Hearing Research 380 (2019) 108–122

Contents lists available at ScienceDirect

Hearing Research

journal homepage: www.elsevier.com/locate/heares

Review Article

Why and how music can be used to rehabilitate and develop speech and language skills in hearing-impaired children

Ritva Torppa [a], Minna Huotilainen [a, b, *]

[a] Cognitive Brain Research Unit, Department of Psychology and Logopedics, Faculty of Medicine, University of Helsinki, Finland
[b] CICERO Learning Network, Faculty of Educational Sciences, P.O.Box 9, 00014, University of Helsinki, Helsinki, Finland

ARTICLE INFO

Article history:
Received 24 April 2018
Received in revised form
11 June 2019
Accepted 14 June 2019
Available online 25 June 2019

Keywords:
Cochlear implant
Hearing aid
Language
Speech
Music
Child
Brain

ABSTRACT

This paper presents evidence for a strong connection between the development of speech and language skills and musical activities of children and adolescents with hearing impairment and/or cochlear implants. This conclusion is partially based on findings for typically hearing children and adolescents, showing better speech and language skills in children and adolescents with musical training, and importantly, showing increases of speech and language skills in children and adolescents taking part in musical training. Further, studies of hearing-impaired children show connections between musical skills, involvement in musical hobbies, and speech and language skills. Even though the field is still lacking large-scale randomised controlled trials on the effects of musical interventions on the speech and language skills of children and adolescents with hearing impairments and cochlear implants, the current evidence seems enough to urge speech therapists, music therapists, music teachers, parents, and children and adolescents with hearing impairments and/or cochlear implants to start using music for enhancing speech and language skills. For this reason, we give our recommendations on how to use music for language skill enhancement in this group.

Contents

1. Introduction

Music has been an integral part of the everyday care of hearing-

* Corresponding author. Cognitive Brain Research Unit, Department of Psychology and Logopedics, Faculty of Medicine, University of Helsinki, Finland.
E-mail address: minna.huotilainen@helsinki.fi (M. Huotilainen).

https://doi.org/10.1016/j.heares.2019.06.003
0378-5955/

impaired children for centuries (in addition to speech therapy and other rehabilitation of speech and language skills). This review examines the scientific foundations of this: we review the reasons why music could and should be used for improving the speech and language skills of children with hearing impairments. In addition, we propose instructions and guidance for the use of music with children of different ages, varying backgrounds, mild to severe hearing impairments, with cochlear implants and/or hearing aids, for speech therapists, music therapists, music educators, parents, and other members of the child's community.

1.1. The tasks of the auditory system

The human auditory system performs an abundance of tasks. During human evolution, as hunter-gatherers, a key task of our auditory system was to serve as **a warning system** of potential danger, perhaps the sound of a predator. The warning system must be very accurate and efficient in detecting danger, while at the same time the system must allow the full use of our cognitive capabilities. A hunter-gatherer can be very heavily engaged in a visual task (for example, searching for and collecting berries in the forest), but also safe at the same time, since the auditory system pre-consciously monitors the safety of the environment (Posner, 1980). If any sound of a potential predator is heard, the auditory system calls for a switch of attention towards the sound (Näätänen, 1992). The possibility of placing trust in the auditory system has allowed humans to develop cognitive skills up to the present high level. This is a balancing act: if the warning system is too sensitive, cognitive activities are disturbed too easily and often by irrelevant sounds, and it is difficult to concentrate (Posner, 1980). On the other hand, if the warning system is not sensitive enough, there is a risk of danger when an important sound is unnoticed.

Another important task of the auditory system is **communication**. Like most mammals, humans use sounds and gestures in communicating with others. Researchers propose that some communicative gestures and sounds evolved into human languages, while others evolved into music and dance (Mithen et al., 2006). Both language and music place high requirements on the auditory system. It has been proposed that by studying the acoustic characteristics and features of all human languages and musical genres we can learn about the capabilities of the auditory system - or, put the other way around - the capacity of the human auditory system dictates the boundaries of expressive features in language and music (Patel, 2010). Language and music, even though constantly changing, would not evolve in directions that require the use of acoustic features that are too difficult to extract, detect, compare or remember for the average human auditory system.

Today, our auditory system still has these two key tasks: monitoring the environment for safety or sounds of interest, and communicating via language and music. Skills in these tasks are relevant for children with hearing impairment who are users of different types of implants and hearing aids.

1.2. Music can enhance auditory processing

Music has very specific acoustic characteristics. Melodies include fast progressions of notes typically chosen from consistent scales that typically include uneven steps. Chords are collections of simultaneously played notes that form harmonies. Musical timbres are characterised by their spectral peaks and their changes, fast friction and noise sounds, sound wave envelopes and several other characteristics, which are highly similar to those that characterise the important basic elements of speech.

Both speech and music are human universals, found in all human cultures (Besson et al., 2011; Patel, 2014). Both language and music consist of perceptually discrete elements that are organized into hierarchically structured, coherent sequences. This organisation of language and music is not random, but proceeds according to syntactic principles (Patel, 2003).

The similarities of the syntactic processing of language and music, as well as the similarities at the acoustic level, have given rise to models and proposals concerning the effects of music on speech perception and language capabilities (Patel, 2003, 2011, 2014). In addition to the similarities and the theoretical work, there is neural evidence that musical activities can affect language skills.

The first evidence for the effects of musical training on brain structure was provided by the seminal studies of Pantev, Elbert, and their coworkers (Elbert et al., 1995; Pantev et al., 1998), showing enlarged motor and somatosensory cortical areas in professional musicians. These effects were originally interpreted as being caused by brain plasticity due to musical practice. However, studies of adult musicians, ranging from observations of structural changes like enlarged and highly active auditory cortical areas and motor and somatosensory areas, and enhanced white matter tracts, even though showing interesting differences between musicians and non-musicians, fail to assess the causality of such differences. Theoretically it is possible that individuals with "musician-like" brain structures determined by genetic factors end up becoming musicians more often than others. As a result, studies of the effects of music have moved towards long-term follow-up studies and interventional paradigms.

Importantly, Hyde et al. (2009) found improvements in auditory skills and neural structures in 5-6-year-old children after musical training of 15 months. The structural neural changes were mainly in the temporal, frontal, and parieto-occipital cortical areas, i.e., the very same areas in which adult professional musicians show the largest and most consistent cortical enlargements. In addition, Dittinger et al. (2017) found that in a task of learning novel words, children with musical training were faster and had enhanced brain responses to learnt words. These findings highlight the connection between musical training and auditory attentional, language and learning functions in children.

Similarly, Putkinen et al. (2014a,b) studied a group of children starting musical hobbies at the age of 7 years and a comparable control group starting other hobbies, and found that brain responses related to sound perception, discrimination and attention allocation were initially very similar for the two groups, but two or more years later, the brain responses had increased in those children who started musical hobbies.

Moreno et al. (2011) used an intensive, 20-day intervention with randomised groups of 4-6-year-old children who played a computer game teaching either music or visual arts for 2 h per day. Only the musical training improved the verbal intelligence (vocabulary scores from the Wechsler Preschool and Primary Scale of Intelligence; Wechsler, 2010) of the children and there was a parallel increase in neural indices of executive functions and auditory working memory. For the visual training, there was a trend for an improvement only in spatial skills, which could not be distinguished from a practice effect. In two other studies (Janus et al., 2016; Moreno et al., 2015) a similar intervention of 20 days, 2 h/day showed improvements in musical skills and music-related brain responses as well as executive functions in children whose intervention taught them musical skills. These cognitive aspects are important for speech perception, language learning and learning in general. Thus, improvement in cognitive skills with musical activities is probably one reason for their positive effects for speech perception and language skills (for a review, Moreno and Bidelman, 2014).

Kraus and Strait (2015) gave children the possibility of attending musical training for two years, and observed several changes in domains of language. First, after two years, the fidelity of the brain stem response in replicating the acoustic content of a consonant-vowel syllable had significantly increased. Second, high brain stem response fidelity and temporal accuracy correlated with better reading skills. In a waiting-list design, the children served as their own controls, enhancing the value of the results.

Tierney et al. (2015) investigated whether musical training starting in adolescence (without prior musical training in childhood) and offered at school can affect the development of the auditory system and language processing. They found that three years of in-school musical training accelerated the development of the N1–P1-response which was used as an index of the maturation of the auditory cortex in comparison to a group receiving leadership training. Futher, they observed improved phonological awareness, but not phonological memory or rapid naming in the group receiving musical training compared to leadership training. Musical training across life has been shown to be associated with faster neural timing in response to speech in late adulthood (White-Schwoch et al., 2013).

Most of the research focusing on music-induced enhancements of brain responses to sounds or performance in neuropsychological tests has used adult-led or computerized musical training. Such training is straightforward to quantify in terms of minutes or hours of training per day or per week. Informal musical activities, in contrast, are difficult but not impossible to quantify. Putkinen et al. (2013) formulated a large questionnaire tackling all possible types of musical activities that a child can spontaneously engage herself or himself in, with the parents, siblings and friends, or alone. A comparison of the amounts of such informal musical activity to brain responses recorded in a distractive-sound paradigm which measures the brain responses to surprising, attention arousing sounds showed smaller distraction-related brain responses in children with the largest amount of informal musical activities. This was interpreted as a more developed attention-allocation system to relevant and irrelevant sounds. Auditory attentive skills are highly relevant for language learning, since all sensory modalities (auditory, visual, tactile, even taste and smell) constantly send a myriad of stimulation, only a fraction of which reaches the working memory and can thus be effectively learnt (Cowan, 1988; Gomes et al., 2000).

It should be noted, however, that in many of the studies described above, the musical hobbies were chosen by the children and their families. Children who choose musical hobbies often come from families with a higher-than-average socio-economic status (Hartas, 2011). Even though this is typically compensated for in the control group and in the statistical analysis, interventional studies where children are randomly allocated to musical learning and other types of hobbies are the strongest studies when it comes to the causality of the effects.

Jaschke et al. (2018) randomised 6-year-old children ($n = 147$) to two musical intervention groups, one active visual arts group, and a no-arts control group. For the musical intervention (1–2 h/week), early lessons introduced melody, meter and rhythm as well as different musical instruments. The lessons started with a welcoming song, followed by music theoretical and historical information in the context of the song and ended with collective music making, singing, playing and improvising. The children were followed for 2.5 years. Development of verbal intelligence and executive functions as well as academic performance were assessed for each group. Test scores for executive functions (inhibition and planning) and verbal intelligence increased significantly more for the two music groups than for the visual art and no-arts controls. Recently, Linnavalli et al. (2018) found similar improvement of verbal intelligence (Vocabulary, Block design and Matrix reasoning subtests from WISC IV), and additionally, phoneme processing, while not of executive functions (inhibition from NEPSY II test battery) for children whose kindergartens offered musical play school (where activities include singing and musical instrument playing) as a weekly routine. They did not find similar improvements for children in two types of control groups (in kindergartens offering dancing activities or no extra training). Thus, both of the studies above and the study of Moreno et al. (2011) indicate that musical activities offered to randomly chosen children improve verbal intelligence (vocabulary skills) while evidence for the improvement of non-verbal intelligence and executive functions is unclear (for a review, see Linnavalli et al., 2018).

The majority of studies investigating the perception of speech in noise by musicians and non-musicians show improvements for musicians (for a review, see Coffey et al., 2017). There is also evidence for improvement of perception of speech in noise with musical training for normally hearing children. Slater et al. (2015) conducted a study using children participating in community-based musical activities (age approximately 7 years at the beginning of the study). After a first assessment using the Hearing in Noise Test (HINT), participants were randomly assigned to one of two groups: one group began musical training right away and completed 2 years of training (including singing and musical instrument playing), while the second group waited a year and then received 1 year of musical training. It was found that speech-in-noise perception improved only for the group receiving 2 years of training.

There is also much evidence on the effects of musical training, including singing and musical instrument playing, on phonological awareness (for a meta-analysis, see Gordon et al., 2015), including controlled intervention studies (Flaugnacco et al., 2015; Patscheke et al., 2018). Interestingly, Patscheke et al. (2018) compared rhythmic training with musical instruments (no singing) to pitch-based training with singing. They found that phonological awareness improved only with singing training.

All in all, the studies reviewed above and several others show that musical training, be it instrument training, singing or musical play school, and informal musical activities all enhance the development of the auditory system in childhood and adolescence, and that such enhanced development is in many cases accompanied by improved language-perception skills. Advancing language development and communication in general is, however, not the only use of music. Humans use music for several other reasons, such as relaxation, well-being, inspiration, social cohesion, and building and communicating cultural norms and systems (MacDonald et al., 2002; Saarikallio, 2011; Saarikallio and Erkkilä, 2007). All of these should be taken into account when considering the rights and needs of children to be involved in the world of music - whether they have typical hearing or are users of different types of hearing aids or implants.

Children with hearing impairment have deficits in auditory attention (Fagan and Pisoni, 2009; Houston et al., 2003), in auditory working memory and in perception of spectral details (for an overview, Torppa et al., 2014a), similarly to adults with hearing impairments (Moore, 2003). These evidently partially underlie their difficulties in perception of phonemes (Eisenberg, 2007), speech in noise (Asp et al., 2012; Caldwell and Nittrouer, 2013; Moore, 2003), simultaneous sounds, sound localization, and perception of pitch and prosody (word and sentence stress, Lyxell et al., 2009; O'Halpin, 2010; emotional prosody, Kalathottukaren et al., 2017; question vs. statement intonation, Peng et al., 2008). They often lag behind typically hearing children in language skills, such as expressive and receptive language skills (Fitzpatrick et al., 2011), vocabulary (Lund, 2016; Percy-Smith et al., 2013; Välimaa et al., 2018), expressive morphological and syntactic skills (Boons et al., 2013; Soleymani et al., 2016), production of narratives

(Boons et al., 2013), phonological awareness (Ambrose et al., 2012; Soleymani et al., 2016), and verbal intelligence (Geers and Nicholas, 2013; Hashemi and Monshizadeh, 2012; Wu et al., 2008).

From the evidence reviewed above, showing how music-related exposure and training can enhance the activity of the auditory system and the brain, as well as auditory attentive, language, and learning performance, it is tempting to suggest that music should be used as a rehabilitation method for children with varying types of hearing impairments, both to help them enhance their speech and language skills, and to advance their skills in hearing in general. It has indeed become increasingly common to use music as part of speech therapy and as part of the general rehabilitation of these children. For example, Auditory Verbal Therapy (AVT, Estabrooks, 1994), the Hanen program (Manolson, 1992), the Lindfors Foundation MUKULA-project (http://lindforsinsaatio.net/) in Finland, and several materials (like STEPS Together, http://www.earfoundation.org.uk/shop/items/76, Baby Beats, Rocca, 2015) emphasize the role of music and especially singing in auditory and language rehabilitation. The Mary Hare School in the UK has for several years used music as an integral part of the education of deaf children (Rocca, 2012). It is, however, crucial to investigate the outcome of such music-related methods, preferably using intervention studies with control groups and with children randomly allocated to the intervention and control groups, and preferably with long-term follow-up of the development of speech and language skills. Such studies are very demanding. In the following, we describe studies that report any type of effect of using music with hearing-impaired children.

2. Musical activities and children with hearing impairments

Only a few studies have addressed the correlation of musical activities with speech perception or language skills for children with hearing impairments. Moreover, Gfeller (2016) concluded that there is no evidence from randomised, fully controlled intervention studies on the impact of musical training interventions on speech perception or language skills of children with CIs. This is in strong contrast to the musical intervention studies showing the impact of musical training on speech perception and language skills of children with typical hearing, reviewed above.

One major reason for the lack of intervention studies is the small population of children with CIs and with other hearing impairments compared to typically hearing children. Another reason is that families with hearing-impaired children may live long distances from each other, and they typically have to visit clinics, also far from home, for tuning of the hearing aid or CI. The families are also busy with rehabilitation, like speech and language therapy. Therefore, they may not have the resources needed to take part in an intervention study. All in all, research with large-scale randomised controlled trials (RCT) in CI users and hearing-impaired children and adolescents is scarce.

Due to the lack of RCTs, it is necessary to assess the correlational and longitudinal evidence, which hopefully provides a basis for future large-scale intervention studies. Moreover, musical activities at home are enjoyable and typical for children with both normal and impaired hearing (Driscoll et al., 2015). The important role of parents and home activities in auditory rehabilitation and in speech and language therapy for children with hearing impairments is well known (Hull, 2013; Estabrooks, 1994). Thus, it is also important to inspect how informal musical activities at home might improve speech perception and language skills in children and adolescents with hearing impairment or CIs.

Results for the perception of pitch (the perceptual correlate of fundamental frequency, f0) are included in this review because f0 is an important cue for the perception of prosodic stress, also for children with CIs (Torppa et al., 2014a). Perception of stress, in turn, is an important feature in assisting speech segmentation (on the role of prosodic stress, see Jusczyk et al., 1999), speech perception (on the role of stress and word stress patterns, i. e., speech rhythm, see Bolger et al., 2014; Mattys, 1997; Schön and Tillmann, 2015) and language learning (on the role of word and sentence stress, see Cutler and Foss, 1977; Männel and Friederici, 2013; Thiessen and Saffran, 2007). Because hearing impairments often lead to deficits in the perception of pitch (Oxenham, 2008), improving the perception of pitch and prosody with musical activities is especially important for hearing-impaired children. We also include studies assessing the perception of musical rhythm since, for normal-hearing adults, this is connected to the perception of word stress (Hausen et al., 2013) and speech in noise (also for children with CIs, see Torppa et al., 2018). Due to this connection, an improvement in the perception of musical rhythm may be of importance also for language perception. Furthermore, we assess the possible connections between speech-in-noise and music perception, since these connections are thought to be a prerequisite for musical training to improve speech perception and language skills (Besson et al., 2011; Patel, 2014).

2.1. Correlational and cross-sectional studies

Correlational studies related to speech perception or language skills are presented in Table 1. Cross-sectional studies are included in Table 1 and in the current section since, even though they give information about links to musical activities, similarly to other correlational studies, they cannot address causality.

Correlational and cross-sectional evidence for hearing-impaired children shows better perception of pitch (Chen et al., 2010) and music (cued with changes in f0 or duration; Polonenko et al., 2017) with longer duration of musical training (listening, singing, or musical instrument playing; Table 1).

Two studies have assessed connections between the perception of speech and of music, with different measurements and results. Koşaner et al. (2012) failed to find connections between speech and music perception assessed with a questionnaire (music questions: singing skills, recognizing songs, tunes, and timbre) for hearing-impaired children (see Table 1). Torppa et al. (2018) examined whether the cortical processing of musical instrument sounds for children with CIs is correlated with the perception of speech in noise. For the entire group of children with CIs, the perception of speech in noise was better for children with larger mismatch negativity (MMN) brain responses (improved neural discrimination) to a change of sound from piano to cymbal (musical instrument timbre). For the children with CIs who sang regularly at home, "CI singers" (for details, see Table 1; see also section 2.3), speech-in-noise perception was better for children with earlier P3a responses, reflecting an attention shift towards sound changes salient for the listener, for all three changes in musical instrument (from piano to cembalo, violin and cymbal).

Torppa et al. (2010; Table 1) found that, for children with CIs, the perception of sentence and word stress was better with more parental singing and with more musical instrument playing at home, while the perception of sentence stress was also better with more participation in music play school-like activities. The correlation of stress perception with listening to music from television or CDs was not significant.

Rochette et al. (2014) conducted a cross-sectional study of prelingually deaf children who used CIs and/or hearing aids. They compared children attending musical activities for several years (see Table 1) to those who did not participate in musical activities. They found that compared to children with no musical training, children with musical training performed better in tasks measuring

Table 1
Correlational and cross-sectional studies in children with hearing impairments

Study	N, age, device	Design of the study	Measurements	Results
Studies investigating relationships of musical training with pitch and music perception only				
Chen et al., (2010)	N = 27 (13 in musical training), age 5–14 years, CI.	13 CI children attended YAMAHA Music School for 2–36 months with NH children; listening, singing, score reading, and instrument playing. Correlations of pitch (f0) perception with duration of musical training (and with current age, age at first CI, gender, and type of CI) were studied.	Test stimuli consisted of 2 sequential piano tones, ranging from C (256 Hz) to B (495 Hz). Children identified the pitch (f0) relationship between the 2 tones (same, higher, or lower). In statistical analyses, children divided into older than 6 years vs. ≤ 6 years.	For all children, pitch (f0) perception was better with longer duration of musical training. (Pitch (f0) perception was better in children older than 6 years vs. ≤ 6 year and with larger pitch intervals; no correlations between pitch perception and the age at first CI, gender, or type of CI).
Polonenko et al. (2017)	N = 50. 26 bilateral CI, 8 CI + HA, 16 NH children; age 6–18 years.	Performance of 26 CI, CI + HA, NH children was compared. Interviews showed that 12 bilateral CI and 2 CI + HA, and 11 NH children had participated in musical training 1–10 years: music theory classes, practicing at least one non-percussive instrument, and/or singing training. To determine the results for effect of musical training, in RM ANOVA (controlling for age), the between-subject factors were hearing group (normal and bilateral device hearing) and music group (no musical training, musical training).	MBEMA (iPad application). For first 4 subtests (ST): Discrimination between different or similar melodies: The note changed to an out-of-key note (Scale ST), changed the pitch direction (Contour ST), the interval while maintaining the same scale and contour (Interval ST) or the duration between notes (Rhythm ST). In the last ST (incidental Memory), the children indicated if they had heard the excerpt before or not. 2 practice and 20 test items for each ST.	Children who had participated in musical training were faster and more accurate in music perception, regardless of their hearing status. Reaction time on specific subtests decreased with years of musical training, age, and, for CI users, better residual hearing.
Studies investigating relationships with perception of prosody				
Torppa et al., (2010)	N = 17, age 4–12 years, CI. (The same subjects as in the larger sample in Torppa et al., (2014a,b), 2018, in print.	Correlations of amount of parental singing and other musical experience at home with children's perception of word stress and sentence stress were studied. Duration of experience on parental singing: up to 9 years, starting from implantation. Performance was compared for children participating in musical play school -like activities and those who did not participate in these.	Perception of compound vs. phrasal stress (word stress) and narrow focus (sentence stress). Questionnaire assessing musical and hearing-related background.	In the CI group, better sentence stress perception correlated strongly with more parental singing and less strongly with playing more a musical instrument at home. Sentence stress perception was better with more participation in musical play school -like activities. Word stress perception was better with more parental singing and playing instruments. Correlations with listening to music from television or CDs not significant.
Studies investigating relationships with perception of speech in quiet and noise				
Koşaner et al., 2012 (see also Table 2)	Group A: N = 12, age 19–37 months; Group B: N = 7, age 34–60 months; Group C: N = 6, age 49–91 months. CI.	Correlations of speech perception with music perception (and age at first CI fitting, length of CI use, and chronological age) were investigated in children participating in musical intervention, separately for subgroups (A and B).	Auditory speech perception from the EARS test or from LEAQ. Evaluation form, filled in by teachers: Singing skills, Recognizing songs, tunes, and timbre; Responding to music and rhythm.	Correlations of scores on the subscales 'Recognizing songs, tunes, timbre' with LEAQ or LiP scores (Group A)/scores on the Bisyllabic Closed-Set speech perception (Group B) not significant. (A significant correlation between Total evaluation score and length of CI use for both groups; Correlations with age at first CI not significant).
Rochette et al., (2014)	N = 28, age 6–10 years, CI and/or HA.	Performance was compared for 14 children with HI without musical activities and 14 HI children who had participated 1,5 to 4 years in group music lessons (5–6 children in each), using voice and musical instruments, sensomotor activities with music, musical exercises involving memory, analyzing the emotional value of musical pieces, playing simple self-written pieces of music together. Assignment to groups based on type of hearing devices. Groups did not differ significantly in age, age at HI correction, duration of device use and type of correction (HA/CI).	Sound identification; Auditory stream segregation task (changing or not-changing simultaneous animal sound streams); Auditory working memory task (reproducing sounds using the keyboard); Same-different identification of mono- or bisyllabic nonsense words with different phonemes.	Musically trained children were better in auditory stream segregation, auditory working memory and phonemic discrimination tasks. Multiple-regressions suggested that good performance was at least partly driven by music lessons.
Torppa et al., (2018) (see also Table 3)	N = 21, age 4–13 years, CI.	Relationships of perception of speech in noise with ERP responses (MMN and P3a) and discrimination of pitch and intensity in synthesized bisyllables were analyzed with LMM (age controlled for) where group factor "singing" was included (12 CI children who sang regularly and vs. 9 CI non-singers) (see Table 3). Duration of singing experience (parental/child): up to 10 years, starting from implantation.	SRT for 75% correct words in sentences in steady male-weighted noise. MMN (preattentive discrimination of) and P3a (attentions shift towards) changes in f0, intensity and timbre; discrimination of f0 and intensity in synthesized bisyllables.	The perception of speech in noise in children with CIs was better with larger amplitude of MMN to a change of sound from piano to cymbal, and in the CI singing group only, with earlier P3a to changes in timbre.
Studies investigating relationships with language skills				

Table 1 (*continued*)

Study	N, age, device	Design of the study	Measurements	Results
Torppa et al. in print	N = 21, age 5–13 years, CI; NH reference group.	In 21 children with CIs, and 31 children with NH, the relationships of word and sentence stress perception, formal musical activities with emphasis on singing (CIm/NHm group) vs. others (CIn/NHn group) and parental activities (singing, reading, other activities) with language skills were investigated with linear regression analysis (for the musical training in the CI group, see Table 3, Torppa et al., 2014a).	Word finding test, WISC vocabulary (VIQ), production of rhymes (phonological awareness).	In the CI children, all language skills were better with more musical activities, and word finding and VIQ improved with more parental singing and better stress perception. Similar associations of word finding and VIQ with musical activities were found for children with NH. For all children, all language skills improved with better stress perception.

N = number of participants. CI = cochlear implant, HA = hearing aid, NH = normal hearing. HI = hearing impairment. F0 = fundamental frequency; pitch is perceptual correlate of f0. EARS = the Evaluation of Auditory Responses to Speech test battery. LEAQ = LittlEARS Auditory Questionnaire. LiP = Listening Progress Profile; Nikolopoulos et al., 2000. MBEMA = Montreal Battery of Evaluation of Musical Abilities (Peretz et al., 2013). RM ANOVA = repeated measures analysis of variance. LMM = linear mixed modeling. VIQ = verbal intelligence quotient, measured with vocabulary subtest of the WISC-IV (Wechsler, 2010). ERP = event-related potential. MMN = mismatch negativity brain response. P3a = positive response peaking after MMN, reflects attention shift towards sound change.

auditory working memory, in auditory scene analysis, and in phonetic discrimination. Multiple-regression analyses indicated that the improved performance was partly driven by the musical training.

For normally hearing children several RCT studies have shown improvements in language skills with musical activities (see section 1.2). RCT studies assessing this issue in children with hearing impairments are still lacking. However, Torppa et al. (in print) found that musically active children with CIs (at age 5–13 years), after participation in singing and playing at home and outside of the home for several years, performed better than other children with CIs in word finding, verbal intelligence (WISC vocabulary; the same task as in Linnavalli et al., 2018; Moreno et al., 2011, see section 1) and phonological awareness measured with production of rhymes (see Gordon et al., 2015, and section 1.2), while musically non-active children performed more poorly (Torppa et al., in print; Table 1). Similar results on improved language skills for musically active children (for word finding and verbal intelligence) were found for an enlarged normal-hearing group at a similar age. For CI and normal-hearing groups, all language skills improved with better perception of prosodic stress, giving evidence that perception of prosody assists language learning of both child groups (previous evidence for normal-hearing children, see Männel and Friederici, 2013; Cutler and Foss, 1977; Thiessen and Saffran, 2007). It was also found that parental singing was correlated significantly with word finding and verbal intelligence, but only for the children with CIs (Torppa et al., in print).

2.2. Intervention studies without a control group

There are several intervention studies without a control group where performance over time of one group of children with hearing impairments participating in musical intervention has been followed (Table 2). Such studies measure the effect of two things: development of auditory or musical skills related to musical learning, and the development of the same skills related to general maturation and to exposure to speech, practicing of speech and language skills, and so on. In such a study, it is impossible to disentangle these two effects.

Two of these studies have assessed how the development of auditory perception is related to music perception (Table 2). Fu et al. (2015) assessed whether melodic contour training using a home computer could improve the perception of melodies for 5–10 year old children with CIs. After 4 weeks of intensive training, perception of melodic contours markedly improved. Measurements 8 weeks later showed no decline in performance. Innes-Brown et al. (2013) studied development of the perception of musical pitch, timbre and rhythm, and the role of device/hearing in the development of these, for children with CI and/or HAs and normal hearing (age 9–13 years) participating in a weekly Music Club at school. No development in test performance was found.

Koşaner et al. (2012) designed, implemented, and evaluated an 18-month family-centered rehabilitation program (Musical EARS®). The program evaluation form included sections on singing, recognizing songs, tunes, and timbre, and responding to music and rhythm. Development in these skills and speech perception (from questionnaires) was assessed. Mean total scores in an evaluation form for musical skills increased for preschool-aged children, while the scores for speech perception did not improve significantly. Lo et al. (2015) conducted two melodic contour training programs and studied their effects on speech perception for 16 adults with CIs and 12 adults with normal hearing. One program manipulated musical interval sizes, and the other program manipulated note durations. Both programs lasted for 6 weeks. There was improvement in speech perception only for CI users in both melodic training programs. Specifically, consonant perception in silence and question/statement prosody was improved. Normal-hearing listeners performed at ceiling for these tasks. No improvement was found for speech perception in noise for either of the groups.

Several studies reported in Table 2 showed that musical activities seem to be enjoyable for children with hearing impairments and their families. Abdi et al. (2001) and Rocca (2012) reported enhancement of musical instrument playing and other musical skills with musical training for children of various ages. Koşaner et al. (2012) and Rocca (2015) studied musical programs targeted for very young children with CIs and their families. Koşaner et al. (2012) found that participation in and enjoyment of musical activities increased for both children and parents. Rocca determined if the program could be used for babies, and found that parents observed increased vocalisation, attention, and anticipation of the activities in their babies, and increased confidence in singing, moving, and playing with their baby, including during daily routines. The reports of the teachers of children participating in the study of Innes-Brown et al. (2013) suggested that participation in the Music Club improved children's confidence with voice, psychosocial development, social engagement with peers and involvement in general music classes (Table 2).

2.3. Musical interventions with a control group

This section introduces results from musical intervention studies with several study and intervention designs, all including a

Table 2
Intervention studies without control group.

Study	Device/age and N	Type and size of music group/duration of intervention	Specific goals/statistical analyses	Outcome measures	Results
General goal: To improve music (pitch/f0) perception					
Fu et al. (2015)	CI /5–10 years, N = 6 in intervention, (8 CI children not in musical training; no comparisons between intervention and non-intervention groups).	6 CI children in computer-based melodic contour identification (MCI) home training. They trained 5-tone complex or piano sample melodic contours with 23 root notes. /A half hour per day, every day for a period of 10 weeks.	The improvement of musical pitch/ melodic contour perception./ANOVA for assessing development of the musical intervention group.	The participants identified changes in melodic contours (5tone, 3tone, and 5piano sample stimuli). They clicked on one of the nine response choices on the screen; response boxes were labeled and included an illustration of the f0 contour pitch direction.	After 4 weeks of training, MCI performance sharply improved for all test stimuli. Performance did not decline during 8 weeks after training stopped. (For the 6 trained subjects, there was a significant effect of contour length).
General goals: To study and develop a music program, and the development of musical skills and/or music perception					
Abdi et al., (2001)	CI /2,5–12,5 years, N = 23.	All CI children participated in a music program based on Orff method and se-tar playing. /3 to 13 months, 1 lesson per week.	To assess the feasibility and methods of utilizing music as a means of habilitation of children with CIs./Case studies; no statistical analyses.	Teachers rated musical skills and responsiveness to music.	All children improved in playing se-tar. Musical skills and responsiveness to music were reported to increase; all parents expressed their satisfaction with the program.
Rocca (2012)	CI and/or HA /NA.	Music program of Mary Hare School. Parents of babies and preschool children are encouraged to integrate musical activities into their daily routine. Music theory, playing and singing in group settings and individual music instrument/singing lessons. /Weekly music lessons up to the age of 14.	To describe the benefits of the music program for social communication skills and musicality. /No statistical analyses.	The UK National program of the Early Years Foundation stage profile is used at Mary Hare. The article gives a general overview of the development of musical skills.	Many children with CIs can play, sing, and participate confidently in social musical contexts. Some past student recipients have trained at universities in the United Kingdom to become music teachers, performers, and composers.
Innes-Brown et al., (2013)	CI, CI + HA, 2 HAs /9–13 years, N with CI or CI + HA = 6, N with 2 HAs = 5, N with NH = 4 (in tests, 15–17 children/per time point).	All children participated in a weekly Music Club during lunch time at school 45 min per week: vocal play, the integration of aural, visual, and kinesthetic modes of learning: Kodaly method. /A school year.	To assess the development of perception of musical pitch, timbre and rhythm to assess the role of device/ hearing for the development. /LMM.	Tonal, rhythmic tests from IMMA; timbre perception test.	Improvement in test performance was not significant. Teachers reported that participation in the Music Club improved children's confidence with voice, psychosocial development, social engagement with peers and involvement in general music classes.
General goals: To study and develop a music program; development of musical skills, speech perception or language skills					
Koşaner et al., 2012	CI /Group A: N = 12, age 19–37 months; Group B: N = 7, age 34–60 months; Group C: N = 6, age 49–91 months.	All children participated in Musical EARS® program: singing, recognizing songs, tunes and timbre, and responding to music and rhythm. Activities introduced in group sessions were repeated in individual sessions and parents were encouraged to repeat activities at home. Recorded music was mostly used. /18 months.	To increase the quality and quantity of musical activities in habilitation; feasibility of the evaluation tool./ ANOVA.	Evaluation form, filled in by teachers: Singing skills, recognizing songs, tunes, and timbre; responding to music and rhythm. Auditory speech perception from the EARS test or from LEAQ.	Evaluation form scores increased significantly: increase of speech scores not significant. Participation in and enjoyment of musical activities increased for both children and parents.
Rocca (2015)	Pre-CI group: HAs, post-CI group, CI or CI + HA. N = 15. /age 5–11 months.	All children participated in Baby BeatTM program for parents and babies. Aims to elicit in deaf babies musicality through the use of backing tracks and the parent's voice. 4 key areas: music and movement, instrumental (timbre) & music/singing, early symbolic sounds, musical symbolism. Imitation of the vocalisations of Ling sounds and words, their anticipation. /8 months.	To determine if the program could be used to monitor outcomes for babies. Program is designed to improve parent interaction, listening behaviour, communication, social and emotional development, pre-post-implantation./ No statistical analyses.	Questionnaires for parents and professionals, completed at the end of an 8-month trial.	The program was appropriate for babies and for parents' use at home. Parents observed increased vocalisation, attention, and anticipation of the activities in their babies, increased confidence in singing, moving, and playing with their baby, also during daily routines.

N = number of participants. CI = cochlear implant. HA = hearing aid. LMM = linear mixed modeling. ANOVA = analysis of variance. F0 = fundamental frequency; pitch is perceptual correlate of f0. EARS = the Evaluation of Auditory Responses to Speech test battery; LEAQ = LittlEARS Auditory Questionnaire. MCI = melodic contour identification. NA = not applicable. IAMMA = Intermediate Measures of Music Audiation (Gordon, 1979).

control group with a minimal amount of musical activities or training (Table 3; note that Welch et al., 2015, used a normal-hearing reference group which had only slightly less musical activities than the hearing-impaired intervention group). This section also describes results from adults with CIs, one study comparing auditory learning and auditory-motor learning related to lyrics (not included in Table 3), and one study where hearing-impaired children served as controls for themselves (AB-BA design, Hidalgo et al., 2017, Table 3).

Not all intervention studies with a control group showed improvements with musical training on perception of music or prosody-related auditory cues, or speech perception. Petersen et al. (2015) conducted a musical intervention (rhythm, singing and ear training and computer-based exercises, Table 3) using adolescents with CIs. Normal-hearing adolescents served as control subjects. The duration of the intervention was 6 days (20 h), distributed over 2 weeks. They measured mismatch negativity (MMN) brain responses for changes in f0, rhythm, intensity and timbre, behavioral discrimination of these same features, and speech perception in noise. No improvement with training was found (see also Innes-Brown et al., 2013, Table 2, for null results).

There are studies indicating improvements with musical training in music perception and musical skills but not in speech perception. In the pioneering study of Yucel et al. (2009, Table 3), parents trained their recently cochlear-implanted children at home using a keyboard (f0 and rhythm discrimination exercises) and encouraged their children to listen to and dance with simple, repetitive melodies (Table 3). Compared to children without musical training, the musical intervention group was better in open-set speech perception (measured with repetition of sentences) three months after the training began. However, at the end of the 2-year training period there were no differences between groups in speech perception. By the end of the second year, the results from a questionnaire indicated that the music group was better than the control group in all aspects of musical skills, including singing melodies and producing rhythms, thus indicating improvement in the perception of pitch and rhythm with musical training. Welch et al. (2015; Table 3) found rather similar results with singing training (most often in a music class for 29 children, and occasionally in small groups) with 5-7-year-old hearing-impaired children. Normally hearing children participated in class-based singing training, but they did not have training in small groups (see Table 3). It was found that the comfortable singing range, general ability to sing (pitch and rhythm patterns) and pitch perception improved only for the children with hearing impairments. They found no improvement in perception of speech in noise, which the authors interpreted as being due to the context: classrooms with normal-hearing and hearing-impaired children learning together in quite large groups. Moreover, Petersen et al. (2012) found in a controlled musical intervention study (training 6 months, singing, playing piano, computer-based listening), using adults recently implanted with cochlear implants, improvements in music perception (discrimination of timbre, melodic contour, and rhythm) only for the musical intervention group. However, the perception of speech in noise and emotional prosody improved similarly in both musical intervention and control groups. The improved perceptual and musical skills with musical intervention from the two studies above are in line with the correlational results (Chen et al., 2010; Polonenko et al., 2017, Table 1) and results from interventions without a control group for children with CIs (Abdi et al., 2001; Fu et al., 2015; Koşaner et al., 2012; Rocca, 2012, Table 2).

The positive results above are also in line with the results from a study which investigated how singing at home is related to the development of cortical processing of music and attention in 4–13-year-old children with CIs (Torppa et al., 2014b, Table 3). It was assessed how P3a brain responses, reflecting attention shift towards sound changes, developed over 14–17 months in those children with CIs who sang informally and regularly at home (“CI singers”), and those who sang only rarely. The only factor explaining CI-children's singing was that their parents had sung more for them from their early childhood (Torppa, 2015, p. 56; Table 3). The P3a was elicited by a change in a sound sequence with a regular and predictable rhythm. The CI singers had consistently larger and earlier P3a responses than the CI non-singers. The largest and most statistically significant differences between groups were found for the P3a responses to changes in musical instruments (timbre) and f0. The P3a responses became larger and earlier during the follow-up period for the CI singers only. It was also found at the second time point of the measurements that the CI singers sang the rhythms of a children's song (“Twinkle twinkle little star”) better, indicating better perception of rhythm for them than for the CI non-singers. These results suggest that informal singing at home could lead not only to better music perception but also to better auditory attention (Torppa et al., 2014b).

Only one study reported improved perception of speech in noise with musical activities for children with CIs (for null results, for hearing-impaired children, Petersen et al., 2015, and Welch et al., 2015, Table 3; for adults, Lo et al., 2015, see section 2.2 above; Fuller et al., 2018; Petersen et al., 2012). Torppa et al. (2018; Table 3) studied how CI singers (who sang informally and regularly at home) and CI non-singers developed in the perception of speech in noise during 14–17 months. It was expected that compared to the CI non-singers, the CI singers would perceive speech in noise better, since their attention shift towards sound changes was improved, and attention is important for the perception of speech in noise, and also because they sang rhythms better (for more details, Torppa et al., 2018). As expected, the CI singers had better speech perception in noise than the CI non-singers, which is in line with results from normal-hearing children, showing improvement of perception of speech in noise with long-term (2 years) musical training, including singing and musical instrument playing (Slater et al., 2015; see section 1). However, in the study of Torppa et al. (2018), compared to the CI non-singers, the CI singers did not develop in this skill more during the follow up. It was concluded that even though the results could not address causality, a connection was found between improved speech perception in noise and long-term singing at an early age of the CI singers, by children themselves and/or by their parents. The study (and the study of Torppa et al., 2014b) could not differentiate the role of parental singing from the singing of the children themselves, since these two were strongly connected (Torppa, 2015). It is worth noting that the parents often sang face to face with the child. This could improve attention to spectral changes because the child could see the mouth and lip shapes and movements, which are related to the spectral content of consonant and vowel sounds. The slow rate and predictability of children's songs may be particularly beneficial for the perception of these spectral changes. However, it cannot be ruled out that better perception of the sound intensity envelope (important for rhythm perception, for which the CI singers were better than the CI-non-singers; Torppa et al., 2014b) also plays a role, since this is known to be an important cue for perception of speech and for perception of musical instrument timbre, especially for CI users (Drennan and Rubinstein, 2008; Kong et al., 2011).

Since the CI singers sang the rhythms of a song better than the CI non-singers, it is possible that the CI singers could benefit from the regular rhythm of the stimuli (see above, Torppa et al., 2014b). Their auditory system may have been better able to track the moments when important information was expected. Triggered by the

Table 3
Intervention studies with a control group.

Study	Size and type of control group/ allocation to control and music groups	Device /age	Size and type of music group /duration of intervention	Specific goals /statistical analyses	Outcome measures	Results
General goals: Music perception (pitch/f0) and auditory attention						
Torppa et al. 2014b	9 CI peers did not sing at home (CI non- singers). No differences from the CI singers with respect to other musical background than parental singing (parents of CI non-singers sang less), age, hearing-related aspects, CI type, age at CI, gender, socio-economic background, etiology. /Based on a questionnaire.	CI /4–13 years.	12 CI children (CI singers) sang regularly at home before and between tests; regular parental singing starting from implantation /first tests (T1) at age 4–13 years, second tests (T2) 14–17 months later. /Total duration of singing to 10 years (on average 5 times per week before T1, 4 times per week between T1/T2).	Development of preattentive discrimination and attention shift toward changes in musical tones. Accuracy of singing at T2. /LMM.	Event-related potentials: MMN, P3a for changes in pitch (f0), timbre, duration, (intensity) and gaps in every other tone; evaluation of accuracy of singing (f0, rhythm and lyrics) of the CI children.	Only CI singers developed in attention shift (P3a), significantly towards changes in timbre; Compared to CI non-singers, CI singers had larger and earlier P3a for changes in pitch (f0) and earlier P3a for changes in timbre, and they sang better rhythms of songs.
General goals: Music perception and/or perception of prosody						
Torppa et al., (2014a)	13 CI peers (CIn children) with non-musical hobbies. Compared to music group, parental education lower, which was controlled for in all statistical analyses. No differences from the music group with respect to age, hearing-related aspects, CI type, age at CI, gender, etiology. /Based on a questionnaire.	CI /4–13 years.	8 CIm children in musical play school-like activities with parents or alone (small groups) + home activities = singing by parents and children, playing instruments, dancing /starting from implantation, first tests (T1) at age of 4–13, second tests (T2) 14–17 months after. /Total duration up to 10 years. Weekly + musical activities at home.	Perception of prosody and auditory cues for prosody (f0, intensity, duration). /LMM.	Perception of word and sentence stress; discrimination of f0, intensity and duration in synthesized bisyllables; digit span forward, PIQ.	CIm children performed similarly to NH controls in stress and pitch (f0) perception in bisyllables (and digit span). CIn children performed more poorly than CIm and NH groups. Only CIm children improved with age in word stress and intensity perception in bisyllables, and improved over time in digit span.
Good et al., (2017)	9 CI peers in visual arts training. No difference from the music group with respect to age, age at CI, CI experience, speech perception./ Pseudorandom or random allocation.	CI /6–15 years.	9 CI children in individualized, private piano lessons: technical exercises with piano, music theory rudiments, learning songs and rehearsal of the songs vocally. /6 months.	Perception of music and emotional speech prosody. /Mixed-design ANOVA.	MBEMA (scale, contour, interval, rhythm, and incidental memory), perception of emotional speech prosody (audio-only and audiovisual).	Musical training enhanced: discrimination of melodic contour, rhythm, memory for melodies, and emotional prosody especially in audio-only task. Art training did not lead to the same improvements.
Hidalgo et al., (2017)	The same HI children participating a speech therapy session. /AB-BA design.	CI and/or HA /5–6 years.	Rhythmic and audio-motoric exercises: following the beat of the song (clapping the hands, shaking maracas, body tapping, imitating different rhythms of songs, presented by the speech therapist on a djembe. /30 min.	Temporal adaptation in speech interaction. /RM ANOVA.	Picture naming in alternation with a virtual partner. Alternation rate and temporal predictability (match vs. mismatch of stress occurrences) were manipulated.	Children with HI became sensitive to the manipulation of temporal regularity of stress occurrences only after rhythmic training.
General goals: Music perception and/or perception of speech in quiet or noise						
Yucel et al., (2009)	9 CI children without musical intervention. Newly implanted, the age at implantation ranged between 12 and 36 months.	CI, CI + HA /newly implanted, the age at implantation ranged between 39 and 96 months.	9 CI children. Parents trained their children at home to recognize pitch (f0) differences between notes and to recognize rhythms using a keyboard. Parents also played simple melodies repeatedly and encouraged their children to listen and dance with them. /2 years.	Pitch (f0) and rhythm perception; speech perception. /Mann-Whitney U-tests.	Meaningful auditory integration scale (MAIS) or infant–toddler MAIS and the meaningful use of speech scale (MUSS); musical stages questionnaire, open- and closed-set speech perception.	By the end of 3rd month, music group was better in open-set speech perception. Music group had more exposure to music at the end of the first year. By the end of the second year music group developed more than the control group in all aspects of musical skills.
Petersen et al., (2015)	10 NH peers without musical training.	CI /15–18 years.	11 CI adolescents in musical training: rhythm, singing, ear training and computer-based	Preattentive and behavioral discrimination of changes in music. Perception of speech in	MMN brain responses for musical pitch (f0), rhythm, intensity and timbre changes,	No improvement associated with training.

			exercises. /6 days (20 h), over 2 weeks.	noise. /Mixed-effects ANOVA; t-tests.	discrimination of these, SRT for 50% correct words in sentences.	
Welch et al., (2015) .	17 NH peers in music lessons with the HI group. They did not have small-group training.	CI and/or HA /5–7 years.	12 HI children in weekly music lessons in large groups (n = 29) with NH peers, occasionally in small-group interactions (HI pairs). Emphasis on building a repertoire of simple songs with actions and vocal exploration. Also activities that drew on visual imagery for sound and that included simple notation and physical gesture. /Weekly across two school terms.	Singing competence, chord pitch discrimination, speech perception in noise. /RM ANOVA.	A singing competence profile, based on that used in the evaluation of the National Singing Programme (NSP) Sing Up (Welch et al., 2015); a specially designed chord pitch discrimination test; Speech perception in noise: In sentences, 6 colour and 8 number options. Speech-shaped noise was adjusted adaptively to obtain the SRT.	Comfortable singing range, general ability to sing (pitch and rhythm patterns) and pitch (f0) perception improved in the HI children. No effects in perception of speech in noise.
Torppa et al. (2018)	The same as in Torppa et al., 2014bsee above; the same study as in Table 1.	CI/4–13 years.	The same as in Torppa et al., 2014bsee above. Parental singing started from implantation, also CI children sang before the follow-up started.	Perception of speech in noise. /LMM.	SRT for 75% correct words in sentences in steady noise. Sentences/words were illustrated in 4 × 4 picture matrix.	CI singers were better in perception of speech in noise than CI non-singers.

CI = cochlear implant; NH = normal hearing; HI = hearing impairment; HA = hearing aid. AB-BA design = all children participated in intervention and control training and served as controls and intervention group. Order of intervention and control training was counterbalanced across children. LMM = linear mixed modeling. ANOVA = analysis of variance. RM = repeated measures. MMN = mismatch negativity brain response. P3a = positive response peaking after MMN, reflects attention shift towards sound change salient for the listener. F0 = fundamental frequency; pitch is perceptual correlate of f0. PIQ = performance intelligence quotient (block design) from WISC (Wechsler, 2010). SRT = speech reception threshold. MBEMA = a children's version of the MBEA, the Montreal Battery for Evaluation of Musical Abilities (Peretz et al., 2013).

rhythm of music and speech, attention shift to the expected moments is known to lead to better speech perception at these moments (Mattys, 1997; Schön and Tillmann, 2015). Based on results of Cason et al. (2015), rhythmic priming can improve phonological production in children with hearing aids and CIs (not included in the tables). They conducted an experiment where children had to repeat sentences that were or were not preceded by a rhythmical prime which either matched or mismatched the meter (i.e., the chain of stressed syllables) of the sentence. Matching conditions resulted in greater phonological accuracy than baseline and mismatching conditions. Plausibly, musical rhythm may have built expectations which improved both the perception and production of speech. This process is thought to assist speech perception in general (Cason and Schön, 2012; see also Mattys, 1997; Schön and Tillmann, 2015).

Good et al. (2017; Table 3) investigated the effect of musical training for children with CIs (age 6–15 years). The children were assigned to individual musical training (including playing piano and rehearsal of songs vocally) and individual painting lesson groups. Participants could choose the location of training without knowing the type of training, or they were assigned randomly to musical and painting training groups. The groups did not differ in age at testing, age at implantation, CI experience, or speech perception skills. In line with the correlational and interventional evidence above (Tables 1–3), musical training was associated with improved discrimination of melodic contour and rhythm and incidental memory for melodies as well as emotional prosody. Art training did not lead to the same improvements. Interestingly, Fuller et al. (2018) conducted a randomised, controlled intervention study using adults with CIs. The participants attended 6 weeks at face-to-face music therapy (training of rhythm perception, musical speech perception, music perception, singing, vocal emotion identification, and music improvisation), computer-based melodic contour training or non-musical activities. Improvement of perception of emotional prosody was found only with face-to-face music therapy. No improvement in the perception of speech in quiet or noise was found in this study for any of the groups (Fuller et al., 2018).

Torppa et al. (2014a; Table 3) studied children with CIs (age 4–13 years), determining how vocal (synthesized speech) f0, intensity and duration discrimination and prosodic perception (perception of word and sentence stress) and auditory working memory developed for 21 children exposed to music (CIm) or not (CIn). Measurements were conducted twice, 14–17 months apart. Children with CIs in the CIm group participated in musical activities (singing, sensorimotor activities, and music instrument playing), before and between the measurements (Table 3), most of them from immediately after implantation. Compared to the CIn children, the CIm group took part in significantly more musical activities in the home. The CIn children participated in other than musical hobbies. The musically active CIm group performed as well as normal-hearing children in stress perception and f0 discrimination and in auditory working memory (digit span), while the CIn group performed more poorly. Additionally, only the CIm group improved with age in word-stress perception and intensity discrimination, and over time (during the follow up), in digit span (for the link of musical training to auditory working memory of hearing-impaired children, see also Rochette et al., 2014, Table 1).

Hidalgo et al. (2017; Table 3) studied how preceding short-term rhythmic musical training or speech therapy affected speech perception for children with CIs and/or hearing aids. The participating children named pictures presented on a screen, taking turns with a virtual partner. Alternation rate (fast or slow) and temporal predictability (match vs mismatch of word stress occurrences) were manipulated. The children with hearing impairment were tested twice, once after 30 min of traditional speech therapy and once after 30 min of individual musical rhythmic training conducted by a speech therapist. It was found that children with hearing loss became sensitive to the manipulation of the temporal regularity of speech stress occurrences only after rhythmic training, when they could adapt their turns to the speech rhythm (stress patterns) of the interlocutor. The authors concluded that rhythmic training may help children with hearing impairment to structure the temporal flow of their verbal interactions. According to the authors, this could be indicative of meter (i.e., the regular recurrence of a beat or accents) perception and/or production being underdeveloped in children with hearing loss, since normally hearing children were able to do the task without rhythmic training. It is thus possible that rhythmic training improves the ability to perceive and understand rhythmical and metrical structure (Cason et al., 2015). However, musical training may also have enhanced the encoding of acoustic cues such as f0, intensity and duration, that characterise stress patterns (Torppa et al., 2014a), or training could have enhanced auditory processing in general (Hidalgo et al., 2017).

Vongpaisal et al. (2016; not included in the tables) studied how children with CIs learned new songs in listening only (auditory learning), or listening and dancing (auditory-motor learning) conditions. The children could listen or listen and dance to the songs until they felt they had learned the songs. After the learning phase, the ability to identify song excerpts, mistuned excerpts (with the original instruments), and the same songs played with a piano sound was studied. Compared to listening only, the combination of listening and dancing led to better identification of songs in versions that preserved the original instrumental beats and lyrics.

2.4. Summary

For children with hearing impairments, improvements in musical skills and/or music perception (pitch or rhythm), linked to perception of speech prosody, have been found with musical activities in several studies (in 2/2 correlational, 2/3 intervention studies without a control group and with statistical analyses, 4/5 intervention studies with a control group; Tables 1–3). There are also signs of improvement of detection of temporal regularities (related to perception of stress patterns and speech in general) with musical activities (Hidalgo et al., 2017; Torppa et al., 2014b, Table 3). Perception of prosody, which is important for speech perception and language acquisition (see section 2), improved only with musical activities in the 3/3 intervention studies with a control group (emotional prosody: Good et al., 2017, stress perception, Torppa et al., 2014a; plausibly also in Hidalgo et al., 2017, where the children served as controls for themselves, Table 3) (for adult CI users, question-statement prosody, see Lo et al., 2015, section 2.2; emotional prosody, Fuller et al., 2018, section 2.3). Cortical processing of changes in timbre of musical instruments, which is connected to better perception of speech in noise, showed improvement with singing in one study only (Torppa et al., 2014b, 2018, Tables 1 and 3; see also improvement of perception of timbre in adults with CIs, Petersen et al., 2012, section 2.3). And finally, signs of improvements with musical activities have been found for perception of phonemes (Rochette et al., 2014, Table 1; see also Cason et al., 2015, section 2.3; for adult CI users, see Lo et al., 2015, section 2.2) and speech in noise (Torppa et al., 2018, Table 3), auditory attention (Torppa et al., 2014b; Table 3), auditory working memory (Rochette et al., 2014, Table 1; Torppa et al., 2014a, Table 3) and language skills (Torppa et al., in print), which are important for learning and educational success.

Even though the results are promising, more evidence is needed. The number of studies and participants in the studies reviewed is small, the study designs vary, and even the studies with a control group are not always well controlled (see Tables 1–3). There is a lot to improve in the research paradigms, such as assessing speech perception with a larger battery of tests, and in reporting the content and practicalities of the intervention in more detail (for factors affecting the results of musical training, from the perspective of speech-in-noise perception, see Coffey et al., 2017). Above all, there is lack of RCTs assessing the effects of musical activities on language skills of children with hearing impairments.

Children and their families enjoy musical activities. Families who know about the benefits of music or appreciate music, most often encourage their children to take part in musical hobbies and also to make music at home (Driscoll et al., 2015).

According to the studies reviewed above, musical activities may increase involvement in music, and all studies showing significant results show improvements of musical skills, music or speech perception or cognitive aspects with musical activities; none of them report negative effects. Music may have positive consequences for the lives of children with hearing impairments. From an ethical point of view, it is not wise to exclude them from musical activities at home or outside of the home. Therefore, while waiting for better scientific evidence, we feel that it is important to list some principles and give our recommendations for the use of music for children with CIs and/or hearing aids.

3. How to use music to enhance speech and language skills of hearing-impaired children

It should be understood clearly that traditional speech and language therapy is of vital importance to hearing-impaired children and adolescents. However, musical activities can be used in the context of speech and language therapy, as an additional therapy, as a separate hobby, and/or as an activity at home.

We have drafted the following recommendations on the basis of the intervention studies and correlational studies described above, and on the basis of the traditional auditory rehabilitation, music therapy methodologies, and speech and language therapy methods.

1. Start using music systematically at an early age, before implantation or the application of hearing aids. Continue musical activities more than one year, to improve speech perception.

For children with hearing impairments, the early start of musical activities, like singing or musical play school, may be beneficial for the perception of prosody and for the perception of speech in noise, and perhaps for language skills (see the children's ages at the start of musical activities in Torppa et al., 2014a, 2018; vs. null results from adolescents, Petersen et al., 2015; adults, Fuller et al., 2018). Furthermore, families of children with CIs feel that they and their babies benefit from and enjoy musical activities starting before implantation (Rocca, 2015), and a hearing-impaired child can benefit from musical activities even before implantation or receiving a hearing aid due to residual hearing or tactile perception of low frequencies in time synchrony with visual stimulation (multisensory perception, see below). It is also known that the brain is most plastic at an early age, before 3–4 years (for a review, Sharma et al., 2015), and therefore, musical activities at this age can lead most efficiently to changes in the brain. However, it may also be good to continue at least one year or longer with musical activities to improve speech perception (see the duration of activities in Chobert et al., 2014; Slater et al., 2015; Torppa et al., 2018; vs. Fuller et al., 2018; Petersen et al., 2015).

2. Use bodily movements in the rhythm of the music. Use orientations.

The use of music, especially when it involves dance and other sensorimotor activities (used in musical play schools and similar activities, Torppa et al., 2014a), or dancing, seems to be beneficial for the learning of lyrics (dancing, Vongpaisal et al., 2016) or perception of prosody (Torppa et al., 2014a) by children with CIs. Rhythmic,

(*continued*)

multisensory stimulation simultaneously with lyrics can improve the perception of speech (for a review, see Torppa et al., 2018). The joy of music that the child can observe in group music situations can awake the curiosity of the child, and he/she will naturally want to join in (Abdi et al., 2001; Innes-Brown et al., 2013; Koşaner et al., 2012; Rocca, 2015; for normally-hearing children, Krueger, 2011). For small infants with hearing impairment, holding the baby against the adult's body while singing or humming, and carrying the baby while walking or dancing to the rhythm of the music are good methods for stimulating the audio-tactile-vestibular system (Phillips-Silver and Trainor, 2005), and for keeping the child near enough to hear the lyrics well (the closer the distance between the singer and the child is, the louder is the sound is for the child).

Use consistent, large body movements that are rhythmically co-occurring with the music. Let your body movements reflect the style of the music: fast or slow, happy or sad, aggressive or melancholic, to aid learning of the rhythm and beat of music (see for example Rocca, 2015), which are both plausibly important for the perception of speech (section 2.3). Repeat the same bodily movements with the same piece of music consistently. Repetition is highly important for the auditory learning of children with hearing impairments (Estabrooks, 1994; Hull, 2013).

Help the child locate musical sounds in space: point with your finger and anchor your gaze to the direction of the sound. You can make this into a game: where is the sound coming from? This gives the child the opportunity to learn to recognize sounds and to practice sound localization, and therefore these are common activities in speech and language therapy for hearing-impaired children (Estabrooks, 1994). Multisensory integration at the neural level is vital for making sense of multisensory information like speech, which contains both visual and auditory stimulation, and this has been extensively studied (Calvert et al., 1998; King and Calvert, 2001; Shimojo and Shams, 2001).

Be consistent with your movements with respect to the sound parameters. In all musical play with hearing-impaired children, sounds high in f0 should be connected with high hand movements, and sounds low in f0 should be connected with low hand movements or movements of the feet. Move your hand or a toy up and down with the f0 of the music (Rocca, 2012). These exercises give an opportunity for multisensory, audio-visual learning of changes in f0. Especially early-implanted children may be good multisensory integrators (Schorr et al., 2005), and may benefit from visual cues. Hand movements which visualize f0 are also used in musical training for normal-hearing children (for example, Kodaly, https://en.wikipedia.org/wiki/Kod%C3%A1ly_method).

3. **Use singing as your main instrument, especially with a young child.**

All studies of hearing-impaired children showing improvement of speech perception (prosody, phonemic discrimination, speech in noise) associated with musical activities have included singing, face-to-face with children (see Tables 1 and 3, and the review above; see also Fuller et al., 2018, for adults with CIs). There are several reasons why singing can be more efficient for speech perception than musical instrument playing (for an overview, Torppa et al., 2018).

Make sure that the hearing-impaired children can see your lips moving when you sing. This helps their brains connect the auditory information to lip and tongue movements (multisensory perception, Schorr et al., 2005). Especially vowels are accompanied by changes in the spectral content of speech stimulus (Stevens, 1998), and seeing lip and tongue movements can lead to better perception of spectral details and better perception of speech in quiet or noise (for an overview, see Torppa et al., 2018). This is most natural at an early age, with parents. It is also important to keep in mind that it is easiest for the hearing-impaired auditory system to make sense of music when one instrument, especially singing, is presented without accompaniment (for the difficulties in perception of simultaneous musical sounds by hearing-impaired individuals, see Galvin et al., 2009; Looi et al., 2008).

4. Engage children in musical activities in small groups; use several musical instruments and pictures/toys presenting lyrics.

Ensure that the group size is small enough (plausibly up to 6 children) to avoid excessive noise and to keep the interest of the child on the lips and voice of the group leader or the other group members and in making music. For hearing-impaired children, large group sizes are associated with null-results on speech-in-noise perception (Welch et al., 2015), while studies suggesting improvement of perception of prosody or other aspects of speech perception with musical activities used individual lessons (Good et al., 2017), individual singing at home (Torppa et al., 2018) or groups of 5–6 children (Rochette et al., 2014).

Use small, colourful, interesting instruments like rhythmic instruments, xylophones, and small stringed instruments to let the children become curious about musical sounds. Let the children be active and try out different types of musical instruments. Playing an instrument by oneself is a highly multisensory activity which can lead to better perception of f0, timbre, or rhythm, linked to perception of prosody or speech in noise (Schorr et al., 2005; Torppa et al., 2014a, 2018), and may be more effective than listening only (Lappe et al., 2008). Playing staccato or legato can also improve the perception of intensity envelopes (Patel, 2011), which are also important for perception of speech (Chobert et al., 2014). Since the perception of lyrics is challenging when children or group leaders play instruments together with singing (see Galvin et al., 2009; Looi et al., 2008, above), use pictures visualizing lyrics, especially at the first stage of learning of lyrics of songs.

5. Use plenty of repetition.

Sing and play the same songs over and over again. Repetition is very helpful for auditory memory and it allows the auditory system to form models of the song and, over the course of the repetitions, make the model more and more precise (Estabrooks, 1994; Hull, 2013). Using the same song always at the beginning and at the end of the music session will help the child orientate and grasp the structure of the music and the session better – a method that is traditionally used in musical play schools and in music therapy.

6. Use plenty of turn-taking.

Use songs which include turn-taking: The child will be given an opportunity for auditory closure (to continue the song when the adult stops singing, as used in the Hanen program and AVT, Estabrooks, 1994), or the adult will sing a very short section first and then it is the child's turn to repeat it. Using short sections is important, since children with hearing impairments have difficulties with auditory working memory (for an overview, see Torppa et al., 2014a), and, thus, in memorizing long sections. Moreover, turn-taking allows the child to listen, to produce speech sounds, and to compare the adult's and his/her own speech production, including phoneme quality and prosodic features. This is important since repeating lyrics with slow tempo, which is typical for music (Patel, 2014), may facilitate the learning of phonological codes for words (for an overview, see Torppa et al., 2018).

7. Give advice to families on how to use music with their child.

Involve families in music-making with their child. Use videos and teaching materials to help the parents understand how integral and easy music-making can be in everyday life. Teach songs to the parents and help them engage their own child into the world of music in their own home. This can increase the amount of singing and other musical activities at home, which can further lead to improvements in the perception of prosody, in attention functions, and further, in the perception of speech in noise and in language skills (see the review above; Torppa et al., 2014a,b; Torppa et al., 2018; Torppa et al., in print). Help parents if they encounter problems with music schools or academies, to help children to continue musical activities long enough to improve speech perception and language skills (see suggestion 1 above).

If the hearing-impaired child has siblings, involve them in the musical activities, as well as the parents of the child. The siblings, when engaged in musical activities, will continue singing and playing music at home, with plenty of repetition of music and a model for music making, thus creating a good environment for their hearing-impaired sibling (Driscoll et al., 2015; for the role of repetition, see above).

8. Use computer games and apps to help the child perceive and produce sounds.

Give the hearing-impaired child, his/her parents, and teachers lists of apps and computer games that are available for practicing sound perception and production. Advise the child and his/her parents on how to use the software. (For the possible benefits of computer-based melodic contour training for adult CI recipients, for perception of prosody and consonants: see Lo et al., 2015; for perception of melodic contours, see Fuller et al., 2018; for perception of melodic contours for children with CIs, see Fu et al., 2015, Table 2).

9. Give advice to school music teachers.

The hearing-impaired child has the right to take part in daycare and school music lessons, and to obtain a positive and encouraging image of his/herself as a music maker. To achieve this, not only inform speech and language therapists, professionals at daycares and school teachers, including music teachers, about the results and suggestions in this review, but also give advice to them about the effects of the hearing impairment on music perception of the child. For example, the teacher should know that a child with a CI has good possibilities for learning rhythm (for an overview, Gfeller, 2016), but should not be asked to sing alone in front of other children. Poor perception of pitch (see section 1.2, and Gfeller, 2016) make it difficult to sing in tune. Thus, singing in front of normally hearing peers can lead to unpleasant feeling or even bullying. However, it is also important to keep in mind that pitch-based training can improve the perception of pitch and together with this, speech perception (see section 2.4 and Tables 1–3). To motivate adolescents, a good solution for school music lessons is a band practice room where the hearing-impaired child can be part of a pop/rock band playing drums and percussion. Such activities are often very much appreciated by children and teenagers and provide a good basis for healthy, positive self-esteem as a

(*continued on next page*)

(*continued*)

music maker, as noted in the Resonaari music camps of the association for children with CIs and their families in Finland (LapCI ry), in Mary Hare School (Rocca, 2012), and for normally-hearing teenagers (Saarikallio, 2011).
10. Support musical hobbies of teenagers with hearing impairments.
There are several ways that children and teenagers with hearing impairments can have musical hobbies. In music schools, an individual study plan is needed. The United Nation's Declaration of the Rights of the Child states that all children have the right to culture, which includes music (Ruismäki and Ruokonen, 2009). A hearing impairment should not prevent the child from taking part in musical hobbies. Musical schools and academies need to realize this right and make it practically possible for all children and adolescents to take part in their teaching. Foundations and other sources that lend musical instruments to students should specifically consider hearing-impaired students.

With this list of advice and recommendations, we believe that hearing-impaired children, their parents, siblings, other family members, teachers, speech therapists and other people close to them can enhance the environment with music, making it possible for these children to benefit from musical activities in respect to speech perception and learning, thus supporting these children and adolescents to reach their abilities as full members of the society and in actively contributing as citizens.

Contributions

The two authors have equally contributed to the initial idea of the review, to the drafting the first version and revision of the manuscript, and R. T. finalized it.

Declaration of interest

None.

Funding

This work was supported by the Signe and Ane Gyllenberg Foundation (the grant for the first author, Ritva Torppa).

Acknowledgements

We thank the reviewers and especially Brian Moore for helpful comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heares.2019.06.003.

Torppa et al.,

References

Abdi, S., Khalessi, M.H., Khorsandi, M., Gholami, B., 2001. Introducing music as a means of habilitation for children with cochlear implants. Int. J. Pediatr. Otorhinolaryngol. 59 (2) https://doi.org/10.1016/S0165-5876(01)00460-8, 1051–13.

Ambrose, S.E., Fey, M.E., Eisenberg, L.S., 2012. Phonological awareness and print knowledge of preschool children with cochlear implants. J. Speech Lang. Hear. Res. 55, 811–823. https://doi.org/10.1044/1092-4388(2011/11-0086.

Asp, F., Mäki-Torkko, E., Karltorp, E., Harder, H., Hergils, L., Eskilsson, G., Stenfelt, S., 2012. Bilateral versus unilateral cochlear implants in children: speech recognition, sound localization, and parental reports. Int. J. Audiol. 51 https://doi.org/10.3109/14992027.2012.705898, 8178–32.

Besson, M., Chobert, J., Marie, C., 2011. Transfer of training between music and speech: common processing, attention, and memory. Front. Psychol. 2, 94. https://doi.org/10.3389/fpsyg.2011.00094.

Bolger, D., Coull, J.T., Schön, D., 2014. Metrical rhythm implicitly orients attention in time as indexed by improved target detection and left inferior parietal activation. J. Cogn. Neurosci. 26, 593–605. https://doi.org/10.1162/jocn_a_00511.

Boons, T., De Raeve, L., Langereis, M., Peeraer, L., Wouters, J., van Wieringen, A., 2013. Expressive vocabulary, morphology, syntax and narrative skills in profoundly deaf children after early cochlear implantation. Res. Dev. Disabil. 34, 2008–2022. https://doi.org/10.1016/j.ridd.2013.03.003.

Caldwell, A., Nittrouer, S., 2013. Speech perception in noise by children with cochlear implants. J. Speech Lang. Hear. Res. 56, 1330. https://doi.org/10.1044/1092-4388(2012/11-0338.

Calvert, G.A., Brammer, M.J., Iversen, S.D., 1998. Crossmodal identification. Trends Cognit. Sci. 2, 247–253. https://doi.org/10.1016/S1364-6613(98)01189-9.

Cason, N., Hidalgo, C., Isoard, F., Roman, S., Schön, D., 2015. Rhythmic priming enhances speech production abilities: evidence from prelingually deaf children. Neuropsychology 29. https://doi.org/10.1037/neu0000115, 1021–07.

Cason, N., Schön, D., 2012. Rhythmic priming enhances the phonological processing of speech. Neuropsychologia 50 (11), 26522–26658. https://doi.org/10.1016/j.neuropsychologia.2012.07.018.

Chen, J.K.C., Chuang, A.Y.C., McMahon, C., Hsieh, J.C., Tung, T.H., Li, L.P.H., 2010. Music training improves pitch perception in prelingually deafened children with cochlear implants. Pediatrics. https://doi.org/10.1542/peds.2008-3620 peds-2008.

Chobert, J., Francois, C., Velay, J.L., Besson, M., 2014. Twelve months of active musical training in 8- to 10-year-old children enhances the preattentive processing of syllabic duration and voice onset time. Cerebr. Cortex 24, 956–967. https://doi.org/10.1093/cercor/bhs377.

Coffey, E.B.J., Mogilever, N.B., Zatorre, R.J., 2017. Speech-in-noise perception in musicians: a review. Hear. Res. 352, 496–499. https://doi.org/10.1016/j.heares.2017.02.006.

Cowan, N., 1988. Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. Psychol. Bull. 104 (2), 163. https://doi.org/10.1037/0033-2909.104.2.163.

Cutler, A., Foss, D.J., 1977. On the role of sentence stress in sentence processing. Lang. Speech 20, 1–10. https://doi.org/10.1177/002383097702000101.

Dittinger, E., Chobert, J., Ziegler, J.C., Besson, M., 2017. Fast brain plasticity during word learning in musically-trained children. Front. Hum. Neurosci. 11, 233. ISSN : 1662-5161.

Drennan, W.R., Rubinstein, J.T., 2008. Music perception in cochlear implant users and its relationship with psychophysical capabilities. J. Rehabil. Res. Dev. 45, 779–789. https://doi.org/10.1682/JRRD.2007.08.0118.

Driscoll, V., Gfeller, K., Tan, X., See, R.L., Cheng, H.Y., Kanemitsu, M., 2015. Family involvement in music impacts participation of children with cochlear implants in music education and music activities. Cochlear Implants Int. 16, 137–146. https://doi.org/10.1179/1754762814Y.0000000103.

Eisenberg, L.S., 2007. Current state of knowledge: speech recognition and production in children with hearing impairment. Ear Hear. 28, 766–772. https://doi.org/10.1097/AUD.0b013e318157f01f.

Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., Taub, E., 1995. Increased cortical representation of the fingers of the left hand in string players. Science 270 (5234), 305–307. https://doi.org/10.1126/science.270.5234.305.

Estabrooks, W., 1994. Auditory-Verbal Therapy for Parents and Professionals. Alexander Graham Bell Association for the deaf, Washington DC.

Fagan, M.K., Pisoni, D.B., 2009. Perspectives on multisensory experience and cognitive development in infants with cochlear implants. Scand. J. Psychol. 50, 457–462. https://doi.org/10.1111/j.1467-9450.2009.00743.x.

Fitzpatrick, E.M., Crawford, L., Ni, A., Durieux-Smith, A., 2011. A descriptive analysis of language and speech skills in 4- to 5-yr-old children with hearing loss. Ear Hear. 32, 605–616. https://doi.org/10.1097/AUD.0b013e31821348ae.

Flaugnacco, E., Lopez, L., Terribili, C., Montico, M., Zoia, S., Schön, D., 2015. Music training increases phonological awareness and reading skills in developmental dyslexia: a randomized control trial. PLoS One 10. https://doi.org/10.1371/journal.pone.0138715.

Fu, Q.J., Galvin 3rd, J.J., Wang, X., Wu, J.-L., 2015. Benefits of music training in Mandarin-speaking pediatric cochlear implant users. J. Speech Lang. Hear. Res. 58, 163–169. https://doi.org/10.1044/2014_JSLHR-H-14-0127.

Fuller, C.D., Galvin 3rd, J.-J., Maat, B., Baskent, D., Free, R.H., 2018. Comparison of two music training approaches on music and speech perception in cochlear implant users. Trends Hear 22, 1–22. https://doi.org/10.1177/2331216518765379.

Galvin 3rd, J.J., Fu, Q.-J., Oba, S.I., 2009. Effect of a competing instrument on melodic contour identification by cochlear implant users. J. Acoust. Soc. Am. 125, EL98–EL103. https://doi.org/10.1121/1.3062148.

Geers, A.E., Nicholas, J.G., 2013. Enduring advantages of early cochlear implantation for spoken language development. J. Speech Lang. Hear. Res. 56, 643–653. https://doi.org/10.1044/1092-4388(2012/11-0347.

Gfeller, K., 2016. Music-based training for pediatric CI recipients: a systematic analysis of published studies. Eur. Ann. Otorhinolaryngol. Head Neck Dis. 133S, S50–S56. https://doi.org/10.1016/j.anorl.2016.01.010.

Gomes, H., Molholm, S., Christodoulou, C., Ritter, W., Cowan, N., 2000. The development of auditory attention in children. Front. Biosci. 5 (1), d108–d120.

https://doi.org/10.2741/Gomes.
Good, A., Gordon, K.A., Papsin, B.C., Nespoli, G., Hopyan, T., Peretz, I., Russo, F.A., 2017. Benefits of music training for perception of emotional speech prosody in deaf children with cochlear implants. Ear Hear. 38, 4554–4564. https://doi.org/10.1097/aud.0000000000000402.
Gordon, E.E., 1979. Primary Measures of Music Audiation and the Intermediate Measures of Music Audiation. G.I.A. Publications, Chicago, IL.
Gordon, R.L., Fehd, H.M., McCandliss, B.D., 2015. Does music training enhance literacy skills? A meta-analysis. Front. Psychol. 6 https://doi.org/10.3389/fpsyg.2015.01777.
Hartas, D., 2011. Families' social backgrounds matter: socio-economic factors, home learning and young children's language, literacy and social outcomes. Br. Educ. Res. J. 37 (6) https://doi.org/10.1080/01411926.2010.506945, 8939–14.
Hashemi, S.B., Monshizadeh, L., 2012. The effect of cochlear implantation in development of intelligence quotient of 6-9 deaf children in comparison with normal hearing children (Iran, 2009-2011). Int. J. Pediatr. Otorhinolaryngol. 76, 802–804. https://doi.org/10.1016/j.ijporl.2012.02.046.
Hausen, M., Torppa, R., Salmela, V.R., Vainio, M., Särkämö, T., 2013. Music and speech prosody: a common rhythm. Front. Psychol. 4 https://doi.org/10.3389/fpsyg.2013.00566.
Hidalgo, C., Falk, S., Schön, D., 2017. Speak on time! Effects of a musical rhythmic training on children with hearing loss. Hear. Res. 351, 1118. https://doi.org/10.1016/j.heares.2017.05.006.
Houston, D.M., Pisoni, D.B., Kirk, K.I., Ying, E.A., Miyamoto, R.T., 2003. Speech perception skills of deaf infants following cochlear implantation: a first report. Int. J. Pediatr. Otorhinolaryngol. 67, 479–495. https://doi.org/10.1016/S0165-5876(03)00005-3.
Hull, R. (Ed.), 2013. Introduction to Aural Rehabilitation. Plural Publishing, San Diego, CA.
Hyde, K.L., Lerch, J., Norton, A., Forgeard, M., Winner, E., Evans, A.C., Schlaug, G., 2009. Musical training shapes structural brain development. J. Neurosci. 29, 3019–3025. https://doi.org/10.1523/JNEUROSCI.5118-08.2009.
Innes-Brown, H., Marozeau, J.P., Storey, C.M., Blamey, P.J., 2013. Tone, rhythm, and timbre perception in school-age children using cochlear implants and hearing aids. J. Am. Acad. Audiol. 24 (9) https://doi.org/10.3766/jaaa.24.9.4, 7898–06.
Jaschke, A.C., Honing, H., Scherder, E.J.A., 2018. Longitudinal analysis of music education on executive functions in primary school children. Front. Neurosci. 12 https://doi.org/10.3389/fnins.2018.00103.
Janus, M., Lee, Y., Moreno, S., Bialystok, E., 2016. Effects of short-term music and second-language training on executive control. J. Exp. Child Psychol. 144, 84–97. https://doi.org/10.1016/j.jecp.2015.11.009.
Jusczyk, P.W., Houston, D.M., Newsome, M., 1999. The beginnings of word segmentation in English-learning infants. Cogn. Psychol. 39, 159–207. https://doi.org/10.1006/cogp.1999.0716.
Kalathottukaren, R.T., Purdy, S.C., Ballard, E., 2017. Prosody perception and production in children with hearing loss and age- and gender-matched controls. J. Am. Acad. Audiol. 28, 2832–2894. https://doi.org/10.3766/jaaa.16001.
King, A.J., Calvert, G.A., 2001. Multisensory integration: perceptual grouping by eye and ear. Curr. Biol. 11, r322–r325. https://doi.org/10.1016/S0960-9822(01)00175-0.
Kong, Y.-Y., Mullangi, A., Marozeau, J., Epstein, M., 2011. Temporal and spectral cues for musical timbre perception in electric hearing. J. Speech Lang. Hear. Res. 54, 981–994. https://doi.org/10.1044/1092-4388(2010/10-0196.
Koşaner, J., Kilinc, A., Deniz, M., 2012. Developing a music programme for preschool children with cochlear implants. Cochlear Implants Int. 13 (4) https://doi.org/10.1179/1754762811Y.0000000023, 2372–47.
Kraus, N., Strait, D.L., 2015. Emergence of biological markers of musicianship with school-based music instruction. Ann. N. Y. Acad. Sci. 1337 (1), 163–169.
Krueger, J.W., 2011. Doing things with music. Phenomenol. Cognitive Sci. 10 (1), 1–22. https://doi.org/10.1007/s11097-010-9152-4.
Lappe, C., Herholz, S.C., Trainor, L.J., Pantev, C., 2008. Cortical plasticity induced by short-term unimodal and multimodal musical training. J. Neurosci. 8 https://doi.org/10.1523/JNEUROSCI.2254-08.2008, 9632e, 9639.
Linnavalli, T., Putkinen, V., Lipsanen, J., Huotilainen, M., Tervaniemi, M., 2018. Music playschool enhances children's linguistic skills. Sci. Rep. 8 https://doi.org/10.1038/s41598-018-27126-5.
Lo, C.Y., McMahon, C.M., Looi, V., Thompson, W.F., 2015. Melodic contour training and its effect on speech in noise, consonant discrimination, and prosody perception for cochlear implant recipients. Behav. Neurol. 352869 https://doi.org/10.1155/2015/352869.
Looi, V., McDermott, H., McKay, C., Hickson, L., 2008. Music perception of cochlear implant users compared with that of hearing aid users. Ear Hear. 29, 421–434. https://doi.org/10.1097/AUD.0b013e31816a0d0b.
Lund, E., 2016. Vocabulary knowledge of children with cochlear implants: a meta-analysis. J. Deaf Stud. Deaf Educ. 21, 107–121. https://doi.org/10.1093/deafed/env060.
Lyxell, B., Wass, M., Sahlen, B., Samuelsson, C., Asker-Arnason, L., Ibertsson, T., Mäki-Torkko, E., Larsby, B., Hallgren, M., 2009. Cognitive development, reading and prosodic skills in children with cochlear implants. Scand. J. Psychol. 50, 463–474. https://doi.org/10.1111/j.1467-9450.2009.00754.x.
MacDonald, R.A., Hargreaves, D.J., Miell, D. (Eds.), 2002. Musical Identities. OUP, Oxford.
Männel, C., Friederici, A.D., 2013. Accentuate or repeat? Brain signatures of developmental periods in infant word recognition. Cortex 49, 2788–2798. https://doi.org/10.1016/j.cortex.2013.09.003.
Manolson, A., 1992. It Takes Two to Talk. A Parent's Guide to Helping Children Communicate, third ed. Hanen Centre, Toronto.
Mattys, S.L., 1997. The use of time during lexical processing and segmentation: a review. Psychon. Bull. Rev. 4, 310–329. https://doi.org/10.3758/BF03210789.
Mithen, S., Morley, I., Wray, A., Tallerman, M., Gamble, C., 2006. The Singing Neanderthals: the Origins of Music, Language, Mind and Body, by Steven Mithen. Weidenfeld & Nicholson, London, 2005.
Moore, B.C.J., 2003. Speech processing for the hearing-impaired: successes, failures, and implications for speech mechanisms. Speech Commun. 41 https://doi.org/10.1016/S0167-6393(02)00095-X, 819–1.
Moreno, S., Bialystok, E., Barac, R., Schellenberg, E.G., Cepeda, N.J., Chau, T., 2011. Short-term music training enhances verbal intelligence and executive function. Psychol. Sci. 22, 1425–1433. https://doi.org/10.1177/0956797611416999.
Moreno, S., Bidelman, G.M., 2014. Examining neural plasticity and cognitive benefit through the unique lens of musical training. Hear. Res. 308 https://doi.org/10.1016/j.heares.2013.09.012, 849–7.
Moreno, S., Lee, Y., Janus, M., Bialystok, E., 2015. Short-term second language and music training induces lasting functional brain changes in early childhood. Child Dev. 86 (2) https://doi.org/10.1111/cdev.12297, 3944–06.
Näätänen, R., 1992. Attention and Brain Function. Routledge.
Nikolopoulos, T.P., Wells, P., Archbold, S.M., 2000. Using Listening Progress Profile (LIP) to assess early functional auditory performance in young implanted children. Deaf. Educ. Int. 2 (3), 142–151.
O'Halpin, R., 2010. The Perception and Production of Stress and Intonation by Children with Cochlear Implants [dissertation]. University College London, London, UK. http://eprints.ucl.ac.uk/20406/.
Oxenham, A.J., 2008. Pitch perception and auditory stream segregation: implications for hearing loss and cochlear implants. Trends Amplif. 12, 316–331. https://doi.org/10.1177/1084713808325881.
Pantev, C., Oostenveld, R., Engelien, A., Ross, B., Roberts, L.E., Hoke, M., 1998. Increased auditory cortical representation in musicians. Nature 392 (6678), 811. https://doi.org/10.1038/33918.
Patel, A.D., 2003. Language, music, syntax and the brain. Nat. Neurosci. 6 (7), 674. https://doi.org/10.1038/nn1082.
Patel, A.D., 2010. Music, Language, and the Brain. Oxford university press.
Patel, A.D., 2011. Why would musical training benefit the neural encoding of speech? The OPERA hypothesis. Front. Psychol. 2, 142. https://doi.org/10.3389/fpsyg.2011.00142.
Patel, A.D., 2014. Can nonlinguistic musical training change the way the brain processes speech? The expanded OPERA hypothesis. Hear. Res. 308, 98–108. https://doi.org/10.1016/j.heares.2013.08.011.
Patscheke, H., Degé, F., Schwarzer, G., 2018. The effects of training in rhythm and pitch on phonological awareness in four- to six-year-old children. Psychol. Music 1–6. https://doi.org/10.1177/0305735618756763.
Peng, S.C., Tomblin, J.B., Turner, C.W., 2008. Production and perception of speech intonation in pediatric cochlear implant recipients and individuals with normal hearing. Ear Hear. 29, 336–351. https://doi.org/10.1097/AUD.0b013e318168d94d.
Percy-Smith, L., Busch, G., Sandahl, M., Nissen, L., Josvassen, J.L., Lange, T., Rusch, E., Caye-Thomasen, P., 2013. Language understanding and vocabulary of early cochlear implanted children. Int. J. Pediatr. Otorhinolaryngol. 77, 184–188.
Peretz, I., Gosselin, N., Nan, Y., Caron-Caplette, E., Trehub, S.E., Beland, R., 2013. A novel tool for evaluating children's musical abilities across age and culture. Front. Syst. Neurosci. 7, 30. https://doi.org/10.3389/fnsys.2013.00030.
Petersen, B., Mortensen, M.V., Hansen, M., Vuust, P., 2012. Singing in the key of life - a pilot study on effects of musical ear training. Psychomusicology 22, 134–151. https://doi.org/10.1037/a0031140.
Petersen, B., Weed, E., Sandmann, P., Brattico, E., Hansen, M., Sorensen, S.D., Vuust, P., 2015. Brain responses to musical feature changes in adolescent cochlear implant users. Front. Hum. Neurosci. 9 https://doi.org/10.3389/fnhum.2015.00007.
Phillips-Silver, J., Trainor, L.J., 2005. Feeling the beat: movement influences infant rhythm perception. Science 308 (5727), 14301–14430. https://doi.org/10.1126/science.1110922.
Polonenko, M.J., Giannantonio, S., Papsin, B.C., Marsella, P., Gordon, K.A., 2017. Music perception improves in children with bilateral cochlear implants or bimodal devices. J. Acoust. Soc. Am. 141 (6), 4494–4507. https://doi.org/10.1121/1.4985123.
Posner, M.I., 1980. Orienting of attention. Q. J. Exp. Psychol. 32 (1), 3–25. https://doi.org/10.1080/00335558008248231.
Putkinen, V., Tervaniemi, M., Huotilainen, M., 2013. Informal musical activities are linked to auditory discrimination and attention in 2-3-year-old children: an event-related potential study. Eur. J. Neurosci. 37, 654–661. https://doi.org/10.1111/ejn.12049.
Putkinen, V., Tervaniemi, M., Saarikivi, K., de Vent, N., Huotilainen, M., 2014a. Investigating the effects of musical training on functional brain development with a novel Melodic MMN paradigm. Neurobiol. Learn. Mem. 110, 8–15. https://doi.org/10.1016/j.nlm.2014.01.007.
Putkinen, V., Tervaniemi, M., Saarikivi, K., Ojala, P., Huotilainen, M., 2014b. Enhanced development of auditory change detection in musically trained school-aged children: a longitudinal event-related potential study. Dev. Sci. 17, 282–297. https://doi.org/10.1111/desc.12109.
Rocca, C., 2012. A different musical perspective: improving outcomes in music through habilitation, education, and training for children with cochlear implants. Semin. Hear. 33 https://doi.org/10.1055/s-0032-1329229, 4254–33.

Rocca, C., 2015. Developing the musical brain to boost early pre-verbal, communication and listening skills: the implications for musicality development pre- and post-cochlear implantation. It is not just about Nursery Rhymes! Cochlear Implants Int. 16, S.32–S.38. https://doi.org/10.1179/1467010015Z.000000000277.
Rochette, F., Moussard, A., Bigand, E., 2014. Music lessons improve auditory perceptual and cognitive performance in deaf children. Front. Hum. Neurosci. 8 https://doi.org/10.3389/fnhum.2014.00488.
Ruismäki, H., Ruokonen, I., 2009. Children's right to good music education—some practical applications and synthesis towards the ideals of the children's rights declaration. Problems in Music Pedagogy 4, 7–17.
Saarikallio, S., Erkkilä, J., 2007. The role of music in adolescents' mood regulation. Psychol. Music 35 (1), 88–109. https://doi.org/10.1177/0305735607068889.
Saarikallio, S., 2011. Music as emotional self-regulation throughout adulthood. Psychol. Music 39 (3), 307–327. https://doi.org/10.1177/0305735610374894.
Schön, D., Tillmann, B., 2015. Short- and long-term rhythmic interventions: perspectives for language rehabilitation. Ann. N. Y. Acad. Sci. 1337, 32–39. https://doi.org/10.1111/nyas.12635.
Schorr, E.A., Fox, N.A., van Wassenhove, V., Knudsen, E.I., 2005. Auditory–visual fusion in speech perception in children with cochlear implants. Proc. Natl. Acad. Sci. Unit. States Am. 102, 18748–18750. https://doi.org/10.1073/pnas.0508862102.
Sharma, A., Campbell, J., Cardon, G., 2015. Developmental and cross-modal plasticity in deafness: evidence from the P1 and N1 event related potentials in cochlear implanted children. Int. J. Psychophysiol. 95 (2), 135–144.
Shimojo, S., Shams, L., 2001. Sensory modalities are not separate modalities: plasticity and inter- actions. Curr. Opin. Neurobiol. 11, 505–509.
Slater, J., Skoe, E., Strait, D.L., O'Connell, S., Thompson, E., Kraus, N., 2015. Music training improves speech-in-noise perception: longitudinal evidence from a community-based music program. Behav. Brain Res. 291, 244–252. https://doi.org/10.1016/j.bbr.2015.05.026.
Soleymani, Z., Mahmoodabadi, N., Nouri, M.M., 2016. Language skills and phonological awareness in children with cochlear implants and normal hearing. Int. J. Pediatr. Otorhinolaryngol. 83, 16–21. https://doi.org/10.1016/j.ijporl.2016.01.013.
Stevens, K.N., 1998. Acoustic Phonetics. The MIT Press, London, UK.
Thiessen, E.D., Saffran, J.R., 2007. Learning to learn: infants' acquisition of stress-based strategies for word segmentation. Lang. Learn. Dev. 3, 73–100. https://doi.org/10.1080/15475440709337001.
Tierney, A., Krizman, J., Kraus, N., 2015. Music training alters the course of adolescent auditory development. Proc. Natl. Acad. Sci. U. S. A. 112, 10062–10067. https://doi.org/10.1073/pnas.1505114112.
Torppa, R., 2015. Pitch-related Auditory Skills in Children with Cochlear Implants: the Role of Auditory Working Memory, Attention and Music [dissertation]. University of Helsinki, Helsinki, Finland. https://helda.helsinki.fi/handle/10138/157046.
Torppa, R., Faulkner, A., Huotilainen, M., Järvikivi, J., Lipsanen, J., Laasonen, M., Vainio, M., 2014a. The perception of prosody and associated auditory cues in early-implanted children: the role of auditory working memory and musical activities. Int. J. Audiol. 53, 182–191. https://doi.org/10.3109/14992027.2013.872302.
Torppa, R., Faulkner, A., Järvikivi, J., Vainio, M., 2010. Acquisition of focus by normal hearing and Cochlear Implanted children: the role of musical experience. In: Speech Prosody 2010. Chicago, USA. http://hdl.handle.net/10138/23603.
Torppa, R., Faulkner, A., Kujala, T., Huotilainen, M., Lipsanen, J., 2018. Developmental links between speech perception in noise, singing, and cortical processing of music in children with cochlear implants. Music Percept. 36, 156–174. https://doi.org/10.1525/MP.2018.36.2.156.
Torppa, R., Faulkner, A., Laasonen, M., Lipsanen, J., Sammler, D., in print. Links of prosodic stress perception and musical activities to language skills of children with CIs and normal hearing. Ear Hear..
Torppa, R., Huotilainen, M., Leminen, M., Lipsanen, J., Tervaniemi, M., 2014b. Interplay between singing and cortical processing of music: a longitudinal study in children with cochlear implants. Front. Psychol. 5 https://doi.org/10.3389/fpsyg.2014.01389.
Välimaa, T., Kunnari, S., Laukkanen-Nevala, P., Lonka, E., the National Clinical Research Team, 2018. Early vocabulary development in children with bilateral cochlear implants. Int. J. Lang. Commun. Disord. 53, 3–15. https://doi.org/10.1111/1460-6984.12322.
Vongpaisal, T., Caruso, D., Yuan, Z., 2016. Dance movements enhance song learning in deaf children with cochlear implants. Front. Psychol. 7 https://doi.org/10.3389/fpsyg.2016.00835.
Wechsler, D., 2010. Wechsler Intelligence Scale for Children, fourth ed.: Manual. Psykologien Kustannus Oy, Helsinki, Finland.
Welch, G.F., Saunders, J., Edwards, S., Palmer, Z., Himonides, E., Knight, J., Mahon, M., Griffin, S., Vickers, D.A., 2015. Using singing to nurture children's hearing? A pilot study. Cochlear Implants Int. 16, S63–S70. https://doi.org/10.1179/1467010015Z.000000000276.
White-Schwoch, T., Carr, K.W., Anderson, S., Strait, D.L., Kraus, N., 2013. Older adults benefit from music training early in life: biological evidence for long-term training-driven plasticity. J. Neurosci. 33 (45), 17667–17674. https://doi.org/10.1523/JNEUROSCI.2560-13.2013.
Wu, C.-M., Lee, H.-L., Hwang, J.-H., Sun, Y.-S., Liu, T.-C., 2008. Intellectual ability of Mandarin-speaking children using cochlear implants. Audiol. Neurotol. 13, 302–308. https://doi.org/10.1159/000124278.
Yucel, E., Sennaroglu, G., Belgin, E., 2009. The family oriented musical training for children with cochlear implants: speech and musical perception results of two year follow-up. Int. J. Pediatr. Otorhinolaryngol. 73 (7), 1043–1052. https://doi.org/10.1016/j.ijporl.2009.04.009.