Cochlear implants, music perception and musical training

I. M. Venema

23/6/2019

S2724537, BSC Biomedical Technology, Department of Otorhinolaryngology Research School of Behavioral and Cognitive Neuroscience (BCN), Rijksuniversiteit Groningen. Supervised by: prof. dr. D. Başkent and prof. dr. ir. G. J. B. Verkerke

A B S T R A C T

This study investigates the effect of music training on music perception in cochlear implant (CI) users. Listening to music has social and cultural relevance but receivers of a CI often report reduced music enjoyment and engagement after implantation. This is because the auditory signal that their CI provides does not have enough spectral and temporal information for sufficient pitch and timbre perception for music. Technological improvements on CIs are made to overcome this but there will always be limitations due to degradation of the acoustic signal during encoding and a limit to the amount of electrodes that can be placed on an electrode array. Therefore there is a strong drive for alternative solutions. One of the proposed solutions is to provide CI recipients with music training based on observed brain plasticity in the central auditory pathway after implantation that can respond to sound exposure and studies that found a positive correlation between music training and pitch detection in NH populations. In this paper four studies that examined the effect of music training on music perception are summarized. Although all studies used very different methodologies, participant groups and testing methods, an overall positive effect of music training on sound perception seems present. CI users indicate that their music enjoyment is linked to their ability to perceive music. Training this ability might therefore help them enjoy music more.

Table of contents

1. Introduction

The perception of music is a skill most people take for granted. It is a source of entertainment and experiencing music is often associated with expression of meaning and emotion (Hays & Minichiello, 2005). However, studies have found that recipients of a cochlear implant (CI) often find listening to music less pleasant and enjoyable after implantation (Mirza et al., 2013). This paper discusses why this is the case and how music perception and in turn its enjoyment can be enhanced for CI users.

In order to do this first the mechanisms of normal hearing (NH) are explained and the different types of hearing loss (HL) are mentioned. We name several implants that can (partially) restore hearing and then focus on the CI. Then the mechanism and benefits of a CI are discussed as well as some technological constrains that hinder the perception of music. In the following section the importance of music is stated as well as why its perception is more difficult for CI users. Four studies that investigated the effect of music training on music perception for CI recipients are reviewed.

2. The mechanics of hearing and of hearing loss

2.1. The functioning of the ear

The ear consists of three parts: the outer ear, the middle ear and the inner ear (figure 1). Through this sound waves are transported to the brain in order to hear. Sound waves travelling through the air are picked up by the pinna and then transported through the ear canal to the tympanic membrane, generating a mechanic vibration. This vibration is then picked up by the ossicles: the malleus, the incus and the stapes (translated this means hammer, anvil and stirrup). The ossicles amplify the vibrations of the tympanic membrane because in the inner ear the vibrations will be transported through fluid instead of air. In liquid the energy of the sound is severely reduced compared to air (Hill, Wyse & Anderson, 2018). To compensate this reduction the amplification is needed. The malleus is connected to the tympanic membrane and passes its vibrations to the incus, which in turn passes the vibrations on to the stapes. The stapes is attached to the fenestra ovalis (or oval window) on the cochlea, connecting the middle and inner ear. When the tympanic membrane moves inwards because of air pressure, the stapes pushes on the oval window and vice versa, thus creating waves in the cochlear fluid. The cochlea converses these waves into an electrical signal.

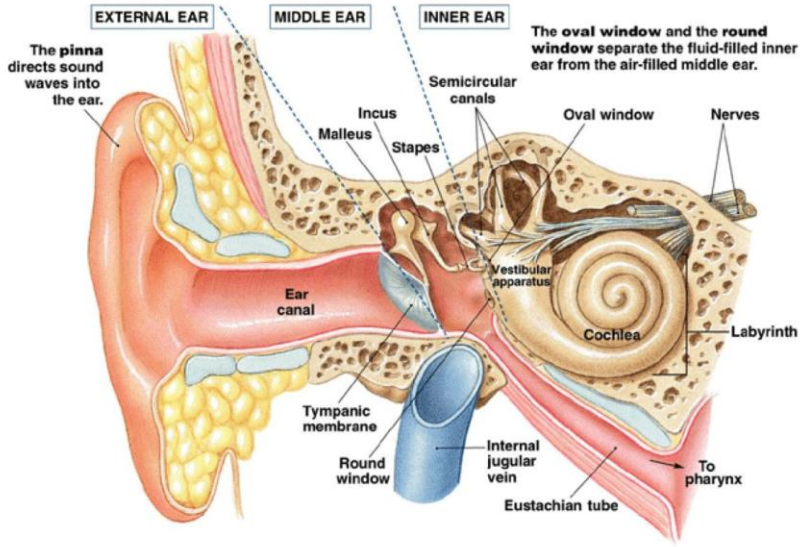

Figure 1: The anatomy of the ear (*Anatomy of ear* 2019).

The cochlea is a hollow bone chamber in the shape of a snail shell that consists of three canals separated by membrane: the tympanic canal (scala tympani), the vestibular canal (scala vestibuli) and the cochlear duct (scala media) (figure 2). These canals are filled with a watery liquid, the first two are filled with perilymph and the cochlear duct is filled with endolymph. The membrane between the scala vestibuli and scala media is so thin that the sound waves travel between them as if there is no membrane. In the middle lies the basilar membrane which is connected to the oval window. As the stapes moves the oval window, the oval window moves the basilar membrane, creating a wave to the end of the cochlea. The basilar membrane is made of fibres that are short and stiff at the oval window and long and limber at the end of the cochlea. This morphology gives the fibres a specific resonating frequency; high frequencies at the beginning (or base) of the cochlea and low frequencies at the end (the apex). On the entire surface of the basilar membrane lies the organ of Corti, which contains thousands of hair cells that respond to movement of the membrane. The hair cells transform the motion of the fluid into an electrical impulse that is carried along the cochlear nerve to the brain. In the cerebral cortex this signal is interpreted. The position of the activated hair cells determines the frequency and the amount of simulated hair cells determines the loudness of the perceived sound ("How Hearing Works", 2019; Pujol, 2019).

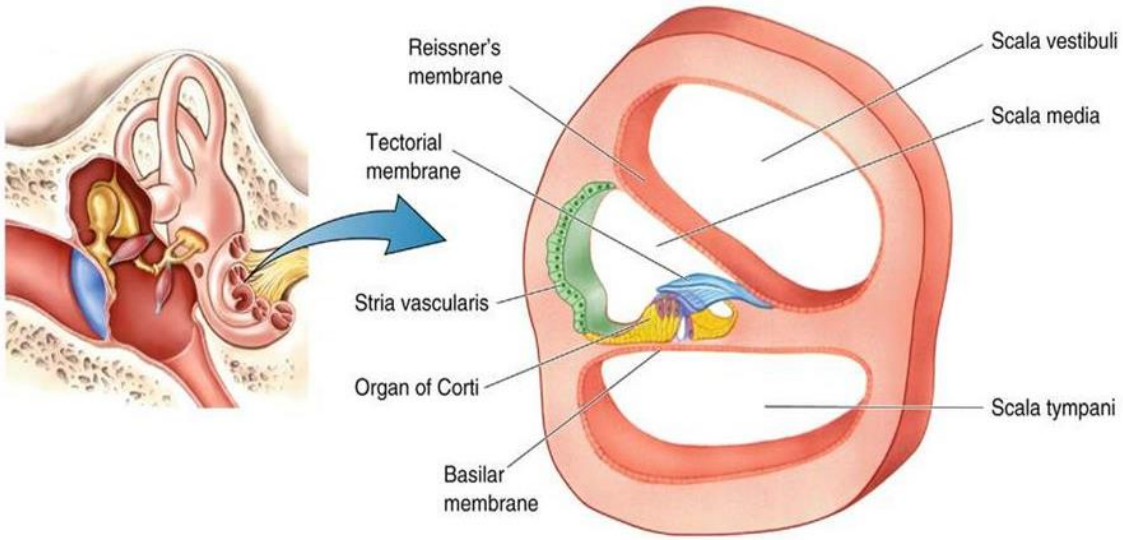

Figure 2: Anatomy of the cochlea, cross section (Anatomy of the cochlea, 2019).

2.2. Hearing loss and implants

The types of hearing loss fall into three categories based on the part of the ear where the hearing loss occurs: conductive hearing loss, sensorineural hearing loss (SNHL) and mixed hearing loss (Elzouki, 2012). Sometimes a fourth category is named: neural hearing loss ("Types of Hearing Loss", 2019).

Conductive hearing loss occurs in the outer or middle ear when the sound is mechanically disrupted and doesn't reach the cochlea. This can happen because of an infection or a blocked ear channel and usually medication or treatment can solve this. Alternatively a bone conduction hearing device can be used to functionally replace the outer and middle ear. When the ossicles dysfunction (for instance because of impaired mobility) this also causes conductive hearing loss. A solution could be an ossicular replacement prosthesis (ORP) which takes over the function of these bones (Beutner & Hüttenbrink, 2009).

SNHL occurs in the inner ear, when the hair cells do not transmit neural impulses normally from the cochlea to the brain. This can sometimes be solved with a conventional hearing aid that amplifies the acoustic signal. Another way to solve this is with a cochlear

implant (CI). When only the hair cells at the beginning of the cochlea are damaged, only low frequencies are heard and the high frequencies are lost. In this case an electric acoustic stimulation (EAS) implant can be used. This is an implant that uses a conventional hearing aid for low frequencies and a CI for high frequencies ("Electric Acoustic Stimulation", 2019). The CI will be discussed in more detail in the next paragraph.

Mixed hearing loss occurs in both the middle and inner ear and involves both conductive hearing loss and SNHL. Sometimes a middle ear implant (MEI) is used, which amplifies the sound waves with a vibrator which is either connected to the ossicles or placed close to the oval window (Beutner & Hüttenbrink, 2009).

Neural hearing loss occurs when the auditory nerve from the cochlea to the brain is functionally or mechanically cut. No sound signal reaches the brain and the patient is completely deaf. In this case the only option is an auditory brainstem implant (ABI) which is an implant that completely bypasses the entire ear and directly stimulates the brain (Shannon, 2011).

3. Cochlear implants: mechanism, benefits and constraints

3.1. The mechanism of a CI

The very first CI was invented in 1957 and used single channel simulation (Svirsky, 2017), which was of limited usefulness because single channel CI's have been found to not adequately convey speech information (Clark, 2009). The modern-day multi-channel CI that is currently mostly in use was independently developed twice and first implanted in 1977 and 1978 (Mudry & Mills, 2013).

A CI consists of several components (see figure 3) that collect, process and deliver auditory information. First the acoustic signal is picked up by a microphone inside the sound processor. The microphone is usually placed in such a way that it can pick up on the sounds in front of the person. In the sound processor the sound is filtered into multiple channels (see figure 4). These channels determine which electrode to stimulate. The envelopes of the bandpass filter outputs are extracted and compressed. Hereafter the corresponding output voltages that determine threshold and loudness for each electrode (also known as "map"), are added to the signal. Then the transmitter sends it wirelessly to the subcutaneous receiver that decodes the signal and sends it in the form of a pulse train to the implanted electrode array in the scala tympani (Greenberg, Ainsworth, Fay & Clark, 2011).

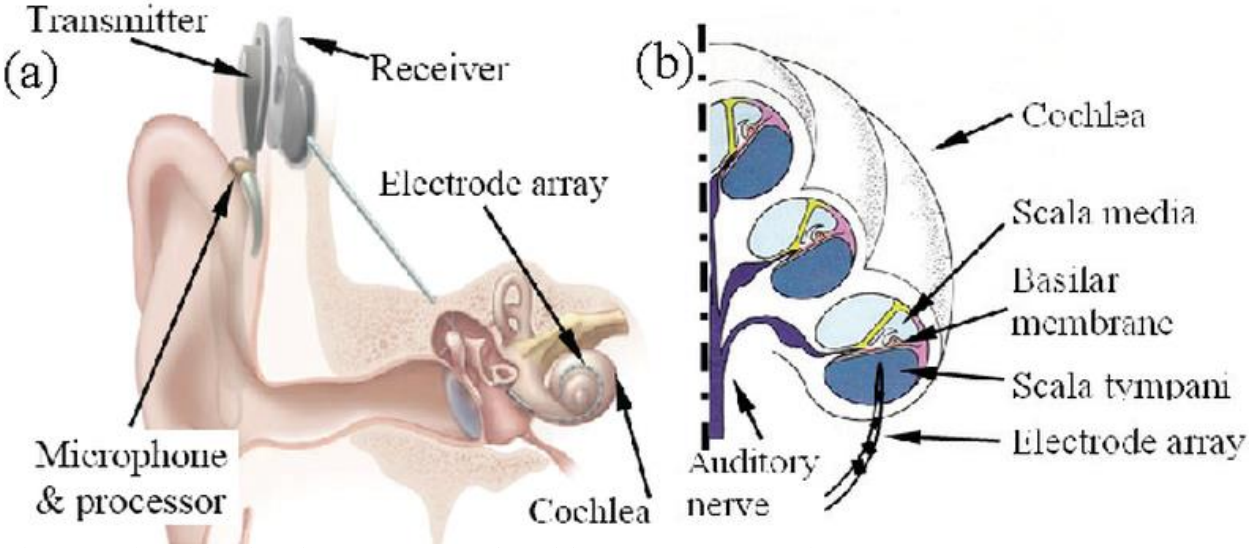

Figure 3: (Cochlea implant system and cochlea anatomy, 2009)

A single-channel implant uses only one electrode and a multi-channel CI uses an electrode array that stimulates different auditory nerve fibres on different places in the cochlea. This multi-channel CI uses the morphology of the cochlea and stimulates electrodes near the base of the cochlea with high frequencies and electrodes at the apex with low frequencies (Loizou, 1998). In normal hearing (NH) the cochlea could be stimulated anywhere but with CIs this is limited to parts where electrodes are placed. It has been theorized that more electrodes lead to more diverse frequency detection and therefore provide better perception of music and speech (Shannon, Fu & Galvin Iii, 2004; Srinivasan, Padilla, Shannon & Landsberger, 2013). However, nowadays only 12 to 22 electrodes are used in CI's (Padilla, Stupak & Landsberger, 2017). When more electrodes are used they start to over stimulate the nerve due to a process called current spread. Conductivity of the fluid in the cochlea is so high that the current of one electrode will spread through the fluid and simulate multiple nerves. When too many electrodes are placed the individual impulses will no longer be detectable and the brain will perceive one big impulse instead several small ones (Padilla, Stupak & Landsberger, 2017).

3.2. The benefits of a CI

The main benefit of a CI is that it provides individuals suffering from severe to profound hearing loss with enough information for speech perception (e.g. Wilson et al., 1991; Clark, 2008). When used bilaterally it also allows its users to localise speech, and to separate noise from speech when their sources are spatially separated (Dorman, Yost, Wilson & Gifford, 2011). CIs are also suited for children who are born deaf and have never developed any linguistic abilities (O'Donoghue, Nikolopoulos & Archbold, 2000). CIs do not provide NH but they have been programmed to provide the user with enough acoustic information for speech intelligibility. Previous studies have shown that CIs combined with lip-reading can teach deaf children to understand conventional speech after some years (e.g. Uziel et al., 1996; Yang & Xu, 2017). All these factors are important for communication and are therefore a significant part of someone's quality of life (QoL).

Another important part of life is the ability to listen to and enjoy music. A study conducted by Looi et al. (2007) compared to the enjoyment of music between regular hearing aid (HA) users and CI users. They found low music appreciation for both groups, but significantly higher music enjoyment for CI users compared to HA users.

3.3. Technological constraints of a CI

CIs have primarily been developed and optimised to encode acoustic cues relevant for speech perception. Music exceeds the acoustic properties of speech in terms of dynamic range and timbral, temporal and spectral complexity (Limb & Roy, 2014). In CIs most signal degradation takes place when the acoustic signal is converted into the electric pulse train that is sent to the electrode array (see figure 4). This process is a main contributor to the music perception deficits (Donnelly, Guo & Limb, 2009; Brockmeier et al., 2011; Ping, Yuan & Feng, 2012) as satisfying music perception relies heavily on accurate pitch perception. Harmonic and melodic relationships in music are based on pitch (Limb & Roy, 2014), but in pitch perception with a CI rate-pitch (temporal cues) and place-pitch (spatial cues) mechanisms are flawed.

In NH rate-pitch information is provided by the auditory nerve that is synchronised to fire at characteristic sound wave cycles (Johnson, 1980). Above 5000 Hz phase locking to auditory input is no longer possible and therefore the natural process occurs below this frequency. Theoretically the same effect could be mimicked by a CI, but in practice CI users demonstrated rate pitch saturation around 300 Hz (Zeng, 2002). Music perception relies on listening to temporal fine cues rather than envelope information (Smith, Delgutte & Oxenham, 2002). In current CIs this fine information is lost so recently several ways to improve on this aspect have been developed (Hochmair et al., 2006; Throckmorton, Selin Kucukoglu, Remus &

Collins, 2006). These new approaches might be very helpful for the perception of music for CI users.

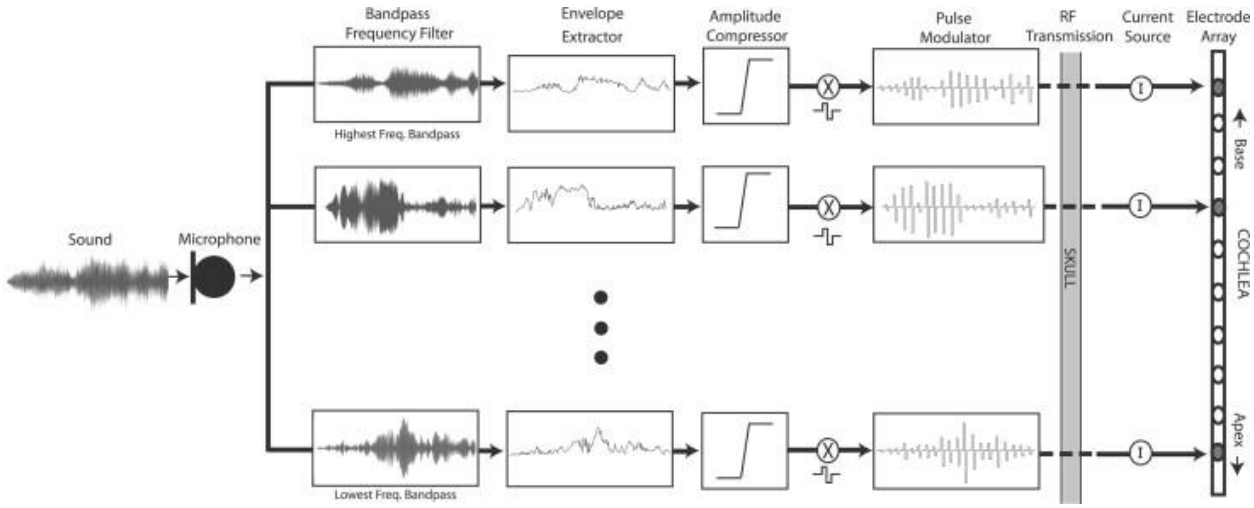

Figure 4: schematic overview of sound processing by multichannel CI (Limb & Roy, 2014).

Place-pitch degradation is partially explained by the fact that the electrodes on the array (maximum 22) have to convey the auditory information that would be conveyed by 3500 inner hair cells in NH. Another factor that contributes to this degradation is a bandpass filter that transmits a specific frequency range to emphasize speech cues (Limb & Roy, 2014). High and low frequencies are removed from the acoustic signal which negatively impacts music perception for CI users as music uses a wider frequency range than the range of speech (Roy, Jiradejvong, Carver & Limb, 2012).

Some new techniques aim to improve frequency resolution by increasing the number of channels without increasing the number of physical electrodes. In order to achieve this they use a technique called “inter-electrode” simulation. They simulate two adjacent electrodes and use the conductivity of the cochlear fluid to deliver a current to the region between them. There is however still a limitation to the maximum number of possible channels (Landsberger & Srinivasan, 2009). The number of channels available relates directly to the conveyance of spectral information and therefore music perception. This limitation means that CI users are still impaired in their music awareness (Crew & Galvin, 2012).

4. Music importance and music therapy

4.1. The importance of music

Music has social and cultural significance, is a form of entertainment and has influence on a person’s psychological well-being (Lee, Chan & Mok, 2010). Listening to music can relieve tension, control moods, alleviate feelings of loneliness and help a person develop self-awareness (Gantz, Gartenberg, Pearson & Schiller, 1978; North, Hargreaves & O'Neill, 2000; Lonsdale & North, 2011).

As mentioned before CIs score higher on music appreciation than regular HAs but the perception of music with CIs is still poor when compared to NH. A study conducted by Mirza et al. (2003) found that 46% of adult CI-users listened to music after implantation and that their enjoyment of music went from 8.7/10 before deafness to 2.6/10 after implantation. This is unfortunate considering that CI users themselves indicate that music is an important part of their social life and well-being (Gfeller et al., 2000). Therefore it is relevant to improve the

perception of music for CI users in order to increase their QoL and enhance their participation in society (Gfeller, Driscoll & Looi, 2012).

Music as a phenomenon is difficult to define but its importance it has been well documented. Generally it can be said that music is sound that uses pitch, timbre and rhythm to convey emotional information.

4.2. The difficulty of music perception for CI users

Previous studies have shown that CIs provide sufficient acoustic information for the perception of rhythm; CI-users show similar accuracy of recognition of rhythmic features in music when compared to NH peers (e.g. Gfeller & Lansing, 1991; Vongpaisal, Trehub, & Schellenberg, 2006).

Timbre is the aspect of sound that allows listeners to differentiate between two different instruments when the same note is played at the same volume (Gfeller, Driscoll & Looi, 2012). The recognition of timbre relies partly on the perception of pitch and fundamental frequency.

Previous studies have shown that CI users score significantly lower on pitch-related listening tasks such as: pitch discrimination, ranking (identifying which note is higher), recognition of a pitch or melody and the production of pitch (Galvin, Fu & Nogaki, 2007; Sucher & McDermott, 2007; Hsiao, 2008; Nakata, Trehub, Mitani & Kanda, 2006). One of the most challenging pitch-related tasks for CI recipients is tuning, either in the form of singing along to an external tune or as the tuning of a musical instrument (Xu et al., 2009). There is big variation between different CI users and their pitch detection skills. Some implanted children have the ability to detect a semitone (the interval between two adjacent notes on a piano) while others only detect interval changes when they are as big as 3-8 semitones (Gfeller et al., 2007). Despite these big differences, generally it can be said that music perception with a CI is significantly more difficult than with NH.

4.3. Music training to enhance music perception

Although technical improvements are made on CIs in order to enhance pitch perception, there are limitations to this (see section 2.3.) which asks for other ways to improve pitch perception for CI recipients. An electroencephalographic study by Koelsch et al. (2004) found that the neural correlates necessary for music processing are present in individuals with a CI. Other studies found magnetoencephalographic evidence of auditory plasticity in individuals suffering from sudden deafness (Po-Hung Li et al., 2003; Li et al., 2006), which allows for the optimization of neural pathways to auditory input after implantation (Pantev, Dinnesen, Ross, Wollbrink & Knief, 2005). This suggests that exposure to sound (for instance by music training) might induce plastic changes in the central auditory pathway that allow for enhanced music processing (Pantev et al., 1998). In NH populations a positive correlation was found between former musical training and pitch detection abilities (Sucher & McDermott, 2007). However the amount of studies that research the effect of music training on music perception is limited. This is probably due to the fact that long-term multi-session training comes with a lot of logistical challenges. Also the training provided needs to take a lot of parameters into account such as motivational factors and individual hearing level of the participants (Gfeller 2016).

In table 1 four studies are summarized that overcame these difficulties. The selection was made in such a way that each of the chosen studies tested a different age group of CI users. All studies used a form of musical training and investigated its effect on various listening tasks. Only one of the studies (C) asked about the perceived quality of the music. In this study the assumption is made that enhanced music perception will lead to enhanced music enjoyment for CI users.

	A) Chen et al. (2010)	B) Innes-Browns et al. (2013)	C) Looi et al. (2015)	D) Petersen et al. (2012)
Number of participants	27	19	10	18
Mean age in years (range)	6.7 (5-14)	10.6 (9-13)	25 (13-47)	58.6 (45—73)
Comparison groups?	Yes.	Yes, 6 CI users, 5 HA users and 9 NH.	Yes, group 2 received same amount of music exposure as group 1, but without training.	Yes, both control group and NH control group.
Hearing loss	Prelingual HL.	Prelingual.	Prelingual and postlingual HL.	5 prelingual HL, 13 postlingual HL.
CI experience	Range 10-69 months of CI use.	Received implants aged 10-16 months.	At least 6 months.	At least 6 months.
Type of implant	Unilateral.	Unilateral (CI) and bilateral (HA).	Unilateral and bilateral.	Unilateral.
Hearing aids (HA)	None.	Participants with HA were allowed to use this normally.	Some, but turned off during training and testing.	Some participants used HA in the non-implanted ear which was turned off during testing.
Previous musical experience?	2 subjects had previous music education.	All children had music lessons in school, 13 had additional lessons (CI: 4, HA: 3 NH: 4).	Occasional lessons to no previous lessons at all.	No form of musical education beyond secondary school.
Form of musical training	YAMAHA music instruction (score reading, listening, singing, playing instruments	Music Club: 45 min of musical training centred around play using Orff and Kodaly pedagogy (listening exercises with solo instruments, vocal play, aural, kinesthetic play).	Group 1: Music Appreciation Training Program (MATP) on a computer. Group 2: Focussed Music Listening (FML)	Musical ear training (listening, playing, singing, drumming and energizing) in order to improve pitch, timbre and rhythm perception.
Duration of musical training	2-36 months (mean 13.2 months).	45 min, weekly class during 24 weeks.	8 weeks, 4x30min per week.	6 months, 1h per week solo music lessons and home computer-based practice.
Variables tested for	Pitch ranking abilities (same, higher, lower) from prime to 11 semitones, ascending and descending.	Discrimination of pitch patterns and rhythm patterns, timbre recognition, observation of enjoyment by teacher.	Pitch ranking, instrument and ensemble ID, music style ID, perceived quality of music, speech-in-noise perception and music quality ratings (2 categories).	(1) musical instrument identification (MII), (2) melodic contour identification (MCI), (3) pitch ranking (PR), (4) rhythmic discrimination (RD), and (5) melodic discrimination (MD).
Results	A positive correlation between duration of musical training and pitch ranking abilities (% of correctness). Pitch interval size had no significant effect on pitch perception.	After a first test baseline test, posttests were conducted. CI users significantly less accurate at pitch discrimination and timbre recognition compared to HA and NH. No significant difference for rhythm discrimination was found. There was no significant improvement after training. Teachers observed enhanced interest and engagement in music.	Pre- and posttraining scores were compared. No significant improvement on pitch ranking. Group 1 had significant improvement on instrument ID. No significant changes for ensemble or style ID. No significant improvement for speech-in-noise perception was found. Group 1 had a significant improvement of music quality in one of the categories, but not in the other.	General: significant improvement of music perception after musical training. (1) highest effect of musical training on results, average end score comparable to NH (2) significant improvement after training but not as good as NH (3) a trend to higher gain when compared to control but not when compared to NH (4) significant improvement after training also compared to control group (5) no significant improvement.

Table 1: Overview of 4 studies that researched the effect of music training on music perception.

4.3.1. Demographics

As stated before, these studies were selected in such a way that four different age-groups of CI users are represented. The two youngest groups (study A and B) only consisted of prelingually deaf participants, which means that these participants all learned to listen with a CI and often don't have a way to compare it to NH. Group C and D are more mixed and some participants first developed NH and later learned to use a CI. It is important to keep in mind that music perception is influenced by behavioural, cognitive and social maturation. Therefore the differences in age might have influenced of the effect of music training (Gfeller, Driscoll, Kenworthy & Voorst Van, 2011).

All studies have a relatively small sample size, especially the studies that used controls or HA participants. This can make it more difficult to find a significant effect.

4.3.2. Previous music experience

There are big differences between the compared studies, but within the individual studies the groups are quite homogeneous. Three of the studies (B, C and D) used a baseline at the beginning of the experiment and compared the final results to that. The effect of any previous music experience is thus not measured. Study A measured the correlation between duration of musical training and improved pitch perception as some participants stayed longer in the program than others and thus received more music training.

4.3.3. Types of music training provided

Study A, B and D used rather conventional modes of music training. Study A and B relied on specific music pedagogical approaches that were developed for school children. Study D provided one-on-one music training from a professional music teacher. These three groups let the participants perform passive (listening and reading) and active (singing, playing, drumming) music tasks to enhance their perception. A downside to these approaches is that strict parameters of music training might be difficult to control as they are pedagogy-based and will often focus more on the participant's need than on strict research parameters.

Study C used MATP, a computer-based auditory training program, first developed in 2012 and adapted specifically for this study. The program is specifically developed to enhance music appreciation, instead of perception. Another way this study differed from the rest is that it is the only study that provided training without any teacher present. They also didn't ask the participants to produce music. Instead they were asked to identify pitch, timbre and music style. The training consisted of 3 phases: 1) teaching phase, 2) training phase and 3) a self-testing phase.

4.3.4. Results

The influence of music training on sound perception was not always found to be significant. Study A and D both found significant improvement after training (although D not for all tested categories). These studies both offered a training approach that asks for active involvement of the participants. Study B also did this, but used less music-producing activities; A and D asked for singing and playing an instrument, B asked for vocal play (i.e. "make a siren sound with your voice"). Study C found significant improvement only for instrument identification and one category of self-reported music appreciation.

5. Discussion

It is almost impossible to directly compare these four very different studies, but they do provide an insight in the effect of music training on music perception.

Firstly, this overview shows that music training can enhance pitch perception at the age of 6 but also at the age of 58 years. However, study D found that age had a significant negative

relationship with music gain. This implies that older participants had a smaller improvement of their general music discrimination skills than younger participants. These findings seem to indicate that music training can be beneficial for participants of every age, but that the benefits are larger for younger participants.

All reviewed studies used a different training method and had different results. This might indicate that the type of music training provided influences which skills are trained. Study A and D provided their participants with more traditional music training (i.e. singing and playing) which seemed to enhance pitch and music perception. Study B used a method based on Kodaly and Orff which are music methodologies developed for children. However they found no significant improvement of listening skills after 24 weeks of training. This can be explained by the sample size of the study; they only had 6 CI participants, which makes it very difficult to establish a significant result. It can also be that the type of music training provided (vocal play, movement) was too abstract to directly relate to music perception. Lastly, the participants received the music training in the lunchbreak of school. Some of the participants indicated that they found this challenging because they spent the whole day listening intently and then had to do so again in their break. Despite this, the teachers noticed that the participants enjoyed themselves a lot during the lessons and only one NH participant dropped out of the study (not included in table 1).

Study C used a very new form of musical training which was also the most passive form of training out of the four compared studies. This study is the only one that did not ask for any kind of production of sound during training. They found a significant improvement of music instrument identification which relies on timbre recognition. This could mean that listening tasks are sufficient to train perception of timbre, but as this method is in an early stage of use, we recommend that more research is done before any conclusions are drawn.

6. Conclusion

Music perception is more difficult for CI users because CIs mechanics have been developed to provide acoustic cues relevant for human speech and music exceeds these acoustic properties (Roy, Jiradejvong, Carver & Limb, 2012, Limb & Roy, 2014). This leads to limited spectral and temporal resolution which makes pitch and timbre perception especially difficult for CI users. Because of this degraded auditory signal postlingual CI recipients report lowered music enjoyment than before implantation (Mirza et al., 2013). Although technical improvements of the CI are being developed to improve frequency resolution, the signal provided by a CI will probably always have limitations due to a maximum number of possible channels (Landsberger & Srinivasan, 2009) which directly relates to spectral information available and so also music perception (Crew & Galvin, 2012).

Music training might be a solution to enhance music perception. The four studies that were reviewed showed various results. It has to be noted that all studies used different methods to test perception skills and as such cannot be directly compared. However, there seems to be an overall positive effect of music training on music perception, enjoyment and engagement. It is not yet clear what type of music therapy is most beneficial for which type of listening skills. Nor do we know the precise effect of chronological age, age of implantation and amount of musical training on music perception. We recommend that more research is done in order to clarify this.

7. Acknowledgements

I'd like to thank my supervisors: prof. dr. Deniz Baskent, dr. Marije aan het Rot and prof. dr. ir. G.J. (Bart) Verkerke. I also want to thank my family for again proofreading my writing.

Bibliography

Anatomy of the cochlea. (2019). [Image]. Retrieved from http://slideplayer.com/slide/10629032/36/images/11/The+Inner+Ear+Anatomy+of+the+Cochlea+Psychology+355.jpg

Anatomy of ear. (2019). [Image]. Retrieved from https://i.pinimg.com/originals/b8/4e/81/b84e81ff7858c12a577cdf41574b5cd9.jpg

Beutner, D., & Hüttenbrink, K. (2009). Passive and active middle ear implants. *GMS Curr Top Otorhinolaryngol Head Neck Surgery*, *8*. doi: 10.3205/cto000061

Brockmeier, S., Fitzgerald, D., Searle, O., Fitzgerald, H., Grasmeder, M., & Hilbig, S. et al. (2011). The MuSIC perception test: A novel battery for testing music perception of cochlear implant users. *Cochlear Implants International*, *12*(1), 10-20. doi: 10.1179/146701010x12677899497236

Chen, J., Chuang, A., McMahon, C., Hsieh, J., Tung, T., & Li, L. (2010). Music Training Improves Pitch Perception in Prelingually Deafened Children With Cochlear Implants. *PEDIATRICS*, *125*(4), e793-e800. doi: 10.1542/peds.2008-3620

Clark, G. (2008). Personal reflections on the multichannel cochlear implant and a view of the future. *The Journal Of Rehabilitation Research And Development*, *45*(5), 651-694. doi: 10.1682/jrrd.2007.05.0064

Clark, G. (2009). The multi-channel cochlear implant: past, present and future perspectives. *Cochlear Implants International*, *10*.

Cochlea implant system and cochlea anatomy. (2009). [Image]. Retrieved from https://www.semanticscholar.org/paper/Model-and-parameter-identification-of-friction-of-Zhang-Bhattacharyya/0e1457f3384573d6c180dec38d6e0f8401b20855#extracted

Crew, J., & Galvin, J. (2012). Channel interaction limits melodic pitch perception in simulated cochlear implants. *The Journal Of The Acoustical Society Of America*, *132*(5), EL429-EL435. doi: 10.1121/1.4758770

Croghan, N., Duran, S., & Smith, Z. (2017). Re-examining the relationship between number of cochlear implant channels and maximal speech intelligibility. *The Journal Of The Acoustical Society Of America*, 142(6), EL537-EL543. doi: 10.1121/1.5016044

Donnelly, P., Guo, B., & Limb, C. (2009). Perceptual fusion of polyphonic pitch in cochlear implant users. *The Journal Of The Acoustical Society Of America*, *126*(5), EL128-EL133. doi: 10.1121/1.3239464

Dorman, M., Yost, W., Wilson, B., & Gifford, R. (2011). Speech Perception and Sound Localization by Adults with Bilateral Cochlear Implants. *Seminars In Hearing*, *32*(02), 212-214. doi: 10.1055/s-0031-1278417

Electric Acoustic Stimulation. (2019). Retrieved from https://www.medel.com/en-gb/hearing-solutions/electric-acoustic-stimulation

Elzouki, A. (2012). *Textbook of clinical pediatrics*. [Berlin]: Springer.

Friesen, L., Shannon, R., Baskent, D., & Wang, X. (2001). Speech recognition in noise as a function of the number of spectral channels: Comparison of acoustic hearing and cochlear implants. *The Journal Of The Acoustical Society Of America*, 110(2), 1150-1163. doi: 10.1121/1.1381538

Galvin, J., Fu, Q., & Nogaki, G. (2007). Melodic Contour Identification by Cochlear Implant Listeners. *Ear And Hearing*, *28*(3), 302-319. doi: 10.1097/01.aud.0000261689.35445.20

Gantz, W., Gartenberg, H., Pearson, M., & Schiller, S. (1978). "Gratifications and expectations associated with Pop music among adolescents". *Popular Music And Society*, *6*(1), 81-89. doi: 10.1080/03007767808591113

Gfeller, K., & Lansing, C. (1991). Melodic, Rhythmic, and Timbral Perception of Adult Cochlear Implant Users. *Journal Of Speech, Language, And Hearing Research*, *34*(4), 916-920. doi: 10.1044/jshr.3404.916

Gfeller, K., Christ, A., Knutson, J., Witt, S., Murray, K., & Tyler, R. (2000). Musical backgrounds, listening habits, and aesthetic enjoyment of adult cochlear implant recipients. *Journal Of The American Academy Of Audiology*, *11*(7).
Gfeller K, Witt S, Adamek M, et al. (2002) Effects of training on timbre recognition and appraisal by postlingually deafened cochlear implant recipients. *J Am Acad Audiol*, 13(3):132–145
Gfeller, K., Turner, C., Oleson, J., Zhang, X., Gantz, B., Froman, R., & Olszewski, C. (2007). Accuracy of Cochlear Implant Recipients on Pitch Perception, Melody Recognition, and Speech Reception in Noise. *Ear And Hearing*, *28*(3), 412-423. doi: 10.1097/aud.0b013e3180479318
Gfeller, K., Driscoll, V., Kenworthy, M., & Voorst Van, T. (2011). Music Therapy for Preschool Cochlear Implant Recipients. *Music Therapy Perspectives*, *29*(1), 39-49. doi: 10.1093/mtp/29.1.39
Gfeller, K., Driscoll, V., & Looi, V. (2012). Music Appreciation and Training for Cochlear Implant Recipients: A Review. *Seminars In Hearing*, *33*(04), 307-334. doi: 10.1055/s-0032-1329222
Gfeller, K. (2016). Music-based training for pediatric CI recipients: A systematic analysis of published studies. *European Annals Of Otorhinolaryngology, Head And Neck Diseases*, *133*, S50-S56. doi: 10.1016/j.anorl.2016.01.010
Greenberg, S., Ainsworth, W., Fay, R., & Clark, G. (2011). *Speech processing in the auditory system* (Chapter 8: Cochlear Implants). New York: Springer.
Hays, T., & Minichiello, V. (2005). The contribution of music to quality of life in older people: an Australian qualitative study. *Ageing And Society*, *25*(2), 261-278. doi: 10.1017/s0144686x04002946
Hill, R., Wyse, G., & Anderson, M. (2018). *Animal physiology*. NY: Oxford University Press.
Hochmair, I., Nopp, P., Jolly, C., Schmidt, M., Schößer, H., Garnham, C., & Anderson, I. (2006). MED-EL Cochlear Implants: State of the Art and a Glimpse Into the Future. *Trends In Amplification*, *10*(4), 201-219. doi: 10.1177/1084713806296720
How Hearing Works. (2019). Retrieved from https://health.howstuffworks.com/mental-health/human-nature/perception/hearing5.htm
Hsiao, F. (2008). Mandarin Melody Recognition by Pediatric Cochlear Implant Recipients. *Journal Of Music Therapy*, *45*(4), 390-404. doi: 10.1093/jmt/45.4.390
Innes-Brown, H., Marozeau, J., Storey, C., & Blamey, P. (2013). Tone, Rhythm, and Timbre Perception in School-Age Children Using Cochlear Implants and Hearing Aids. *Journal Of The American Academy Of Audiology*, *24*(9), 789-806. doi: 10.3766/jaaa.24.9.4
Johnson, D. (1980). The relationship between spike rate and synchrony in responses of auditory-nerve fibers to single tones. *The Journal Of The Acoustical Society Of America*, *68*(4), 1115-1122. doi: 10.1121/1.384982
Koelsch, S., Wittfoth, M., Wolf, A., Müller, J., & Hahne, A. (2004). Music perception in cochlear implant users: an event-related potential study. *Clinical Neurophysiology*, *115*(4), 966-972. doi: 10.1016/j.clinph.2003.11.032
Landsberger, D., & Srinivasan, A. (2009). Virtual channel discrimination is improved by current focusing in cochlear implant recipients. *Hearing Research*, *254*(1-2), 34-41. doi: 10.1016/j.heares.2009.04.007
Lee, Y., Chan, M., & Mok, E. (2010). Effectiveness of music intervention on the quality of life of older people. *Journal Of Advanced Nursing*, *66*(12), 2677-2687. doi: 10.1111/j.1365-2648.2010.05445.x
Li, L., Shiao, A., Chen, L., Niddam, D., Chang, S., & Lien, C. et al. (2006). Healthy-side dominance of middle- and long-latency neuromagnetic fields in idiopathic sudden sensorineural hearing loss. *European Journal Of Neuroscience*, *24*(3), 937-946. doi: 10.1111/j.1460-9568.2006.04961.x

Limb, C., & Roy, A. (2014). Technological, biological, and acoustical constraints to music perception in cochlear implant users. *Hearing Research*, *308*, 13-26. doi: 10.1016/j.heares.2013.04.009
Loizou, P. (1998). Mimicking the human ear. *IEEE Signal Processing Magazine*, *15*(5), 101-130. doi: 10.1109/79.708543
Lonsdale, A., & North, A. (2011). Why do we listen to music? A uses and gratifications analysis. *British Journal Of Psychology*, *102*(1), 108-134. doi: 10.1348/000712610x506831
Looi, V., McDermott, H., McKay, C., & Hickson, L. (2007). Comparisons of Quality Ratings for Music by Cochlear Implant and Hearing Aid Users. *Ear And Hearing*, *28*(Supplement), 59S-61S. doi: 10.1097/aud.0b013e31803150cb
Mirza, S., Douglas, S., Lindsey, P., Hildreth, T., & Hawthorne, M. (2003). Appreciation of music in adult patients with cochlear implants: a patient questionnaire. *Cochlear Implants International*, *4*(2), 85-95. doi: 10.1002/cii.68
Mudry, A., & Mills, M. (2013). The Early History of the Cochlear Implant. *JAMA Otolaryngology–Head & Neck Surgery*, *139*(5), 446. doi: 10.1001/jamaoto.2013.293
Nakata, T., Trehub, S., Mitani, C., & Kanda, Y. (2006). Pitch and Timing in the Songs of Deaf Children With Cochlear Implants. *Music Perception*, *24*(2), 147-154. doi: 10.1525/mp.2006.24.2.147
North, A., Hargreaves, D., & O'Neill, S. (2000). The importance of music to adolescents. *British Journal Of Educational Psychology*, *70*(2), 255-272. doi: 10.1348/000709900158083
O'Donoghue, G., Nikolopoulos, T., & Archbold, S. (2000). Determinants of speech perception in children after cochlear implantation. *The Lancet*, *356*(9228), 466-468. doi: 10.1016/s0140-6736(00)02555-1
Padilla, M., Stupak, N., & Landsberger, D. (2017). Pitch ranking with different virtual channel configurations in electrical hearing. *Hearing Research*, *348*, 54-62. doi: 10.1016/j.heares.2017.02.013
Pantev, C., Dinnesen, A., Ross, B., Wollbrink, A., & Knief, A. (2005). Dynamics of Auditory Plasticity after Cochlear Implantation: A Longitudinal Study. *Cerebral Cortex*, *16*(1), 31-36. doi: 10.1093/cercor/bhi081
Pantev, C., Oostenveld, R., Engelien, A., Ross, B., Roberts, L., & Hoke, M. (1998). Increased auditory cortical representation in musicians. *Nature*, *392*(6678), 811-814. doi: 10.1038/33918
Petersen, B., Mortensen, M., Hansen, M., & Vuust, P. (2012). Singing in the key of life: A study on effects of musical ear training after cochlear implantation. *Psychomusicology: Music, Mind, And Brain*, *22*(2), 134-151. doi: 10.1037/a0031140
Ping, L., Yuan, M., & Feng, H. (2012). Musical Pitch Discrimination by Cochlear Implant Users. *Annals Of Otology, Rhinology & Laryngology*, *121*(5), 328-336. doi: 10.1177/000348941212100508
Po-Hung Li, L., Shiao, A., Lin, Y., Chen, L., Niddam, D., & Chang, S. et al. (2003). Healthy-side dominance of cortical neuromagnetic responses in sudden hearing loss. *Annals Of Neurology*, *53*(6), 810-815. doi: 10.1002/ana.10599
Roy, A., Jiradejvong, P., Carver, C., & Limb, C. (2012). Assessment of Sound Quality Perception in Cochlear Implant Users During Music Listening. *Otology & Neurotology*, *33*(3), 319-327. doi: 10.1097/mao.0b013e31824296a9
Shannon, R., Fu, Q., & Galvin Iii, J. (2004). The number of spectral channels required for speech recognition depends on the difficulty of the listening situation. *Acta Oto-Laryngologica*, *124*(0), 50-54. doi: 10.1080/03655230410017562
Shannon, R. (2011). Auditory Brainstem Implants. *ASHA Leader*, *16*(3), 17. doi: 10.1044/leader.ftr3sb3.16032011.17
Smith, Z., Delgutte, B., & Oxenham, A. (2002). Chimaeric sounds reveal dichotomies in auditory perception. *Nature*, *416*(6876), 87-90. doi: 10.1038/416087a

Srinivasan, A., Padilla, M., Shannon, R., & Landsberger, D. (2013). Improving speech perception in noise with current focusing in cochlear implant users. *Hearing Research*, *299*, 29-36. doi: 10.1016/j.heares.2013.02.004
Sucher, C., & McDermott, H. (2007). Pitch ranking of complex tones by normally hearing subjects and cochlear implant users. *Hearing Research*, *230*(1-2), 80-87. doi: 10.1016/j.heares.2007.05.002
Svirsky, M. (2017). Cochlear implants and electronic hearing. *Physics Today*, *70*(8), 52-58. doi: 10.1063/pt.3.3661
Throckmorton, C., Selin Kucukoglu, M., Remus, J., & Collins, L. (2006). Acoustic model investigation of a multiple carrier frequency algorithm for encoding fine frequency structure: Implications for cochlear implants. *Hearing Research*, *218*(1-2), 30-42. doi: 10.1016/j.heares.2006.03.020
Types of Hearing Loss. (2019). Retrieved from https://www.medel.com/en-gb/about-hearing/types-of-hearing-loss
Pujol, R. (2019). Journey into the world of Hearing - specialists. Retrieved from http://www.cochlea.org/en/hearing
Uziel, A., Reuillard-Artieres, F., Sillon, M., Vieu, A., Mondain, M., Piron, J., & Tobey, E. (1996). Speech-perception performance in prelingually deafened French children using the nucleus multichannel cochlear implant. *The American Journal Of Otology*, *17*(4).
Vongpaisal T, Trehub SE, Schellenberg EG. Song recognition by children and adolescents with cochlear implants. Journal of Speech, Language, and Hearing Research. 2006;49:1091–1103.
Wilson, B., Finley, C., Lawson, D., Wolford, R., Eddington, D., & Rabinowitz, W. (1991). Better speech recognition with cochlear implants. *Nature*, *352*(6332), 236-238. doi: 10.1038/352236a0
Xu, L., Zhou, N., Chen, X., Li, Y., Schultz, H., Zhao, X., & Han, D. (2009). Vocal singing by prelingually-deafened children with cochlear implants. *Hearing Research*, *255*(1-2), 129-134. doi: 10.1016/j.heares.2009.06.011
Yang, J., & Xu, L. (2017). Mandarin compound vowels produced by prelingually deafened children with cochlear implants. *International Journal Of Pediatric Otorhinolaryngology*, *97*, 143-149. doi: 10.1016/j.ijporl.2017.04.012
Zeng, F. (2002). Temporal pitch in electric hearing. *Hearing Research*, *174*(1-2), 101-106. doi: 10.1016/s0378-5955(02)00644-5