = .21, *p* = .02) was not normal distributed. The 0˚-30˚ left condition (*D*(20) = .120, *p* =.200), the 0˚-0˚ control condition (*D*(24) = .100, *p* =.200), the 0˚-30˚ right condition (*D*(19) = .11, *p* = .20) and the 0˚-90˚ right condition (*D*(20) = .16, *p* = .20) were normal distributed. The assumption of sphericity for the ±90º condition, $\chi^2(2) = .64$, *p* = .03 was not assumed. The assumption of sphericity for the ±30º condition, $\chi^2(2) = .69$, *p* = .09. was assumed. One outlier was present in the 0˚-90˚ right condition and in the 0˚-90˚ right condition. These analyses were performed with these outliers, since the outliers appeared to be consistent; no difference in the level of statistical significance (*p* < .05) were present.

No significant main effect of ±90º condition on the p2 latency of the SCC was found, *F*(2,28) = .96, *p* = .39, η^2 = .05. Also, no significant main effect of ±30º condition on the n1 latency of the SCC was present, *F*(2,28) = .717, *p* = .50, η^2 = .05. See table 7 for the mean value and standard deviation of the SCC p2 for the five conditions.

Difference of SCC p2 latency between ±90º and ±30º
The latency of the SCC p2 of the 0-±90º condition disappeared earlier (*M* = 606.86, *SD* =14.73) compared to the latency of the n1 of the 0-±30º condition (*M* = 607.86, *SD* = 17.30). This difference, 1.00, was not significant, 95% CI [-4.79, 6.79], *t*(20) = .36, *p* = .72; and represented a weak effect, *d* = .06.

Table 7. Mean and standard deviation per condition for the latency of the SCC p2.

	M	***SD***
0˚-90˚ left	607.28	16.41
0˚-30˚ left	604.40	19.31
0˚-0˚ control	610.56	20.65
0˚-30˚ right	605.73	18.15
0˚-90˚ right	604.67	16.70

6.2 Spatial change complex in patients with unilateral sensorineural hearing loss

6.2.1 SCC P-P amplitude

Effect of ±90º and ±30º condition on the P-P amplitude of the SCC
The Kolmogorov-Smirnov test has shown that the P-P amplitude of the SCC of the 0˚-90˚ left condition was not normal distributed (*D*(5) = .447, *p* = .001). The 0˚-30˚ left condition (*D*(8) = .18, *p* =.20), the 0˚-0˚ control condition (*D*(12) = .12, *p* = .20), the 0˚-30˚ right condition (*D*(4) = .88, *p* = .34) and the 0˚-90˚ right condition (*D*(7) = .23, *p* = .20) were normal distributed. The analyzes were performed using bootstrap. The condition 0˚-90˚ left had one outlier. The analyzes were performed with these outliers, since the outliers are reliable data and no difference in the level of statistical significance (*p* < .05) was present.

No significant difference between the 0˚-90˚ left condition (*M* = 4.14, *SD* = 4.07) and the 0˚-0˚ control condition (*M* = .25, *SD* = .17) was found, 95% CI [-1.16, 8.94], *t*(4) = 9.92, *p* = .099. However, a very strong effect was represented, *d* = 1.35.

A significant difference between the 0˚-30˚ left condition (*M* = 2.24, *SD* = 1.02) and the 0˚-0˚ control condition (*M* = .53, *SD* = .28) was found, 95% CI [.71, 2.72], *t*(6) = 7.03, *p* = .01. This represented a very strong effect, *d* = 2.29.

No significant difference between the 0˚-30˚ right condition (*M* = 3.50, *SD* = 2.43) and the 0˚-0˚ control condition (*M* = .35, *SD* = .15), 95% CI [-2.68, 8.98], *t*(2) = 6.39, *p* = .15. However, a very strong effect was represented, *d* = 1.83.

A significant difference was found between the 0˚-90˚ right condition (*M* = 3.75, *SD* = 1.42) and the 0˚-0˚ control condition (*M* = .42, *SD* = .30), 95% CI [1.69, 4.69], *t*(5) = 7.25, *p* = .01. This represented a very strong effect, *d* = 3.25. (see figure 21 and 22). The raw data is visible in the appendix VII, figure 16.

Difference of SCC P-P amplitude between ±90º and ±30º
A larger SCC P-P amplitude was visible in the 0˚-±90˚ condition (*M* = 3.59, *SD* = 2.57) compared to the 0˚-±30˚ condition (*M* = 2.90, *SD* = 1.19). This difference, .69, was not significant, 95% CI [-3.16, -1.77], *t*(5) = -.72, *p* = .01; a very strong effect was represented, *d* = 1.65 (see figure 21 and 22).

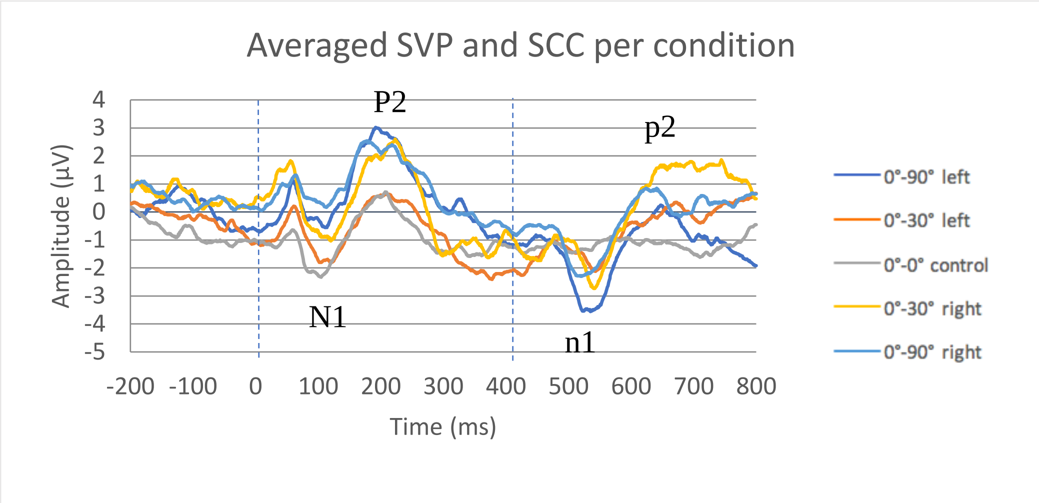


Figure 21. Grand mean averaged ERP signals of all normal hearing participants for the five conditions. The blue dotted lines indicate the onset of stimulus.

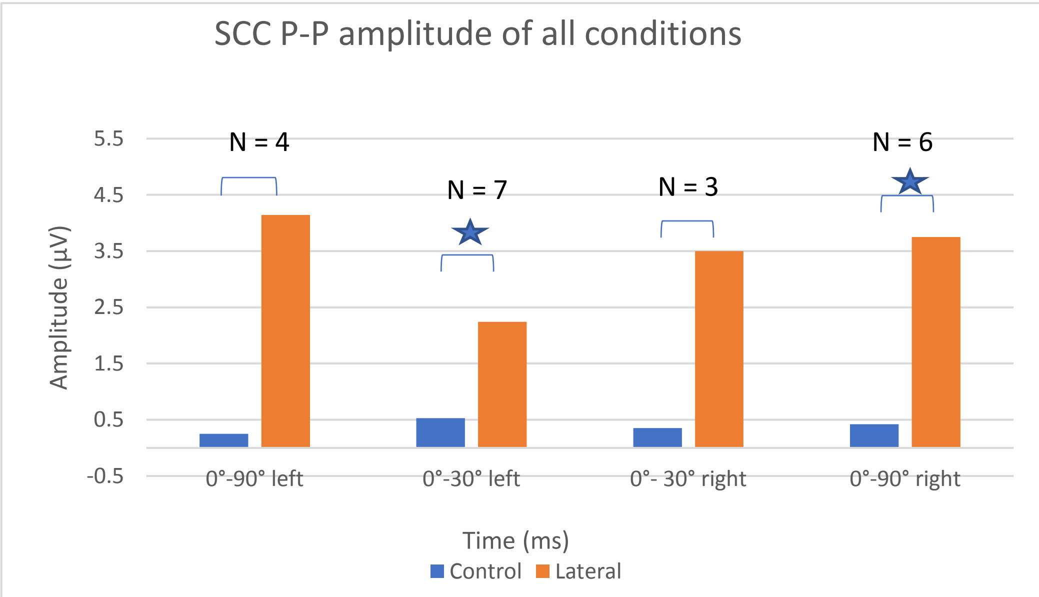


Figure 22. Bar charts showing the mean P-P amplitudes in µV of the SCC's in the control condition and lateral conditions for the patient group. The asterisk indicates whether it is a significant difference ($p < .05$).

In figure 23 are the large, clear cortical responses of a participant with unilateral sensorineural hearing loss (no. 4) on the five conditions visible. There are large SVP's and SCC's present. In figure 24 are the responses of a participant with unilateral sensorineural hearing loss (no. 5) on the five conditions visible. his patient was unable to locate subjectively correctly. No SCC's were visible.

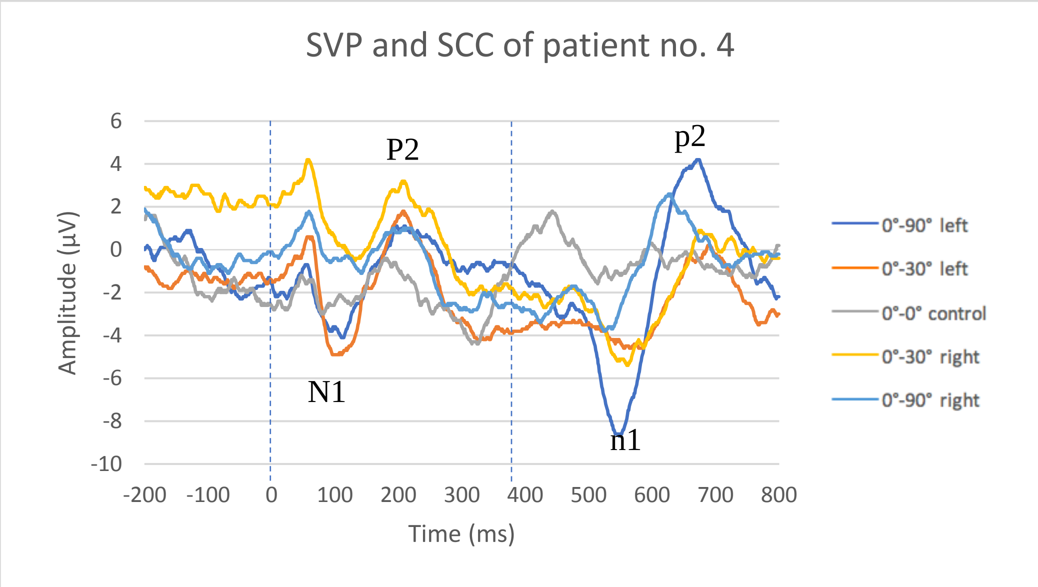


Figure 23. Example of responses of a patient with unilateral sensorineural hearing loss who could subjectively locate the five conditions of broadband sounds. The blue dotted lines indicate the onset of stimulus.

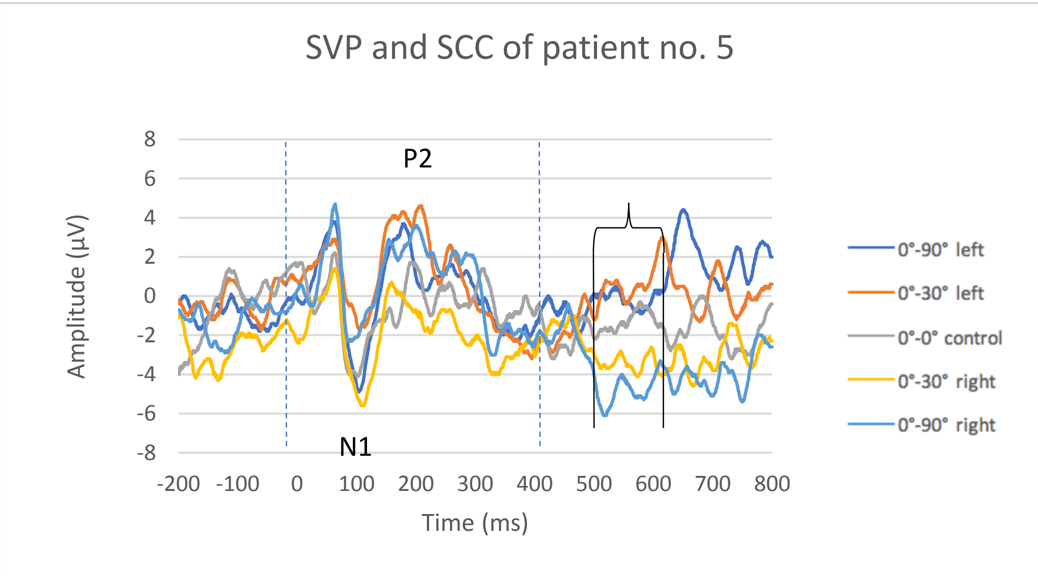


Figure 24. Example of responses of a patient with unilateral sensorineural hearing loss who was unable to subjectively locate the five conditions of broadband sounds. The accolade indicates the period where normally the n1 and p2 of the SCC are located. The blue dotted lines indicate the onset of stimulus.

Difference between left and right presented stimuli

For the participants with unilateral sensorineural hearing loss at the left ear, no significant difference was found between the SCC P-P amplitude of the 0˚-90˚ left condition (M = 7.00, SD = 6.22) and the 0˚-90˚ right condition (M = 5.15, SD = 1.34), 95% CI [-41.99, 45.69], $t(1)$ = .54, p = .69; a weak effect was represented, d = .41 .

For the participants with unilateral sensorineural hearing loss at the left ear, no significant difference was found between the SCC P-P amplitude of the 0˚-30˚ left condition (M = 2.93, SD = 1.42) and the 0˚-30˚ right condition (M = 2.57, SD = 2.07), 95% CI [-3.02, 3.76], $t(2)$ = -.25, p = .69; a weak effect was represented, d = .20.

Because insufficient data was available from the group of patients with hearing loss on the right ear, the difference between left and right presented stimuli could not be statistically calculated.

6.2.2 SCC latencies

Latency of the SCC n1

The Kolmogorov-Smirnov test has shown that the latency of the SCC n1 of the 0˚-90˚ left condition ($D(8) = .15$, $p = .20$), the 0˚-30˚ left condition ($D(8) = .19$, $p =.20$), the 0˚-0˚ control condition ($D(10) = .20$, $p = .20$), the 0˚-30˚ right condition ($D(3) = .90$, $p = .40$) and the 0˚ - 90˚ right condition ($D(7) = .16$, $p = .20$) were normal distributed. No outliers were present.

No significant difference between the n1 of the 0˚-90˚ left condition (*M* = 533.67, *SD* = 25.88) and the n1 of the 0˚-0˚ control condition (*M* = 522.83, *SD* = 18.54) was found, 95% CI [-3.68, 25.35], $t(5) = 1.92$, $p = .11$. This represented a weak effect, $d = .49$.

No significant difference between the n1 of the 0˚-30˚ left condition (*M* = 539.17, *SD* = 25.21) and the n1 of the 0˚-0˚ control condition (*M* = 528.33, *SD* = 20.12) was found, 95% CI [-3.41, 25.08], $t(5) = 1.96$, $p = .11$. This represented a weak effect, $d = .48$.

No significant difference between the n1 of the 0˚-30˚ right condition (*M* = 542.00, *SD* = 19.47) and the n1 of the 0˚-0˚ control condition (*M* = 536.67, *SD* = 8.02) was found, 95% CI [-32.71, 42.71], $t(2) = .61$, $p = .60$. This represented a weak effect, $d = 0.36$.

No significant difference between the n1 of the 0˚-90˚ right condition (*M* = 532.86, *SD* = 16.42) and the n1 of the 0˚-0˚ control condition (*M* = 531.43, *SD* = 10.49) was found, 95% CI [12.07, 12.07], $t(6) = .33$, $p = .75$. This represented a weak effect, $d = 0.10$. See table 8 for the mean value and standard deviation of the SCC n1 for the five conditions.

Difference of SCC n1 latency between ±90º and ±30º

The latency of the SCC n1 of the 0-±90º condition disappeared later (*M* = 529.33, *SD* =23.03) compared to the latency of the n1 of the 0-±30º condition (*M* = 527.50, *SD* = 23.37). However, this difference, 1.83, was not significant, 95% CI [-9.74, 6.08], $t(8) = -.54$, $p = .61$; and represented a weak effect, $d = .08$.

Table 8. Mean and standard deviation per condition for the latency of the SCC n1.

	M	***SD***
SCC n1 0˚ - 90˚ left	530.25	25.39
SCC n1 0˚ - 30˚ left	533.25	26.35
SCC n1 0˚- 0˚ control	526.40	16.07
SCC n1 0˚ - 30˚ right	542.00	19.47
SCC n1 0˚ - 90˚ right	532.86	16.42

Difference between left and right presented stimuli

For the participants with unilateral sensorineural hearing loss at the left ear, no significant difference was found between the SCC n1 latency of the 0˚-90˚ left condition (*M* = 549.33, *SD* = 22.30) and the 0˚-90˚ right condition (*M* = 535.00, *SD* = 11.00), 95% CI [-16.73, 45.39], $t(2) = 1.99$, $p = .19$; however, a strong effect was represented, $d = .82$.

For the participants with unilateral sensorineural hearing loss at the left ear, no significant difference was found between the SCC n1 latency of the 0˚-30˚ left condition (*M* = 558.50, *SD* = 12.02) and the 0˚-30˚ right condition (*M* = 534.50, *SD* = 20.51), 95% CI [-268.24, 316.24], $t(1) = 1.04$, $p = .47$; a very strong effect was represented, $d = 1.43$.

Because insufficient data was available from the group of patients with hearing loss on the right ear, the difference between left and right presented stimuli could not be obtained.

Latency of the SCC p2

The Kolmogorov-Smirnov test has shown that the latency of the SCC p2 of the 0˚ -90˚ left condition ($D(6) = .21$, $p = .20$), the 0˚-30˚ left condition ($D(5) = .24$, $p = .20$), the 0˚-0˚ control condition ($D(9) = .21$, $p = .20$), the 0˚-30˚ right condition ($D(3) = 1.00$, $p = 1.00$) and the 0˚ -90˚ right condition ($D(7) = .27$, $p = .12$) were normal distributed. One outlier was visible in the 0˚-90˚ right condition. The analyzes were performed with these outliers, since the outliers are reliable data and no difference in the level of statistical significance ($p < .05$) was present.

No significant difference was found between the p2 of the 0˚-90˚ left condition (M = 611.20, SD = 26.85) and the p2 of the 0˚-0˚ control condition (M = 627.60, SD = 15.13), 95% CI [-45.84, 13.04], $t(4) = -1.55$, $p = .20$. This represented an averaged effect, $d = 0.75$.

No significant difference was found between the p2 of the 0˚-30˚ left condition (M = 627.00, SD = 27.41) and the p2 of the 0˚-0˚ control condition (M = 623.00, SD = 12.19), 95% CI [-29.90, 37.90], $t(3) = .38$, $p = .73$. This represented a weak effect, $d = 0.19$.

No significant difference was found between the p2 of the 0˚-30˚ right condition (M = 637.00, SD = 20.00) and the p2 of the 0˚-0˚ control condition (M = 625.67, SD = 13.44), 95% CI [-44.23, 66.90], $t(2) = .88$, $p = .47$. This represented an averaged effect, $d = 0.67$.

No significant difference was found between the p2 of the 0˚-90˚ right condition (M = 628.00, SD = 16.42) and the p2 of the 0˚-0˚ control condition (M = 633.85, SD = 17.47), 95% CI [-20.80, 9.08], $t(6) = -.96$, $p = .38$. This represented an averaged effect, $d = .35$. See table 9 for mean value and standard deviation of the SCC p2 for the five conditions.

Difference of SCC p2 latency between ±90º and ±30º

The latency of the SCC p2 of the 0-±90º condition disappeared earlier (M = 622.88, SD = 24.78) compared to the latency of the p2 of the 0-±30º condition (M = 628.38, SD = 23.99). This difference, 5.50, was not significant, 95% CI [-14.98, 25.98], $t(3) = .86$, $p = .46$; and represented a weak effect, $d = .23$.

Table 9. Mean and standard deviation per condition for the latency of the SCC p2.

	M	***SD***
SCC p2 0˚ - 90˚ left	612.00	24.09
SCC p2 0˚ - 30˚ left	618.60	30.27
SCC p2 0˚- 0˚ control	626.67	22.02
SCC p2 0˚ - 30˚ right	637.00	20.00
SCC p2 0˚ - 90˚ right	628.00	13.44

Difference between left and right presented stimuli

For the participants with unilateral sensorineural hearing loss at the left ear, no significant difference was found between the SCC p2 latency of the 0˚-90˚ left condition (M = 626.33, SD = 24.01) and the 0˚-90˚ right condition (M = 624.33, SD = 16.77), 95% CI [-19.22, 23.22], $t(2) = .41$, $p = .72$; a weak effect was represented, $d = .10$.

For the participants with unilateral sensorineural hearing loss at the left ear, no significant difference was found between the SCC p2 latency of the 0˚-30˚ left condition (M = 650.50, SD = 2.12) and the 0˚-30˚ right condition (M = 647.00, SD = 14.14), 95% CI [-104.50, 111.50], $t(1) = .41$, $p = .75$; a weak effect was represented, $d = .35$.

Because insufficient data was available from the group of patients with hearing loss on the right ear, the difference between left and right presented stimuli could not be obtained.

6.3 Difference in spatial change complex between patients with unilateral sensorineural hearing loss and normal hearing subjects

6.3.1 P-P amplitude of the SCC

Levene's Test for equality of variances indicated that variance of the 0-90 left condition (F (1, 27) = 1.30), p = .27), the 0º-30º left condition (F (1, 29) = 3.70), p = .06), the 0˚-0˚ control condition (F (1, 33) = 1.15), p = .20), the 0º-30º right condition (F (1, 24) = .01), p = .91) and the 0º-90º right condition (F (1, 29) = 1.92), p = .18) was assumed.

For the 0º-90º left condition, the normal hearing group obtained a larger SCC P-P amplitude (M = 5.96, SD = 2.50), than the patient group (M = 5.00, SD = 4.07). This difference, .96, 95% CI [-.99, 4.63], was not significant t(27) = 1.33, p = .38; it represented a weak effect, d = 0.28.

For the 0º-30º left condition, the normal hearing group obtained a larger SCC P-P amplitude (M = 5.43, SD = 2.73), than the patient group (M = 2.44, SD = 1.09). This difference, 2.99, 95% CI [-.53, 4.61], was significant t(29) = 2.57, p = .02. It did represent a very strong effect, d = 1.44.

For the 0˚-0˚ control condition, the normal hearing group obtained a bigger SCC P-P amplitude (M = .67, SD = .11), than the patient group (M = .43, SD = .25). This difference, 0.24 95% CI [-.09, .57], was not significant t(33) = 2.57, p = .15. However, it did represent a strong effect, d = 1.24.

For the 0º-30º right condition, the normal hearing group obtained a bigger SCC P-P amplitude (M = 4.30, SD = 2.30), than the patient group (M = 3.18, SD = 2.09). This difference, 0.19, 95% CI [-1.43, 3.67], was not significant t(24) = .91, p = .37; it represented an average effect, d = .51.

For the 0º-90º right condition, the normal hearing group obtained a bigger SCC P-P amplitude (M = 5.37, SD = 2.88), than the patient group (M = 3.57, SD = 1.38). This difference, 1.80, 95% CI [-.52, 4.12], was not significant t(29) = 1.59, p = .12; it represented a weak effect, d = .12, see figure 25.

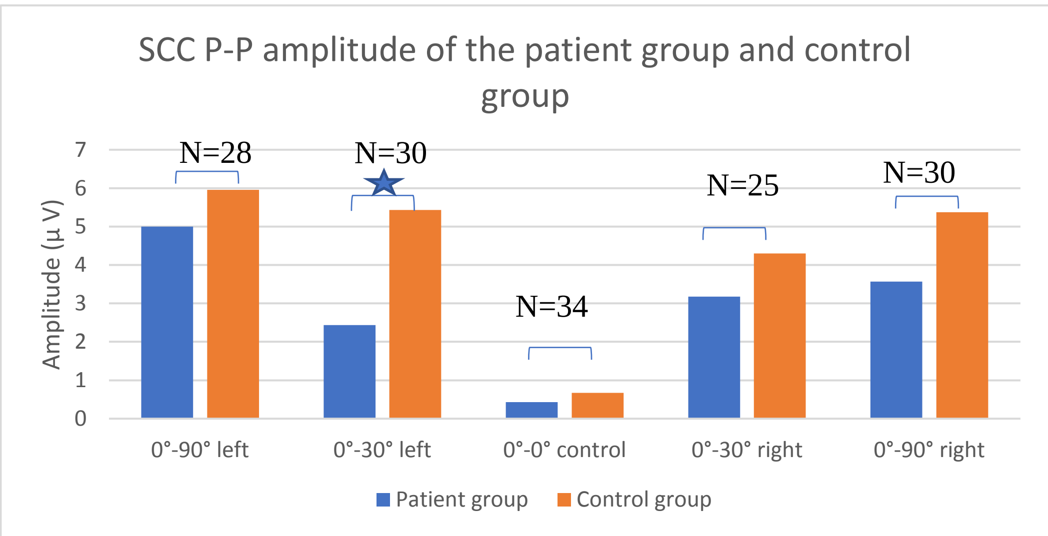


Figure 25. Bar charts showing the mean P-P amplitudes in µV of the SCC's of each condition for the patient group and control group. The asterisk indicates whether it is a significant difference (p < .05).

6.3.2. SCC latencies

Latency of the SCC n1

Levene's Test for equality of variances indicated that the 0-90 left condition (*F* (1, 31) = 9.08), *p* = .06, the 0º-30º left condition (*F* (1, 30) = 8.78), *p* = .01) was not assumed. The 0º-0º control condition (*F* (1, 33) = .50), *p* = .46, the 0º-30º right condition (*F* (1, 23) = .01), *p* = .93 and the 0-90 right condition (*F* (1, 30) = .32, *p* = .58) was assumed.

For the 0º-90º left condition, the normal hearing group obtained an earlier SCC n1 latency (*M* = 521.68, *SD* = 10.51), than the patient group (*M* = 530.25, *SD* = 25.39). This difference, 8.57, 95% CI [-29.93, 12.79], was not significant *t*(7.78) = -.93, *p* = .38; it did represent a weak effect, *d* = 0.44.

For the 0º-30º left condition, the normal hearing group obtained an earlier SCC n1 latency (*M* = 526.00, *SD* = 11.62), than the patient group (*M* = 533.25, *SD* = 26.25). This difference, 7.25, 95% CI [-29.45, 14.95], was not significant *t*(7.93) = -.75, *p* = .47; it did represent a weak effect, *d* = 0.36.

For the 0º-0º control condition, the normal hearing group obtained a earlier SCC n1 latency (*M* = 525.96, *SD* = 12.14), than the patient group (*M* = 526.40, *SD* = 16.07). This difference, 0.44 95% CI [-10.58, 9.70], was not significant *t*(33) = -.09, *p* = .93, it represented a weak effect, *d* = .03.

For the 0º-30º right condition, the normal hearing group obtained an earlier SCC n1 latency (*M* = 525.27, *SD* = 17.93), than the patient group (*M* = 542.00, *SD* = 19.47). This difference, 16.73, 95% CI [-39.73, 6.27], was not significant *t*(23) = -1.50, *p* = .146; however, it did represent a strong effect, *d* = 0.89.

For the 0º-90º right condition, the normal hearing group obtained an earlier SCC n1 latency (*M* = 520.96, *SD* = 13.43), than the patient group (*M* = 532.86, *SD* = 16.42). This difference, 11.89, 95% CI [-24.19, 0.40], was not significant *t*(30) = -1.98, *p* = .06; it did represent an averaged effect, *d* = 0.79. See table 10 for the mean values and standard deviations of the latency of the SCC n1 for the normal hearing group and the patient group.

Table 10. Mean and standard deviation per condition for the latency of the SCC n1 of the normal hearing group and patient group.

	Normal hearing group		***Patient group***	
	M	***SD***	***M***	***SD***
SCC n1 0˚ -90˚ left	521.68	10.51	530.25	25.39
SCC n1 0˚ -30˚ left	526.00	11.62	533.25	26.25
SCC n1 0˚-0˚ control	525.96	12.14	526.40	16.07
SCC n1 0˚ -30˚ right	525.27	17.93	542.00	16.42
SCC n1 0˚ -90˚ right	520.96	13.43	532.86	16.42

Latency of the SCC p2

Levene's Test for equality of variances indicated that the 0º -30º left condition (*F* (1, 27) = 6.49), *p* = .02) was not assumed. The 0º-90º left condition (*F* (1, 28) = 1.87), *p* = .18, the 0º-0º control condition (*F* (1, 32) = .05), *p* = .83, the 0-30 right condition (*F* (1, 23) = 31.), *p* = .05 and the 0-90 right condition (*F* (1, 29) = .42, *p* = .52) was assumed.

For the 0º-90º left condition, the normal hearing group obtained an earlier SCC p2 latency (*M* = 608.17, *SD* = 17.32), than the patient group (*M* = 612.00, *SD* = 24.10). This difference, 3.83, 95% CI [-3.83, 8.54], was not significant *t*(28) = -.45, *p* = .66; it did represent an averaged effect, *d* = .18

For the 0º-30º left condition, the normal hearing group obtained an earlier SCC n1 latency (*M* = 607.08, *SD* = 16.70), than the patient group (*M* = 618.60 *SD* = 30.27). This difference, 11.52, 95% CI [-48.58, 25.55], was not significant $t(4.52) = -.83$, $p = .45$; it did represent a averaged effect, $d = 0.47$.

For the 0º-0º control condition, the normal hearing group obtained an earlier SCC n1 latency ($M = 611.40$, $SD = 19.40$), than the patient group ($M = 626.67$, $SD = 22.02$). This difference, 15.27 95% CI [-31.17, 0.64], was not significant $t(32) = -1.96$, $p = .06$; it represented an averaged effect, $d = 0.74$.

For the 0º-30º right condition, the normal hearing group obtained an earlier SCC n1 latency ($M = 602.00$, $SD = 27.62$), than the patient group ($M = 637.00$, $SD = 20.00$). This difference, 35.00, 95% CI [-39.73, 6.27], was not significant $t(23) = -2.10$, $p = .05$; however, it did represent a very strong effect, $d = 1.45$.

For the 0º-90º right condition, the normal hearing group obtained an earlier SCC n1 latency ($M = 602.67$, $SD = 16.06$), than the patient group ($M = 628.00$, $SD = 13.44$). This difference, 25.33, 95% CI [-39.00, 11.67], was not significant $t(29) = -3.79$, $p < .01$; however, it did represent a very strong effect, $d = 1.71$. See table 11 for the mean values and standard deviations of the latency of the SCC p2 for the normal hearing group and the patient group.

Table 11. Mean and standard deviation per condition for the latency of the SCC p2 of the normal hearing group and patient group.

	Normal hearing group		***Patient group***	
	M	***SD***	***M***	***SD***
SCC p2 0˚- 90˚ left	608.17	17.32	612.00	24.09
SCC p2 0˚- 30˚ left	607.08	16.70	618.60	30.27
SCC p2 0˚- 0˚ control	611.40	19.40	626.67	22.02
SCC p2 0˚- 30˚ right	602.00	27.62	637.00	20.00
SCC p2 0˚- 90˚ right	602.67	16.06	628.00	13.44

6.4 Sensitivity, specificity and accuracy

6.4.1. Sensitivity, specificity and accuracy of the normal hearing group

In the normal hearing group, a SCC was detectable in 76% of the GAs. This means that at 24% no SCC was visible. Since no subjective incorrect localizations were present, the sensitivity could not be determined. The specificity was .72, so was the accuracy.

In the 0º-30º condition, an SCC was detectable at 72%. The specificity and accuracy were .80.

In the 0º-90º condition, an SCC was detectable at 80%. The specificity and accuracy were .76 (see table 12).

Table 12. Sensitivity, specificity and accuracy for the 0º-30º, 0º -90º and 0º-30º+0º-90º conditions.

	0º-30º	**0º-90º**	**0º-30º + 0º-90º**
Sensitivity	-	-	-
Specificity	.72	.80	.76
Accuracy	.72	.80	.76

6.4.2. Sensitivity, specificity and accuracy of the patient group

In the patient group, an SCC was visible in 40% of cases. In 54% of the cases, the sound was subjectively incorrectly located. In 21% of these incorrect locations, an SCC was unjustified present. In 63% of the subjective correct localizations, an SCC occurred. The sensitivity was .79, the specificity was .63 and the accuracy was .71.

A SCC was present in 38% of cases of 0º-30º condition. However, in 64% of the cases, the stimuli were subjectively incorrect located. At 17% of these, an SCC was unjustified present. At 75% of the subjectively correct localizations, an SCC was present. The sensitivity was .83, the specificity was .75 and the accuracy was .80.

In the 0º-90º condition, an SCC was detectable in 43% of cases. In 47% of the cases, the stimuli were subjectively incorrect located. At 28% of these, an SCC was unjustified present. In 63% of the subjectively correct localizations, an SCC was present. The sensitivity was .72, the specificity was .55 and the accuracy was .63 (see table 13).

Table 13. Sensitivity, specificity and accuracy for the 0º-30º, 0º -90º and 0º-30º+0º-90º conditions.

	0º-30º	**0º-90º**	**0º -30º + 0º-90º**
Sensitivity	.83	.72	.79
Specificity	.75	.55	.63
Accuracy	.80	.63	.71

6.4.2. Sensitivity, specificity and accuracy of normal hearing group and patient group

In the normal group and patient group, an SCC was detectable in 57% of cases. In 29% of the cases, the stimulus was subjectively incorrectly located. In 21% of these, unjustified, an SCC occurred. At 72% of the subjectively correct locations, an SCC occurred. The sensitivity of objective assessment of auditory spatial change complex perception using single-channel electroencephalography was .78. The specificity was .72 and the accuracy was .74.

In the 0º-30º condition, an SCC occurred in 54%. In 34% of the cases, the stimulus was subjectively incorrectly located. In this group, an SCC was detectable in 17%. At 73% of the subjectively correct localizations, an SCC occurred. The sensitivity was .83. the specificity was .73 and the accuracy was .76.

In the 0º-90º condition, an SCC occurred in 40%. In 24% of the cases, the stimulus was subjectively incorrectly located. In this group, a SCC was detectable in 28%. At 70% of the subjectively correct localizations, an SCC occurred. The sensitivity was .72. the specificity was .70 and the accuracy was .71 (see table 14).

Table 14. Sensitivity, specificity and accuracy for the 0º-30º, 0º -90º and 0º-30º+0º-90º conditions.

	0º-30º	**0º-90º**	**0º-30º + 0º-90º**
Sensitivity	.83	.72	.78
Specificity	.73	.70	.72
Accuracy	.76	.71	.74

7. Discussion and conclusion

7.1 The spatial change complex P-P amplitudes and latencies in normal hearing persons and persons with unilateral hearing loss

The P-P amplitudes of the SCCs in the normal hearing group in the lateral conditions (0°-±90° and 0°-±30°) were found to differ significantly with the 0°-0° control condition. This effect was as expected, since a change of angle was present in the lateral condition. Although the control condition consisted of the same signal structure, it was offered from the same loudspeaker for a duration of 790 ms. Thus, no angle change was present. These findings are consistent with studies investigating the Acoustic Change Complex (ACC). Like the ACC, the SCC is a cortical auditory evoked potential that consists of a negative peak (n1) followed by a positive peak (p2) and occurs after a change within the stimulus (Tremblay, Friesen, Martin & Wright, 2003). However, a significant difference was found between the 0°±30° and 0°±90° condition for SCC P-P amplitude, i.e. larger P-P amplitudes in the 0°±90° condition. It is therefore likely that the 0°-90° condition subjectively is better distinguished than the 0º-30º condition, what corresponds with a higher specificity and accuracy in the 0°±90° condition compared to the 0°±30° condition. This outcome is in line with the study of Tremblay et al. (2003). In their research, they used four naturally-produced stimuli (/bi/, /pi/, /ʃi/ and /si/). The largest P-P amplitude was generated by the /bi/-/pi/ stimulus. It could be that the /bi/ /pi/ are acoustically most different (voiced vs. unvoiced) compared to the /ʃi/ and /si/ stimuli thus evoking larger P-P amplitudes.

In only 40% of the patients a SCC was present, because of missing data. Because of these missing values, it was not possible to execute a repeated measures ANOVA. So, the analyses are performed with a Paired-Samples t-tests. A disadvantage of this test is that the chance of a Type I error is increased (Field, 2013). From these tests, it has been found that the 0°-30° left condition and 0°-90° right condition differed from the 0°-0°control condition. The expectation was that the SCC would be significantly larger than the 0°-0° control condition, as a change of angle in the stimulus was present in the lateral condition. However, no significant effect was present between the 0°-90° left condition and the 0°-0° control condition, which also applies to the 0°-30° right condition and the 0°-0° control condition. One possible explanation could be the low number of subjects. In the 0°-90° left condition, only data of four patients was available and at the 0°-30° right condition data of only three patients. At the 0°-30° left condition and 0°-90° right condition, data of seven and six patients was respectively present. In addition, the 0°-30° left condition and 0°-90° right condition, which differed from the control condition, respectively, a SCC P-P amplitude of 2.24 uV and 3.75 uV was found. The 0°-90° left condition and the 0°-30° right condition had, respectively, an amplitude of 4.14 uV and 3.5uV. Generally, it seemed that there is a difference in P-P amplitude between all lateral conditions (±90° and ±30º) and the 0º-0º control condition, although in some cases, this was not present, because of a small number of subjects. In addition, no difference was found between the 0±30° and 0±90° condition for SCC P-P amplitude. The aforementioned statement might also apply to this result.

Since no SCC should be present in the 0°-0° control condition, this is determined by placing the n1 and p2 in the same interval as in the lateral condition where, in most cases, an SCC was present. It is therefore not possible to state with certainty that the SCC would actually be present on these points. The latency differences of the n1 and p2 of the control versus the lateral condition show no significant differences.

The paired samples T-test showed that the SCC P-P amplitude in the 0°-30° left condition significantly differed between the normal hearing group and the patient group with unilateral sensorineural hearing loss. In the other conditions (0°-90° left, 0°-0°, 0°-30° right and 0°-90° right), there appeared to be no difference. In the 0˚-0˚ control condition, there should also be no difference, as no SCC in this condition was present. A reason why a significant difference was found between the normal group and the patient group on the 0°-30° left condition was because a T-test has been performed. As the group averages are compared, the probability of a Type I error increases (Field, 2013). It might be that the P-P SCC value of a single patient was low, so that the group average was pulled down. As little data was available from the patient group, this is a prerequisite reason. However, a difference between the normal group and patient group could be expected, as the normal hearing group had an ear threshold of <20 dB and thus observed the stimuli with both ears. In the group of patients, the participants suffered from unilateral hearing loss, so that, in contrast to the normal hearing group, no summation effect were present. The summing effect ensures that when a sound is heard with two ears, the brain receives the signals louder as opposed to one hearing ear (Pyschny et al., 2014). The amplitude of the n1 and p2 becomes larger by an increasing intensity of the stimulus (Picton et al., 2000). Another reason for a potentially smaller SCC P-P amplitude in patients is that, because of the HSE, the patient was exposed to the stimulus for minimal 45 times, and could possibly subjectively locate the speaker after a few number of offers. For example, if the patient couldn't detect the stimulus for the first twenty times, it could be that no SCC occurred. But after these twenty times, the patient was able to locate the speaker because the stimuli were offered at a fixed sound level. As a result, an SCC became visible, but this was averaged with the measurements in which no SCC occurred. In this case the amplitude could then be relatively smaller.

7.2 Lateralization preference

Regarding the SCC n1 and p2 latency, no significant difference between the normal hearing group and the patient group was found. However, in the 0º-30º right and 0º-90º right conditions, a strong effect was present. This was also the case with the SCC p2 of the 0º-90º right condition. A trend was visible; in all conditions, the n1 and p2 appeared earlier in the normal group than in the patient group. It is possible that, with a larger group size, there is a significant difference between the patient group and the normal group. However, Picton et al. (2000) found that the difference between a standard and the deviant does not affect latency. So far, the SCC P-P amplitude appears to be a better indication of the directional horn than the SCC latency times.

For both the SCC P-P amplitude and the SCC n1 and p2 latency times, no difference was found between left and right stimuli. However, there seems to be a trend in the normal hearing group; the SCC P-P amplitude appears at 0°-90° left larger than 0°-90° right. This also applied to the 0°-30° condition. A possible explanation for a larger P-P amplitude for sounds presented from the left side compared to sounds from the right side might be that tones are better processed in the right hemisphere. Speech signals are better processed in the left hemisphere. Because the nervous tracts run down the cortex contralateral, the left-handed offered stimuli are better heard in the left ear, and that allows a larger P-P amplitude (Gu, Zhang, Hu & Zhao, 2013). Hanss et al. (2009) examined the cortical organization in normal hearing adults. This showed that the cortical activation pattern is characterized by shorter and larger neurophysiological responses in the hemisphere contralateral to the stimulated ear in response to monaural stimulation. This activation patterns are believed to be based on contralateral dominance in the auditory pathway because the contralateral auditory pathway contains a greater number of nerve fibers than the ipsilateral pathway. Since single-channel EEG measurement has been performed in current research, with the measuring electrode located on the CZ, no comparison between the left and right hemispheres can be made. There might be an effect if multiple participants participate in the research. In the patient group, this is calculated only for the ten patients with hearing loss in the left ear, as insufficient data was available for the patients with an impaired hearing in the right ear to compare stimuli offered from the left with the stimuli offered from the right. Ponton et al. (2001) has shown that brain activity in unilateral deaf patients in the ipsilateral hemisphere of the healthy ear increases. It depends on how long a patient is deaf before this ipsilateral hemisphere adapts on hearing. It might be possible for patients who have recently become deaf, that they show a greater difference between left and right stimuli than patients who are longer deaf. This could be investigated in the future. Because single-channel electro encephalography has been performed in current study, the left and right hemisphere cannot be compared.

7.3 Sensitivity, specificity and accuracy of the Spatial Change Complex

In the normal hearing group, an SCC appeared in 76% of the cases. Since every normal-hearing participant was able to locate sound source subjectively, thus, in 24% no SCC occurred, while it should have been present. In the 0°-30° condition, an SCC occurred in 72%. One reason why SCCs occurred more often in the 0º-90º condition than in the 0º-30º condition was that the difference between 0°-90° condition is larger than between 0°-30° condition, which makes the sound sources of the 0°-90° condition better distinguishable. As described in 7.1.1, the research of Tremblay et al. (2003) had shown that stimuli that is more distinguished generates a larger P-P amplitude. It might be that not only the amplitude is increased, but also an SCC occurs more often. One reason why a SCC was not always present, as it should have been, is that the n1 and p2 are sensitive to sleepiness in persons. This ensures that n1 and/or p2 not always displays (Näätänen, 1992). In this study, the subjects received minimal 45 times stimuli from five different conditions, each condition being measured twice. Although one or more breaks were entered, some patients found it difficult to stay focused. Another reason is that single-channel EEG measurement has taken place in current research, with the electrode on the vertex (Cz). Although in this place the n1 and p2 can best be measured, brain action may be better recorded if more electrodes are used (Martin, Boothroyd, Ali & Leach-Berth, 2010).

In the patient group, an SCC occurred in 40% of cases. Since the subjective measurement was linked to the objective measurement, it was not an addition of the ERPs of the same conditions (GA), but the loose measurements were investigated. It occurred in several cases that a patient was unable to locate the first measurement of a particular condition subjectively correctly, but could do so during the second measurement of the same condition. As a result, the measurements could not be added and said whether the patient could locate the sound source. 54% of the cases were subjectively located incorrect. This means that the patient incorrectly indicated the location of the sound change or didn't even hear any change in angle at all. An SCC was still present in 21% of these subjective incorrect locations. One reason for this is that the patient was unable to identify the correct location during the subjective measurement. During this measurement, the patient heard the stimulus for the first time. Then the EEG measurement was started, with the stimulus being offered at least 45 times. Because of the fixed level of loudness, it may be possible for the patient to be exposed to the stimulus after a number of times, the head shadow effect (HSE) occurred and thereby determined which loudspeaker the sound came from. Agterberg et al. (2011) have investigated the extent to which unilateral deaf patients rely on this HSE in horizontal localization. Their study showed that unilateral deaf persons use head shadow effect in the localization of sound sources. Probably, the patients have learned that under certain condition the HSE may be beneficial for localization, for example in well-known acoustic environments. The observations showed that the azimuth rapidly improves localization when the patients explicitly was told that the sound level was fixed and when visual feedback was given. However, this was not the case in current research. Nevertheless, the persons could have noticed that the same loudness was used during the EEG measurement by condition. In that case, an SCC could still occur. To check this, a second subjective was performed after each objective measurement. This showed that in a number of patients who were unable to correctly locate the sound source during the first subjective measurement, but they were able to localize the sound source during the second subjective measurement. In this case, by several patients a SCC was present, but this was not the case for everyone. It is advisable to use a variation in loudness in a follow-up study so that the participants could not use the HSE.

Another reason for the presence of an SCC in a subjective incorrect localization is that the patients who, despite being unable to detect the precise location of the sound source, observed the sound of the stimulus softer after the change of angle. If a patient with unilateral hearing loss at the left side hear a stimulus from the 0º-90º left condition, he will hear the signal from the frontal (0º) speaker louder compared to the lateral (90º speaker). It may be that the SCC is not a brain response to the spatial change, but a response to the perceptual change in loudness. When there is a acoustic change within a sound, an Acoustic Change Complex (ACC) may occur (Martin & Boothroyd, 2000). This ACC consists, like an SCC, of a negative waveform (n1) followed by a positive waveform (p2). It might be the case that the visible n1-p2 was a result of a subjective change of the signal, because of detecting a softer sound after the change of localization. One patient noticed that, during the EEG measurement, he heard a softer sound from in the second half compared to the first half of the stimuli, but was unable to subjective localize the sound source.

A third reason is that the patient was not able to identify the correct source, while the brain does have processed the stimulus. Sometimes people are only able to point to the correct speaker, as they are very sure of their case. It may be that they doubted at the first exposure of the sound while the brain processed the exposure.

In 63% of cases, the patient was able to locate the sound source subjectively, where actually an SCC occurred. This means that in 37% of cases the patient was able to locate the sound source subjectively, and where no SCC occurred. Also, a probability of 20% was available to designate the appropriate speaker because only five speakers were present. If a patient could hear globally or a left or right sound, this chance was increased because he could choose from two left or right speakers. In the future, more speakers should be used to reduce this chance. Also, the speakers could be made invisible by placing them behind a curtain.

As with the normal group, the patient group showed in the 0º-90º condition an SCC more often and more accurate than in the 0º-30º condition. This was 43% and 38%, respectively. Again, the reason for a relatively more frequent SCC could be that 90º is easier to distinguish than 30º. Especially when a person suffered from unilaterally hearing problems, the distinction between 0º and 30º degrees could be more difficult. However, at the 0º-30º condition, in 64% of the cases, the speaker was subjectively incorrect located, while this was 47% at the 0º-90º condition. This could be because the ±90º speakers are more lateral and are more difficult to detect by persons with unilateral hearing loss. For example, when a person with left-sided deafness is offered a stimulus, it may be that the stimulus from the -90º speaker is more difficult to locate subjectively than the -30º speaker. This is because the -90º speaker is closer to the affected ear and the -30º speaker closer to the unaffected ear. Also, the accuracy is better in the 0º-30º condition compared to the 0º-90º condition, which is in contrast with the normal hearing group.

Both groups taken together in the 0º-30º and 0º-90º condition an SCC occurred in 57% of cases. In 29% of these cases, an SCC occurred while an incorrect subjective localization occurred. The sensitivity of objective assessment of auditory spatial change complex perception using single-channel electroencephalography was .78. The specificity was .72 and the accuracy was .74. This means that no SCC was present if the participant was unable to identify the correct sound source in 78% of the measurements. In other words, in 78% of cases, a patient was as pathological actually labeled as pathological. In 72% of the measurements an SCC was present, in which the participant was also able to subjectively locate the correct sound source. The EEG measurement identified 72% of non-pathological participants as non-pathological. In 74% of the cases, the correct diagnosis was made by the EEG measurement. The sensitivity, specificity and accuracy values cannot be classified in strength measurements simply because the interpretations of these values do not exist.

In the 0º-30º condition, an SCC occurred in 54% of the cases. In the 0º-90º condition, an SCC occurred more often, namely 60%. As mentioned in 7.4.1 and 7.4.2, in both the normal hearing group and the patient group an SCC occurred more in the 0º-90º condition compared with the 0º-30º condition. Also, more correct located stimuli were present in the 0º-90º condition.

7.4 Clinical implications

An SCC can determine whether or not a patient is able to locate different sound sources. However, an SCC does not occur to everyone. The N1-P2 response is criticized because of its variability and sensitivity to the effects of sleepiness of persons (Näätänen, 1992). Deploying this instrument to determine whether a person can locate is especially important for infants, children and mental impaired persons. In these groups, it is difficult to conduct behavioral research. However, during EEG measurement, it is necessary to sit still, which makes the research less suitable for children. However, Martinez, Eisenberg and Boothroyd (2013) had shown that an Acoustic Change Complex could be recorded successfully in children with normal hearing and with hearing loss. Similarly, one can assume that this should be also possible for the SCC successfully.

Since all patients reported to experience localization problems in daily life, the current setup of the research was not sensitive enough because some patients could correctly locate the stimuli subjectively. In this setting, a certain stimulus is often offered, something that is not the case in everyday life. Also, the patients are focused and prepared for the sound to come. The EEG measurement has been taken in a soundproof room where no ambient noise was present. The presence of ambient noise is a factor that often occurs in everyday life and complicates localization. The used stimulus was broadband white noise, which generates the largest P-P amplitude compared to narrowband white noise. Many patients told that they experienced problems with locating specific high and low tones, such as ringing a phone. General daily sounds do not always consist of this large frequency range. Thus, there should be an arrangement that is more consistent with daily life.

7.5 Recommendations for follow-up research

In order to reduce the chance of gambling on the designation of the correct speaker, more speakers should be used. Also, the speakers could be rendered invisible by placing them behind a curtain. To investigate whether patients are able to detect the location of the stimuli above chance, an experiment could be performed that calculates the d' (‘d-prime’).

In current research, single-channel EEG research has been done. In the future, the research could be performed with multiple electrodes, because more brain activity may be measured when using multiple electrodes. Also, the brain activity between the left and right hemisphere can be compared in this way.

In addition, stimuli should be used that generally occur in daily life. Then, there can be given a better picture of the localization problems experienced by patients outside the EEG research setting. Because background noise is present in daily life, it should be investigated whether in the presence of noise, a EEG measurement can be reliably taken.

Also, a variation in loudness should be applied to avoid the head shadow effect. Because nothing is known about the inter- / inter-assessor reliability, it is recommended to investigate them. It is recommended to investigate more participants, including mainly patients, in the future.

Finally, it is important to investigate whether an SCC is generated in infants, children and people with disabilities.

7.6 Conclusion

The SCC is an instrument in development. The clinical populations to apply SCC recording might be infants, young children and, all with hearing impairment who are not able to reliably execute behavioral suprathreshold localization testing. Further research will be necessary for the clinical application of the SCC to test the effectiveness in these young children and in patients with hearing loss, and also to define optimal stimulation presentation parameters. In this study, it has been shown that in 76% of the normal hearing persons an SCC can be generated. In the patient group, this was 40%, which 63% was actually able to locate the speakers correctly. In the normal group, a significantly larger SCC amplitude in the 0º-90º condition was found compared to the 0º-30º condition. In the patient population, no significant difference was found between the 0º-30º condition and 0º-90º condition. No significant difference was found between the P-P amplitude of both groups except for the 0º-30º left condition. Within and between both groups, no difference was found in latency of the SCC n1 and p2. The SCC amplitude is a better indicator for auditory processing than the SCC latency. However, this conclusion only applies to adults aged 18 or older.

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Appendix I: Pilot study

1. Research question

Is a transition between white noise stimulus consisting of two signals presented frontally with a rise-fall time of 20 milliseconds and white noise stimulus consisting of a signal with a rise-fall time of 10 milliseconds subjective perceptible?

2. Method

2.1 Participants

The group consisted of ten normal hearing subjects (four males) in the age of 20.1 through 24.6 years with a mean age of 24.6 years (pure-tone air conduction thresholds from 250 through 4000 Hz ≤20 dB HL [Interacoustics AD629]).

2.2 Stimuli

In this experiment, four different stimuli were used per bandwidth, consisting of broadband white noise (0.5-20 kHz), low frequency white noise (0.5-1.5 kHz) and high frequency white noise (3.5-4.5 kHz). The first stimulus, or stimulus *a*, consisted of one signal of 800 milliseconds with a rise-fall time of 20 milliseconds (see figure 26). The second stimulus, or stimulus *b*, consisted of two signals of each 400 milliseconds with a rise-fall time of 20 milliseconds (see figure 27). The third stimulus, or stimulus *c*, consisted of two signals of 400 milliseconds with a rise-fall time of 10 milliseconds (see figure 28). The last stimulus, or stimulus *d*, consisted of two signals of each 400 milliseconds with both a rise-fall time of 20 milliseconds, with a silence interval of 100 milliseconds taking place between the end of the first signal and the beginning of the second signal (see figure 29). This stimulus is added as a filler item, so that a test person can clearly hear a difference. The stimuli are generated with an audio frequency signal generator (Pigeon, 2012). On all stimuli, a 10^{th} order Butterworth bandpass filter is applied (Hyde, 1994a). The stimuli are all presented at an intensity level of 65 dBA, controlled by a computer 1 meter away from the participant and presented from the speaker at 0°.

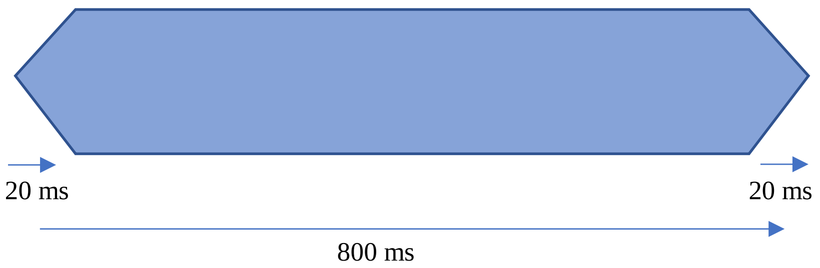


Figure 26. Stimulus (a) with a total duration of 800 ms and a rise-fall time of 20 ms.

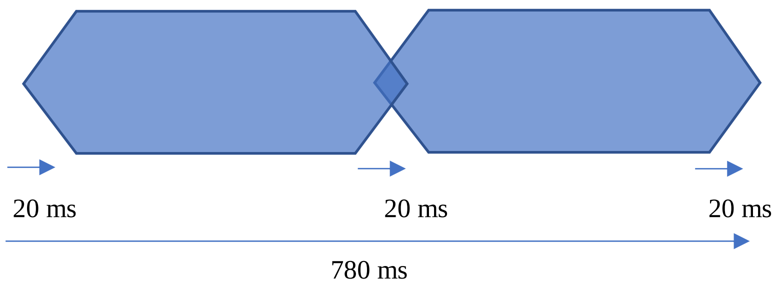


Figure 27. Stimulus (b) with a total duration of 780 ms, consisting of two signals of each 400 ms. Both signals have a 20 ms rise-fall time, with the rise time of the second signal starting when the fall time of the first signal begins. A transition of 20 ms has been created.

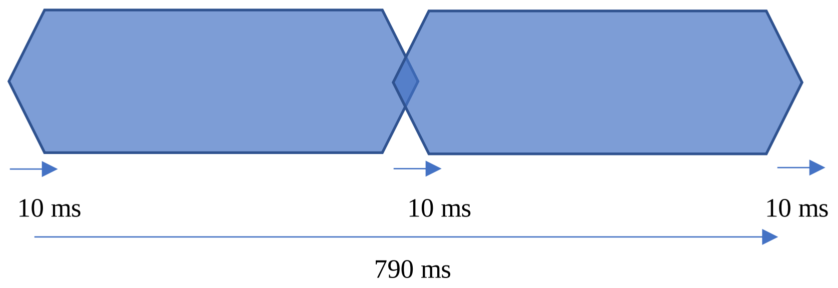


Figure 28. Stimulus (c) with a total duration of 790 ms, consisting of two signals of each 400 ms. Both signals have a 10 ms rise-fall time, with the rise time of the second signal starting when the fall time of the first signal begins. A transition of 10 ms has been created.

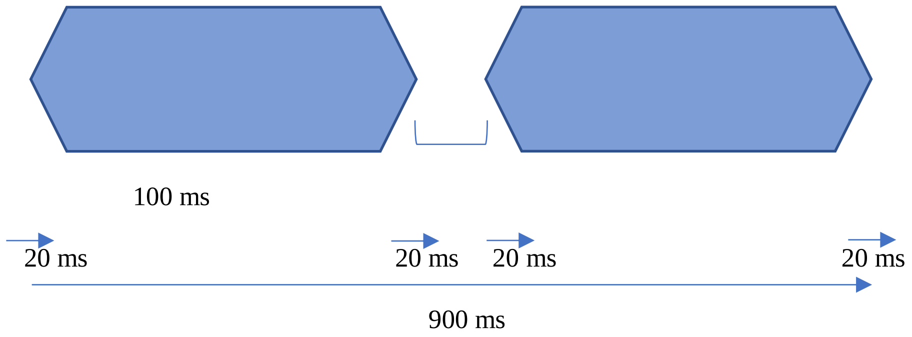


Figure 29. Stimulus (d) with a total duration of 900 ms, consisting of two signals of each 400 ms. Both signals have a 20 ms rise-fall time, with a silence interval of 100 ms.

2.3 Measurement setup

In a soundproof room, a stimulation PC was placed behind the subject. The participant took place on a chair surrounded by three custom made Vifa ball speakers (Falcon Acoustics, appendix IV) in a free field setup. On the stimulation PC, a LabVIEW program has been installed to enter desired stimuli, with the parameters of sound level and stimulation frequency being entered if necessary. The stimuli were presented via an audio amplifier (Ecler MPA4-80R) through free field loudspeakers. Each was located one meter away from the center of the head of the participant at the height of the ears.

2.4 Procedure

The participant sat in a chair. Before the participants received the four stimuli randomly, they were told that they should whether to heard a possible transition in the middle of the signals rather than the length of the stimuli. A 'pair' is seen as a stimulus (a, b, c or d) followed by a second stimulus (a, b, c, d). Each pair was presented four times. After each auditory presented pair, the participant assessed whether they were the same or different, thus creating a 2-forced alternative choice. In total, the subjects assessed 64 pairs. After every sixteen pairs, a short break took place.

In all participants from the control condition, a measurement of pure-tone air conduction [Interacoustics Diagnostic Audiometer, AD629] has been taken to determine the hearing threshold. A person was "normal hearing" if the hearing threshold was ≤20 dB at all octave frequencies.

2.5 Data analysis

This experiment has been carried out based on signal detection analysis, with the d-prime as an outcome measure. D-prime is a measure that determines the distance between 'noise' (N) and 'signal to noise' (SN). The value of the d-prime must be at least 1.0 to confirm that stimuli are correctly discriminated over time (Swets, 1961). For both the stimuli consisting of two signals of 400 milliseconds with a rise-time of 20 milliseconds as for the stimuli consisting of two signals of 400 milliseconds with a rise fall time of 10 milliseconds, the d-prime is calculated. Hereby, the stimuli consisting of a signal of 800 milliseconds have been taken as a reference frame. Then for the number of correctly classified stimuli, or "HIT", the ratio is determined by the following formula:

$$p_{HIT} = N_{HIT}/(N_{HIT}+N_{MISS})$$

In addition, for the number of false negative classified stimuli, or "FA" (false alarm), the proportion is determined by the following formula:

$$p_{FA} = N_{FA}/(N_{FA}+N_{CORRECT\ REJECTJED})$$

If the ratio of both the hit rate and false alarm rate was 0%, a correction was applied by the formula below. *Equal* means the number of times that the participant should not have given a hit.

$$P_{HIT} = 1/(2*equal)$$

$$P_{FA} = (1/(2*equal)$$

If the ratio of both the hit rate and false alarm rate was 100%, a correction was applied by the formula below. *Unequal* means the number of times that the participant should have given a hit.

$$P_{HIT} = 1-(1/(2*unequal))$$

$$P_{FA} = 1-(1/(2*unequal))$$

Subsequently, for the stimuli with a rise-fall time of 20 milliseconds and the stimulus with a rise-fall time of 10 milliseconds, the z value is determined. As indicated by the below formula, the Z-score (False Alarms) of the Z-score (HIT) was collected, which led to the d-prime value.

$$d' = Z(p_{HIT}) - Z(p_{FA})$$

3. Results

3.1 Subjective perception of a transition between two signals consisting of 20 milliseconds

The study has shown that 20% of all participants observed a difference above chance (d’ ≥ 1.0) between the broadband stimuli consisting of a signal of 800 milliseconds with a rise-fall time of 20 milliseconds and the stimuli consisting of two signals of 400 milliseconds, each with a rise-fall time of 20 milliseconds with of a transition 20 milliseconds. The mean value of the d prime in this stimulus was .37, ranging from .0 to 2.22 (*SD* = 0.73).

For the low frequency stimuli consisting of a signal of 800 milliseconds with a rise-fall time of 20 milliseconds and the stimuli consisting of two signals each having a rise-fall time of 20 milliseconds with 20 milliseconds overlap, 20% of all participants observed a difference above chance (d' ≥ 1.0). The average d-prime at these stimuli was .35, ranging from .00 to 2.22 (*SD* = 0.73).

Additionally, in the high frequency stimuli, 20% of all participants were able to observe a difference above chance (d’ ≥ 1.0) observed a difference between the stimuli consisting of the two signals. The average d prime value was .45, ranging from of .00 to 2.22 (*SD* = .91).

2.2 Subjective perception of a transition between two signals consisting of 10 milliseconds

The study has shown that none of the participants observed a difference above chance (d’ ≥ 1.0) between the broadband stimuli consisting of a signal of 800 milliseconds with a rise fall time of 10 milliseconds and the stimuli consisting of two signals of 400 milliseconds, each with a rise-fall time of 10 milliseconds with of a transition 10 milliseconds. The mean value of the d prime in this stimulus was 0.08, ranging from .0 to .47 (*SD* = 0.17).

Also for low frequency stimuli consisting of a signal of 800 milliseconds with a rise fall time of 20 milliseconds and the stimulus consisting of two signals each having 10 milliseconds with 10 milliseconds transition, no difference has been found above chance (d’ ≥ 1.0). The mean value of the d prime in this stimulus was .12, ranging from .00 to .68 (*SD* = .25).

Finally, in the high-frequency stimuli, no difference above chance was observed (d’ ≥ 1.0) between the stimuli consisting of two signals each having a rise-fall time of 10 milliseconds with a transition of 10 milliseconds. The mean value of the d prime in this stimulus was .13, ranging from .00 to .68 (SD = .27).

4. Discussion and conclusion

4.1 Subjective perception of a transition between two signals consisting of 20 milliseconds and 10 milliseconds

The study found that 20% of all participants could detect the transition between the two signals of each 400 milliseconds with a transition of 20 milliseconds. In addition, it has been found that no one perceives the transition between the two signals of each 400 milliseconds with a rise fall time of 10 milliseconds.

Since this study was performed in a relatively small group, results may be different if this experiment is taken over a larger group of individuals. It is advisable to investigate the subjective perception of a transition between two signals with a rise fall time of 10 milliseconds, with a transition of 10 milliseconds.

4.2 Conclusion

The conclusion is, for all frequencies, that a transition of 20 milliseconds is subjective perceptible, but for a transition of 10 milliseconds this is not the case. Therefore, for further investigation, stimuli will be used with a rise fall time of 10 milliseconds, creating a transition of 10 milliseconds between the two signals.

Appendix II: Spectra of the stimuli

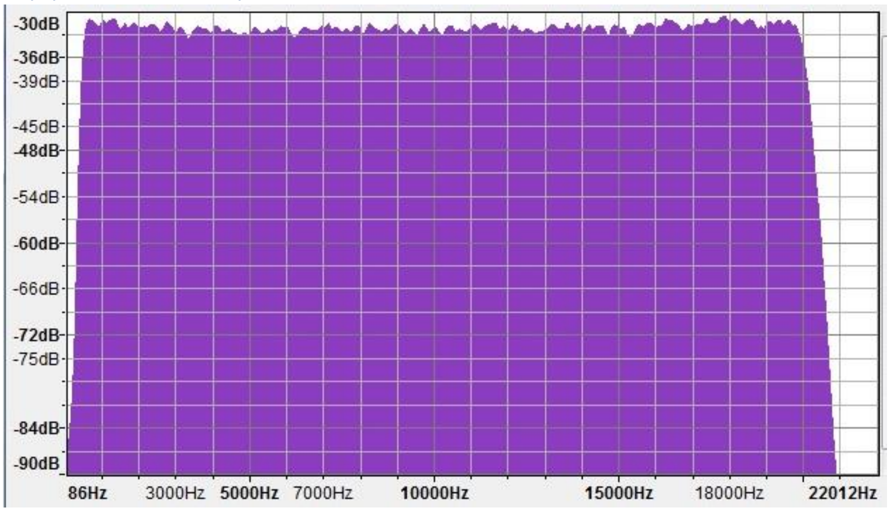


Figure 30. Spectra of broadband signal (cutoff frequency of .5-20 kHz)

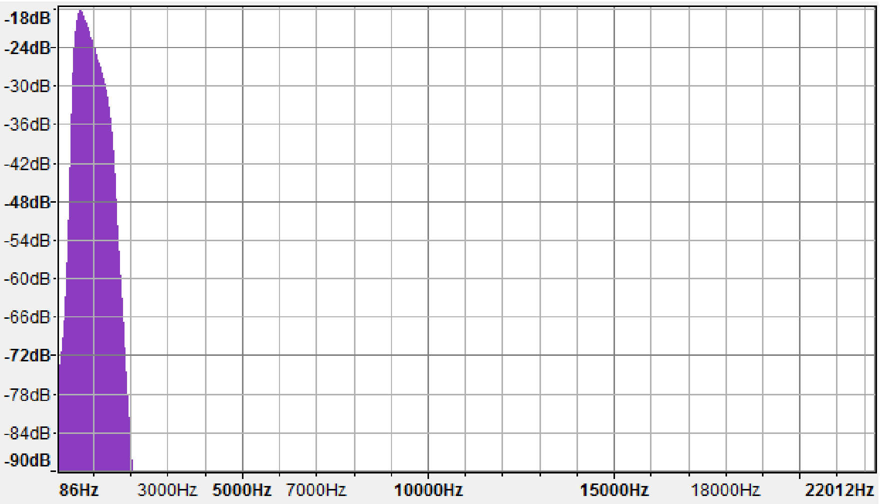


Figure 31. Spectra of low frequency signal (cutoff frequency of .5-1.5 kHz).

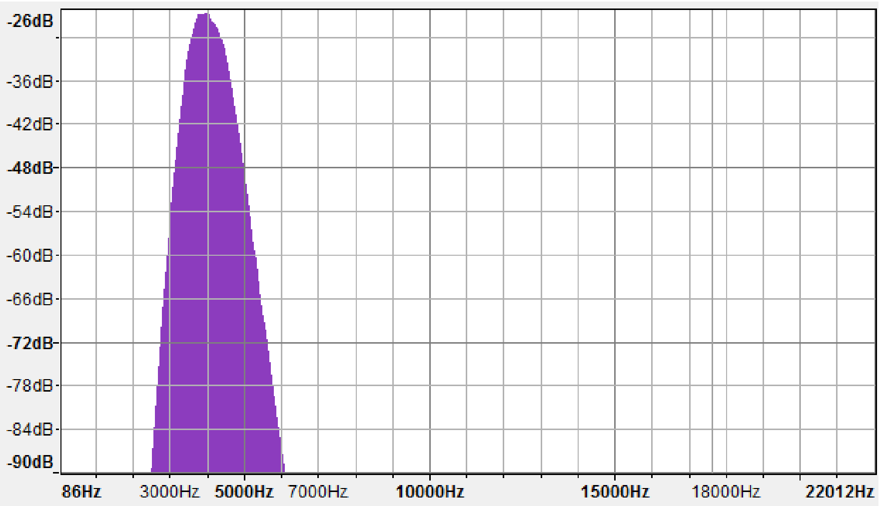


Figure 32. Spectra of high frequency signal (cutoff frequency of 3.5-4.5 kHz)

Appendix III: Measurement setup

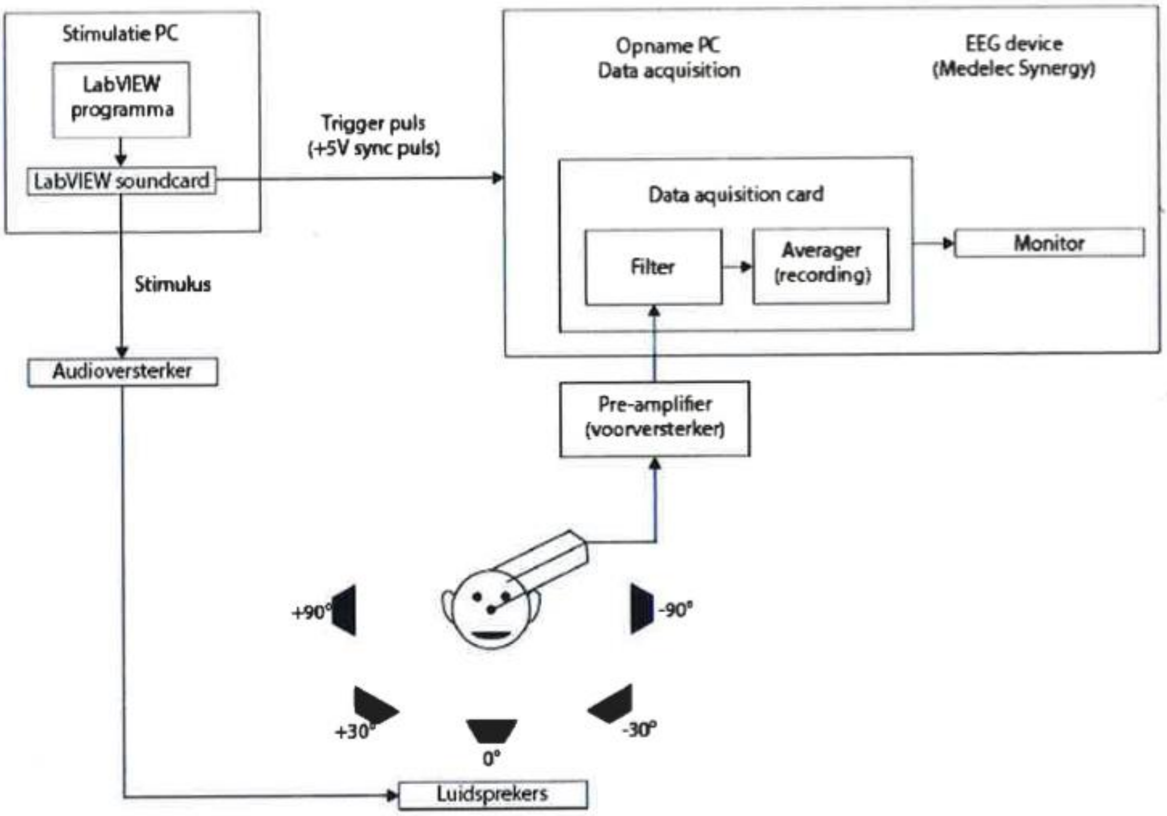
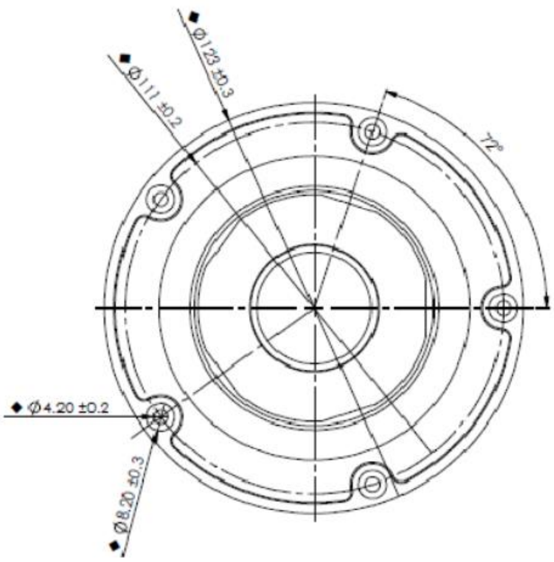


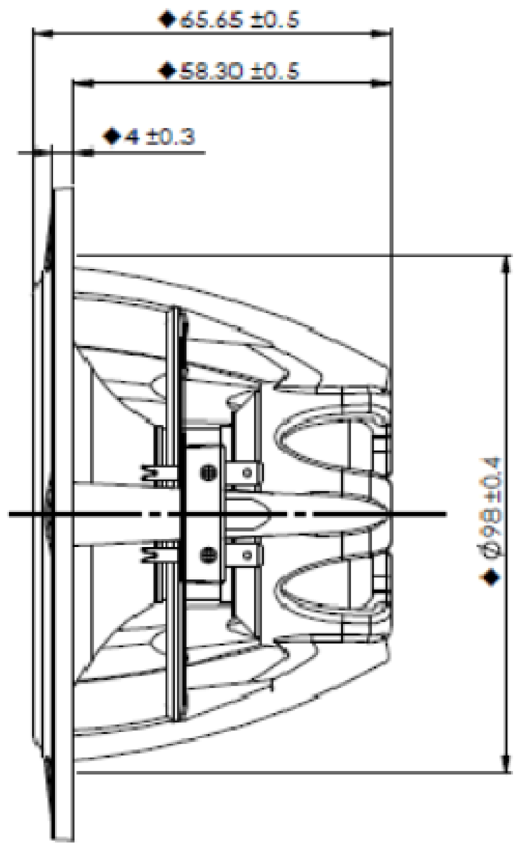
Figure 33. The measurement setup. Taken from: Noordeloos, 2017.

Appendix IV: Specification list of Vifa speakers (Falcon Acoustics, 2016)

Specification list

DC Resistance		R_{evc}	Ω	6.3	5.0%
Minimum Impedance Z_{min}	Ω	7.3		7.5%	
Voice Coil Inductance		L_e	mH	0.06	
Resonant Frequency	F_s	Hz		61	15.0%
Mechanical Q Factor	Q_{ms}	-		4.98	
Electrical Q Factor	Q_{es}	-		0.37	
Total Q Factor	Q_{ts}	-		0.35	
Ratio f_s/Q_{ts}	F	f_s/Q_{ts}		176	
Test Spectrum Bandwidth	60Hz-8kHz			12 dB/Oct	
Energy Bandwidth Product	EBP	$(1/Q_{es})\cdot f_s$		164	
Moving Mass	M_{ms}	g		4.7	
Suspension Compliance	C_{ms}	um/N		1433	
Effective Cone Diameter	D	cm		8.30	
Effective Piston Area	S_D	cm^2		54.1	
Equivalent Volume	V_{as}	L		5.894	
Motor Force Factor	BL	T·m		5.53	
Motor Efficiency Factor	β	$(T\cdot m^2)/\Omega$		4.88	
Voice Coil Former Material	VC_{fm}	-		TiSV	
Voice Coil Inner Diameter	VC_d	mm		32.41	
Gap Height	Gh	mm		4.00	
Maximum Linear Excursion	X_{max}	mm		3.10	
Ferrofluid Type	FF			N/A	
Transducer Size	-	inch		4	
Transducer Mass	-	Kg		0.412	





Appendix V: Settings of the EEG device

Analysis window	1000 ms (incl. 200 ms prior to stimulus onset)
Impedance	<8000 Ohm
Artefact reject level	50-110 μV
Sampling rate	25 kHz
Bandpass filter	0.1 – 30 Hz
Notch filter	50 Hz
Positive electrode	X1 (nose)
Negative electrode	Cz (vertex)
Polarity	positive (5 Volt TTL pulse)

Appendix VI: The Grand Average of the Spatial Change Complex of each normal hearing participant

Table 15. Grand Average (GA) of each normal hearing participant for all conditions.

Participant	0˚-0˚	0˚-90˚ left	0˚-30˚ left	0˚ -30˚ right	0˚-90˚ right
1	-	-	-	4.9	6.1
2	0.5	4.7	9.9	4.7	9.6
3	0.6	5.5	4.3	-	3.6
4	0.9	5.2	-	3.4	3.7
5	0.6	6.7	6.5	8.5	3.6
6	0.7	7.2	-	4.9	6.7
7	0.8	8.3	5.3	2.9	5.5
8	1.3	4.4	-	3.7	3.3
9	2.3	10.8	12.5	5.7	11.1
10	0.9	8.4	6.5	-	3.8
11	-	-	1.9	2.3	7.6
12	0.0	3.7	2.0	-	4.7
13	0.0	5.7	-	-	5.5
14	1.0	2.7	3.1	4.0	4.1
15	0.5	6.6	5.5	-	-
16	0.4	7.0	6.2	5.8	7.7
17	0.7	8.2	6.9	6.0	-
18	0.7	12.0	8.9	10.6	13.2
19	0.7	-	-	3.4	-
20	0.9	-	4.3	2.2	-
21	0.5	4.3	4.7	6.4	5.6
22	1.7	-	3.4	-	-
23	0.7	3.7	2.4	2.2	2.6
24	0.7	3.1	2.2	1.3	-
25	0.2	2.0	1.7	3.0	2.9

Appendix VII: The Grand Average of the Spatial Change Complex of each patient

Table 16. Grand average (GA) of each patient with unilateral sensorineural hearing loss for all conditions.

Participant	0˚-0˚	0˚-90˚ left	0˚-30˚ left	0˚ -30˚ right	0˚-90˚ right
1	0.0	-	-	-	4.7
2	0.9	-	2.3	-	2.2
3	0.4	-	1.00	-	-
4	0.9	11.4	3.7	4.8	6.1
5	0.7	-	-	-	-
6	-	-	3.8	2.2	2.5
7	0.0	2.0	3.1	5.00	-
8	0.2	2.6	-	-	-
9	0.3	2.6	1.3	.7	4.2
10	0.9	-	1.5	-	-
11	0.1	2.1	-	-	3.0
12	-	-	-	-	-
13	0.5	-	2.8	-	2.7
14	0.4	-	0.8	-	-

Appendix VIII: Tables with raw scores for determination of sensitivity, specificity and accuracy

Table 17. Table with raw scores of the normal hearing group for determination of sensitivity, specificity and accuracy.

Subjective Measurement / EEG measurement Abnormal (+) Normal (-)	Change of angle: incorrect	Change of angle: correct	
+ (SCC absent)	Hit (true positive) 0	False alarm (false positive) 24	**24**
- (SCC present)	Miss (false negative) 0	True negative (correct rejected) 76	**76**
	0	**100**	**100**

Table 18. Table with raw scores of the patient group for determination of sensitivity, specificity and accuracy.

Subjective Measurement / EEG measurement Abnormal (+) Normal (-)	Change of angle: incorrect	Change of angle: correct	
+ (SCC absent)	Hit (true positive) 48	False alarm (false positive) 19	**67**
- (SCC present)	Miss (false negative) 13	True negative (correct rejected) 32	**45**
	61	**51**	**112**

Table 19. Table with raw scores of both the normal hearing group and the patient group for determination of sensitivity, specificity and accuracy.

Subjective Measurement / EEG measurement Abnormal (+) Normal (-)	Change of angle: incorrect	Change of angle: correct	
+ (SCC absent)	**Hit (true positive)** 48	**False alarm (false positive)** 43	**91**
- (SCC present)	**Miss (false negative)** 13	**True negative (correct rejected)** 108	**121**
	61	**151**	**212**

Appendix IX: Abbreviations

ABR	Auditory Brainstem Response
ACC	Acoustic Change Complex
ANOVA	Analysis of Variance
CAEP	Cortical Auditory Event Potential
dB	Decibel (intensity)
EEG	Electroencephalography
Hz	Hertz (frequency)
ILD	Interaural Level Difference
ITD	Interaural Time Difference
LLR	Long Late Response
MLR	Middle Late Response
MMN	Mismatch Negativity
ms	Milliseconds
SCC	Spatial Change Complex
SVP	Slow Vertex Potential