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Research Article

Music Training for Children With Sensorineural Hearing Loss Improves Speech-in-Noise Perception

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Purpose: A growing body of evidence suggests that long-term music training provides benefits to auditory abilities for typical-hearing adults and children. The purpose of this study was to evaluate how music training may provide perceptual benefits (such as speech-in-noise, spectral resolution, and prosody) for children with hearing loss.

Method: Fourteen children aged 6–9 years with prelingual sensorineural hearing loss using bilateral cochlear implants, bilateral hearing aids, or bimodal configuration participated in a 12-week music training program, with nine participants completing the full testing requirements of the music training. Activities included weekly group-based music therapy and take-home music apps three times a week. The design was a pseudorandomized, longitudinal study (half the cohort was wait-listed, initially serving as a passive control group prior to music training). The test battery consisted of tasks related to music perception, music appreciation, and speech perception. As a comparison, 16 age-matched children with typical hearing also completed this test battery, but without participation in the music training.

Results: There were no changes for any outcomes for the passive control group. After music training, perception of speech-in-noise, question/statement prosody, musical timbre, and spectral resolution improved significantly, as did measures of music appreciation. There were no benefits for emotional prosody or pitch perception.

Conclusion: The findings suggest even a modest amount of music training has benefits for music and speech outcomes. These preliminary results provide further evidence that music training is a suitable complementary means of habilitation to improve the outcomes for children with hearing loss.

The continual advancement and confluence of effective early intervention, hearing technologies, clinical practice, and community engagement have resulted in better outcomes for children with hearing loss, and the majority achieve suitable proficiency when perceiving speech-in-quiet environments (Blamey et al., 2001). Poorer and more variable outcomes are observed in challenging listening situations such as speech-in-noise (SIN; Davies et al., 2001; Schafer & Thibodeau, 2006), spectral resolution (Landsberger et al., 2017), and prosodic tasks (Chin et al., 2012; Volkova et al., 2013). The perception and appreciation of music and musical features such as pitch and timbre may also present perceptual challenges for many individuals (Gfeller et al., 2011; Jung et al., 2012; Petersen et al., 2015; Trehub et al., 2009). Modern industrial society is inherently noisy, and the primary concern for children with hearing loss is that they have access to adequate audibility and intelligibility in the context of their learning, education, and social communication.

Studies have investigated the use of music training as a means of improving auditory skills in a wide range of adult and pediatric populations. Music training may be especially effective at refining auditory skills because it requires sensitivity to rapidly changing, fine-grained

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spectral and temporal cues (Kraus & Chandrasekaran, 2010). Such benefits may be especially useful for populations with hearing impairment, as supported by research on typical-hearing (TH) professional musicians. A recent review by Coffey et al. (2017) found that 18 of the 20 reviewed studies found support for a "musician advantage"—an enhancement of SIN perception. However, such benefits are difficult to interpret, because musical skills and activities are highly variable among musicians, and SIN can be measured with varying types of noise in a variety of speaker configurations. As such, the mechanisms by which musical skills lead to SIN enhancement have yet to be fully understood. Additionally, these 20 reviewed studies were cross-sectional in design, and it is plausible that individuals with better-than-average auditory skills may be predisposed into pursuing musicianship. On the other hand, a pediatric study by Slater et al. (2015) provided the first longitudinal evidence for a causal SIN benefit from music training. In this study, 38 TH children were equally distributed between a standard curriculum (introductory musicianship followed by group instrumental training) and to a wait-listed (control) group run by the Harmony Project (https://www.harmony-project.org/)—an organization that provides free music education for underserved children in Los Angeles. Randomization removed the risk of sampling bias and preexisting differences, and there were no significant differences in age, sex, gender, IQ, maternal education, SIN, or age of English acquisition. After 2 years of music training, 19 TH children showed a mean improvement of −2.1 dB signal-to-noise ratio (SNR) on the Hearing in Noise Test (Nilsson et al., 1994), demonstrating the efficacy of a community-based music program for improving speech perception outcomes in children.

Music and speech share many acoustic similarities, and the broad principle underlying the mechanism for the musician advantage is generally conceptualized as overlapping (or shared) perceptual or neural processes (Patel, 2014). However, evidence for cognitive transfer functions from music to speech perception is far from established, and there is also conflicting evidence for the functional specialization of brain structures with preference for specific sound categories (Angulo-Perkins et al., 2014; Peretz et al., 2015). Irrespective of these discrepancies, a consolidating perspective is that musicality is a multisensory experience that activates a wide range of brain regions associated with arousal, emotion, cognition, memory, and motor coordination (Brown & Palmer, 2012; Rauscher & Hinton, 2011; Thompson et al., 2001; Wan & Schlaug, 2010)—all of which may contribute to more effective auditory learning (Herholz & Zatorre, 2012; Shams & Seitz, 2008).

Benefits of multisensory activities have also been reported in pediatric hearing loss studies; Vongpaisal et al. (2016) demonstrated that even in a short-term song learning task, training that combined auditory and motor components was more beneficial than auditory training alone for nine cochlear implant (CI) recipients aged between 4 and 12 years. Another study by Innes-Brown et al. (2013) investigated the benefits of a year-long participation in "Music Club"—45-min musical activities centered around play for 11 children with hearing loss aged between 9 and 12 years. While participation did not confer any perceptual advantages, the children and teachers reported a wide range of benefits, such as increased engagement and interest in music, and increased levels of socialization with peers. Taken together, these findings promote physical engagement with music as an effective means of habilitation that may provide benefits beyond the auditory domain. Additionally, while the enjoyment of music is highly variable among children with hearing loss (Gfeller et al., 2011), it is a generally engaging activity that may assist in maintaining motivation and compliance—critical for longitudinal training studies (Gfeller, 2016; Patel, 2011; Trehub et al., 2009).

The number of studies that have investigated the benefits of music training for children with hearing loss is modest, with a wide range of music training protocols, age ranges, and outcomes of interest (for a review of music training for children with CIs, see Gfeller, 2016). The majority have been concerned primarily with music outcomes; Chen et al. (2010) tested 27 CI recipients aged between 5 and 14 years on a same/different pitch task. Half the participants were provided Yamaha Music School classes that involved listening, singing, score reading, and instrument playing over varying durations (2–36 months). A significant correlation was found between the duration of training and pitch perception, suggesting possible neuroplastic changes such as tonotopic reorganization and finer frequency tuning. These findings were further supported by Fu et al. (2015), with 14 CI recipients aged between 5 and 9 years improving in melodic pitch perception after 10 weeks of computer-based training, and in a study by Torppa et al. (2014) that found eight (from a total of 21) unilaterally implanted CI recipients aged between 4 and 13 years with music experience (primarily singing) performed significantly better than those without music experience in auditory perception and attention.

Other investigations have considered potential transfer effects to other domains with a focus on speech perception. Good et al. (2017) compared the effects of 6 months of music training to visual art training for CI recipients aged between 6 and 15 years, which led to an enhancement of musical skills and emotional prosody processing for the musically trained children, but not for the visual art trained children. In a melodic contour training study for native Mandarin-speaking CI recipients aged between 5 and 9 years, significant improvements were observed for melodic contour identification and lexical tone recognition after 8 weeks of training (Cheng et al., 2018). These studies suggest a transfer effect between music and prosodic/intonation tasks, which is well supported by findings in TH studies (Hausen et al., 2013; Thompson et al., 2004), as well as adult CI studies (Lo et al., 2015), all of which implicate the use of pitch and rhythm as primary cues for intonation perception. Additionally, a cross-sectional study by Torppa et al. (2018) compared informal singing experience and its association with speech perception in children with CIs aged between

4and 13 years. Children who sang at least once a week (as reported by their parents in a retrospective questionnaire) had better SIN performance than their peers in the nonsinging group.

Spectral resolution also plays a key role in speech and music perception, which rely on various spectral cues and contrasts. Spectral resolution is the ability to perceive and resolve fluctuations in the spectral domain. A common method of measuring spectral resolution is with spectral ripple tests that have the advantage of avoiding confounds of language due to its nonlinguistic stimuli. Several studies have shown reduced spectral resolution for adults with sensorineural hearing loss (SNHL; Turner et al., 1999) and children with CIs (Landsberger et al., 2017), when compared to their TH peers. Interestingly, in cross-sectional studies, spectral resolution has also been found to correlate with SIN and music performance in postlingually implanted adults (Won et al., 2007) and SIN in prelingually implanted children (Jung et al., 2012).

Separate to perceptual accuracy, music appreciation considers the role of enjoyment and qualitative appraisal as an important, yet often overlooked, outcome measure (for a review, see Looi, Gfeller, & Driscoll, 2012). For example, listeners do not need to identify instruments or specific notes within a composition to derive enjoyment from a musical piece (Looi, Gfeller, & Driscoll, 2012). Music training studies in adult CI populations have shown that music appreciation can be learned and improved (Looi, King, & Kelly-Campbell, 2012). Furthermore, the lack of correlation between perceptual outcomes and appreciation as noted by Gfeller et al. (2008) and Wright and Uchanski (2012) highlights the importance in evaluating appreciation separately. The enjoyment of music in pediatric populations with hearing loss shows individual variability with a general trend toward engagement and enjoyment (Chen-Hafteck & Schraer-Joiner, 2011; Gfeller et al., 2011). Compared to postlingually implanted/aided adults, prelingually implanted/aided children do not have a preconception of what music should sound like. This may provide significant advantages for perceptual and appreciation outcomes.

Multiple studies have recommended the use of music training as a complementary means of habilitation for children with hearing loss (Abdi et al., 2001; Chen et al., 2010; Petersen et al., 2015). However, the current body of evidence that music training is effective or more effective than a standard habilitation program is limited, although recent findings for speech transfer effects are promising (Cheng et al., 2018; Good et al., 2017). Finally, Fuller et al. (2018) suggested extensive and intensive programs that combine face-to-face lessons, along with computer-based pitch training, may yield the greatest benefit, while Chen-Hafteck and Schraer-Joiner (2011) suggest best practice may be the utilization of a wide range of activities to encourage the development of diverse skills.

The purpose of this study was to investigate the benefits of a 12-week music training program, consisting of group-based face-to-face music therapy, supplemented by online music apps for children with prelingual SNHL. Outcome measures included SIN, speech prosody (specifically emotional and question/statement prosody), spectral resolution, pitch and timbre perception, and music appreciation. Based on previous findings by Chen et al. (2010) and Good et al. (2017), we hypothesized music outcomes would improve and pitch perception would likely transfer to speech prosody. Irrespective of any change in perceptual accuracy, it was also hypothesized that participants would report higher levels of music appreciation after training. Additionally, given TH studies indicate an SIN benefit for adults and children with music training (Coffey et al., 2017; Slater et al., 2015) and singing experience is associated with better SIN perception for children with CIs (Torppa et al., 2018), an SIN enhancement was also predicted. A measure of spectral resolution was included as there is evidence that better spectral resolution is associated with better SIN performance in prelingual children with CIs (Jung et al., 2012), as well as music perception in adult CI recipients (Won et al., 2010). Finally, compared to the children with TH, it was expected children with SNHL would have poorer outcomes on all perceptual measures.

Method

Participants

Two groups of participants were tested in the study, stratified by hearing status (children with SNHL and TH). One group consisted of 14 children (seven girls, seven boys) with prelingual bilateral moderate-to-profound SNHL (eight bilateral CIs, four bimodals, two bilateral hearing aids [HAs]) ranging in age from 6.1 to 9.2 years ($M = 7.5$, $SD = 1.1$) when measured at Baseline 2. Inclusion criteria for children with SNHL included prelingual (aiding or implantation < 3.5 years), bilateral SNHL with moderate-to-profound thresholds. Most children with SNHL (9/14) were enrolled in mainstream school settings, while the others attended schools for the deaf and hard of hearing with specialist support. From the group of 14 children with SNHL, 11 commenced the music training, while the remaining three only completed the 12-week double baseline measures. Of the 11 children with SNHL that commenced music training, nine completed all testing sessions, one withdrew after the midpoint due to a surgical operation, and one family left the country at the follow-up stage. Relevant demographic data for children with SNHL can be found in Table 1.

For comparative purposes, 16 TH children (seven girls, nine boys), ranging in age from 6.3 to 8.7 years ($M = 7.6$, $SD = 0.8$), were also included. There was no significant difference in chronological age, $t(25) = 0.86$, $p = .400$, or formal music training, $t(25) = 0.58$, $p = .569$, between children with SNHL and TH. At the start of each session, the TH children underwent pure-tone audiometric testing to confirm hearing thresholds (0.25–8 kHz ≤ 20 dB HL). All participants were native Australian English speakers. Exclusion criteria for all participants included any diagnosed

Table 1. Demographic information for children with sensorineural hearing loss.

ID	Group	Age/hearing age (Baseline 2)	Age at first fitting/ implantation	Sex	Formal music experience[a]	Degree of hearing loss	Device configuration	Device	Processor	Strategy	Active electrodes	Aetiology	Schooling	Other
HL1	1	6.3/6.0	0.3	F	0	L: Profound R: Profound	CI	L: CI422 (SRA) R: CI522 (SRA)	L: CP910 R: CP910	L: ACE R: ACE	L: 22 R: 22	Unknown	Specialized	Withdrew at follow-up
HL3	1	8.3/7.0	1.3	M	3.7	L: Profound R: Profound	CI	L: CI24RE (ST) R: CI522 (ST)	L: CP810 R: CP810	L: ACE R: ACE	L: 7 R: 22	Pneumococcal meningitis	Mainstream	
HL5	1	6.1/3.1	3.0	F	0.7	L: Profound R: Moderate	Bimodal	L: CI24RE (ST) R: Siemens Motion M	L: CP910	L: ACE	L: 22	Enlarged vestibular aqueduct	Specialized	
HL6	1	7.8/7.5	0.3	M	1.3	L: Moderately severe R: Severe	Bimodal	L: Phonak BTE R: CI512 (CA)	R: CP910	R: ACE	R: 22	Unknown	Mainstream	Withdrew at posttraining
HL8	1	8.5/7.7	0.8	F	4.2	L: Moderately severe R: Moderately severe	HA	L: Siemens Motion P R: Siemens Motion P				Usher syndrome	Mainstream	
HL11	2	6.7/6.2	0.5	F	0	L: Moderately severe R: Profound	Bimodal	L: Siemens BTE R: CI24RE (CA)	R: CP910	R: ACE	R: 22	Hypoplasia of the auditory nerve	Mainstream	
HL12	2	7.8/5.8	2.0	M	4.3	L: Profound R: Profound	CI	L: CI24RE (CA) R: CI24RE (CA)	L: CP920 R: CP920	L: ACE R: ACE	L: 22 R: 22	Unknown	Mainstream	
HL14	2	6.7/4.9	1.8	F	0.2	L: Profound R: Profound	CI	L: CI24RE (CA) R: CI24RE (CA)	L: CP920 R: CP920	L: ACE R: ACE	L: 22 R: 21	Waardenburg syndrome type 2	Specialized	
HL15	2	6.3/6.0	0.3	M	1.3	L: Profound R: Profound	CI	L: CI512 (unknown) R: CI422 (unknown)	L: CP920 R: CP920	L: ACE R: ACE	L: 22 R: 22	Unknown	Mainstream	

(*table continues*)

Table 1. *(Continued).*

ID	Group	Age/hearing age (Baseline 2)	Age at first fitting/ implantation	Sex	Formal music experience[a]	Degree of hearing loss	Device configuration	Device	Processor	Strategy	Active electrodes	Aetiology	Schooling	Other
HL16	2	8.6/8.5	0.1	M	4.8	L: Moderately severe R: Moderately severe	HA	L: Phonak BTE R: Phonak BTE				Genetic	Mainstream	
HL17	2	6.8/6.7	0.1	F	4.5	L: Profound R: Severe	Bimodal	L: Concerto FLEX28 R: Siemens BTE	L: Sonnet	L: FS4	L: 12	Connexin 26	Mainstream	
HL18	2	9.2/7.2	2.0	F	0	L: Profound R: Profound	CI	L: CI24RE (ST) R: CI24RE (ST)	L: CP910 R: CP910	L: ACE R: ACE	L: 22 R: 19	Unknown	Specialized	No training—completed baselines
HL19	2	6.8/6.3	0.5	M	0	L: Profound R: Profound	CI	L: CI24RE (CA) R: CI24RE (CA)	L: CP910 R: CP910	L: ACE R: ACE	L: 22 R: 22	Genetic	Specialized	No training—completed baselines
HL20	2	8.8/8.4	0.4	M	3.6	L: Profound R: Profound	CI	L: CI512 (CA) R: CI512 (CA)	L: CP910 R: CP910	L: ACE R: ACE	L: 22 R: 20	Connexin 26	Mainstream	No training—completed baselines

Note. Formal music experience was calculated as the duration (in years) of the musical activity, multiplied by its frequency, divided by the number of categories (n = 6). The musical activity categories were music lessons, singing groups, instrumental groups, dance classes, and group-based classes. As an example, 1 year of weekly piano lessons = 0.7. F = female; L = left; R = right; M = male; CI = cochlear implant; SRA = Straight Research Array; ST = Straight; CA = Contour Advance; HA = hearing aid; ACE = Advanced Combination Encoder.

[a] Measured at the commencement of music training.

psychological or developmental disorder. Relevant demographic data for TH children can be found in Table 2.

Direct invitations were sent via clinics to families within New South Wales fitting the inclusion criteria, and flyers were distributed to clinics and hearing/deafness groups for distribution in newsletters and social media outlets. Parental written consent and participant assent were obtained prior to commencement of testing, and approval for this study was granted by the Macquarie University Human Research Ethics Committee (Medical Sciences; reference: 5201600081).

Experimental Design

Data collection spanned approximately 9 months, using a longitudinal wait-list design. After an initial test session (Baseline 1), children with SNHL were pseudorandomly assigned to commence music training immediately (Group 1, $n = 5$) or placed in the wait-listed group (Group 2, $n = 9$) that commenced music training 12 weeks later. Pseudorandom assignment was due to the lengthy time commitment this study placed on families (i.e., if specific dates were not suitable for participation, they could opt for the other group). For all perceptual measures, double baseline testing occurred, separated by 1 week for Group 1 and separated by 12 weeks for Group 2. The advantage of this experimental design is that it allowed for an assessment of test–retest reliability, a baseline measure of natural development and maturation over a 12-week period for the wait-listed group, and had the additional benefit of maximizing statistical power by not having to split the cohort into a training group and a control group. After the completion of double baselines, participants were tested after 6 weeks of music training (mid), after completion of the full 12 weeks of music training (post), and finally, 12 weeks after training was completed to measure retention (follow-up). An additional cohort of age-matched TH children was included as a comparison group; they completed the same test battery as the children with SNHL but did not receive music training and were only utilized to indicate the broad difference between children with SNHL and TH children. An overview of this design can be seen in Figure 1.

Table 2. Demographic information for typical-hearing (TH) children.

ID	Age range	Sex	Formal music experience
TH1	8.0	F	2.7
TH2	6.3	M	0.7
TH3	7.8	F	10.8
TH4	6.3	F	4.0
TH5	8.2	M	3.3
TH6	8.3	M	2.7
TH7	6.6	F	5.3
TH8	8.6	F	2.5
TH9	6.3	M	0.0
TH10	7.5	M	2.0
TH11	7.2	F	0.3
TH12	8.7	M	1.0
TH13	7.6	M	1.3
TH14	7.3	M	0.0
TH15	8.4	F	7.7
TH16	7.7	M	1.5

Note. F = female; M = male.

Stimuli

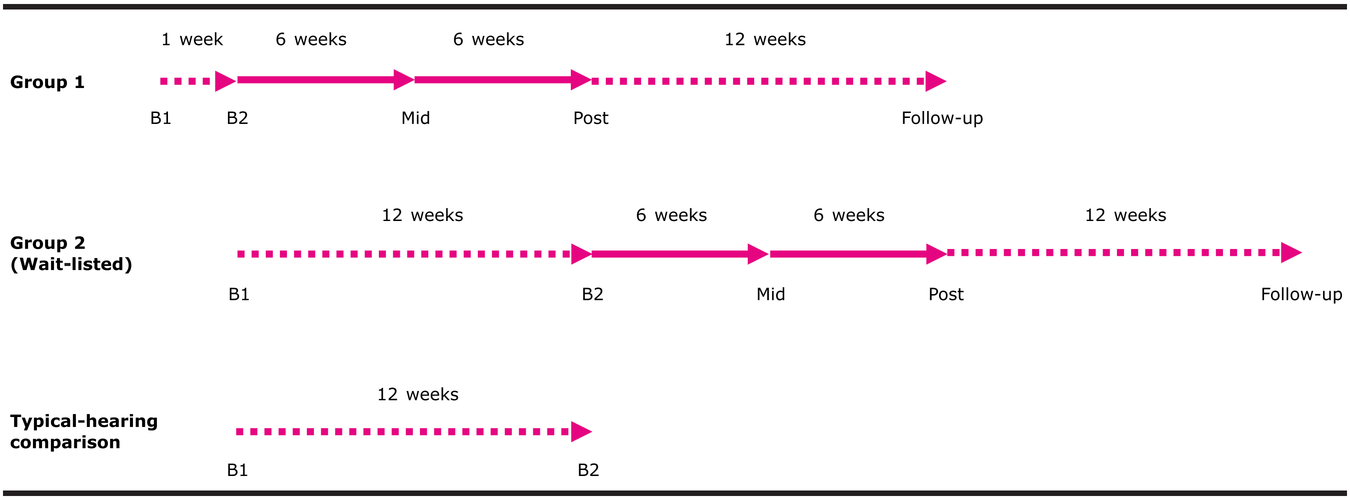
Australian Sentence Test in Noise

SIN was measured with the Australian Sentence Test in Noise (AuSTIN), an adaptive SIN test that has the unique advantage of being specifically designed for Australian English CI recipients (Dawson et al., 2013). The complexity of the speech materials was suitable for children, as the sentences were developed with audiologists and speech pathologists familiar with the linguistic capabilities of Australian children with hearing loss (Dawson et al., 2013). The AuSTIN features an adult female as the target speaker in the presence of four-talker babble featuring two adult female and male speakers. Twenty sentences (each comprising between four and six words or six to eight syllables) were randomly selected without replacement and presented. Participants were asked to repeat the sentence as best as they heard and were morphemically scored (e.g., singing consists of two morphemes: "sing" and "*–ing*"). If the participant scored ≥ 50% morphemes correct, the competing noise level was increased, and if the participant scored < 50% morphemes correct, the competing noise level was decreased. The AuSTIN adaptive rules and speech reception threshold (SRT; defined as the SNR at which 50% of words were correctly perceived) calculation rules were selected. The initial SNR was 12 dB, with 4-dB step sizes for the first four sentences, followed by 2-dB step sizes for the remaining sentences. SRTs were calculated as the average of the SNRs for Sentences 5–20 and the SNR of Sentence 21 (which was not presented) based on the participant's response to Sentence 20. The AuSTIN has been well validated and, using these parameters, has a test–retest reliability of 0.99 dB. Thus, it is a suitable and appropriate SIN test for a longitudinal study with Australian English–speaking children with SNHL.

Spectral-Temporally Modulated Ripple Test

Spectrotemporal modulation detection performance was measured with Spectral-Temporally Modulated Ripple Test (SMRT) Version 1.1 (Aronoff & Landsberger, 2013). The SMRT has been used effectively in studies of children (Kirby et al., 2015; Landsberger et al., 2017). Stimuli were nonharmonic tone complexes with 202 equal amplitude pure-tone frequency components spaced every 1/33.33 of an octave from 100 to 6400 Hz. Stimuli were 500 ms in duration, with 100-ms onset/offset linear ramps generated with a 44.1-kHz sampling rate. Participants were presented with a three-alternative forced choice (3-AFC) task in which two choices were reference stimuli at 20 ripples per octave (rpo). The third choice was the target stimulus at an initial 0.5 rpo, with a 1-up 1-down adaptive procedure

Figure 1. Overview of study design. Periods of music training are denoted by solid lines.



with a step size of 0.2 rpo. After 10 reversals, a threshold was calculated based on the last six reversals.

Macquarie Battery of Emotional Prosody

Emotional prosody was measured with the Macquarie Battery of Emotional Prosody (MBEP; Thompson et al., 2012) that consisted of sentences that varied in emotional prosody. The sentences were semantically neutral, such as "the girl and boy went to the fridge, to get some milk for lunch," and were recorded by four female and four male speakers. Each sentence was 14 syllables in length and spoken with the emotional state of happy, sad, angry, and scared. For this study, the MBEP was configured as a 2-AFC task with two conditions: happy/sad and angry/scared. The happy/sad sentences were representative of an easier task as their acoustic features were more perceptually distinct than angry/scared. Scores were averaged between the two conditions and calculated as percentage correct. While this specific test has not been previously used with children, the sentences and paradigms are not dissimilar to comparable test materials that have been used effectively for children with hearing loss (e.g., Chatterjee et al., 2015).

Question/Statement Prosody Test

The Question/Statement Prosody Test was developed for this study to measure performance in differentiating questions from statements through a rising or falling terminal pitch. Two native adult speakers of Australian English recorded eight simple bisyllabic words (e.g., carrot, garlic, orange; typical fruit and vegetable items) uttered naturally in question form with a rising pitch and in a statement form with a flat or falling pitch. Speakers maintained a consistent vocal effort, tempo, and level of intonation. The tokens were recorded in a sound-proof room with an AKG C535 EB microphone connected to a PreSonus StudioLive 16.4.2 mixing console with Pro Tools 11. High-pass filtering was set on the mixing console at 75 Hz. Each token was saved as an individual .wav file, and the root-mean-square level was adjusted to −25 dB FS. Participants were presented with 32 words in random order (2 speakers × 2 intonations × 8 words), and results were scored as percentage correct. Participants were instructed they would hear one word and had to decide if it sounded like the person speaking was asking the participant if they wanted the item (question utterance) or if it sounded like the person speaking was telling the participant they were simply pointing out an item (statement utterance). On average, the pitch extraction for both male and female speakers for the question utterance was approximately one octave (or 12 semitones) when measured from lowest to highest frequency. The tokens developed for this test were similar to those in the Receptive Turn-End subtest of the Profiling Elements of Prosodic Systems–Child Version (Peppé & McCann, 2003), which is appropriate for both adults and children.

Clinical Assessment of Music Perception

The Clinical Assessment of Music Perception Test (Kang et al., 2009) was developed as a measure of music perception for adult CI recipients but has been successfully administered for child CI recipients (Jung et al., 2012). It consists of three subtests: Pitch Direction Discrimination, Melody Recognition, and Timbre Recognition. In this study, two subtests were used: Pitch Direction Discrimination and Timbre Recognition. Prior to each subtest, participants were provided brief practice sessions.

The pitch direction discrimination task used a 2-AFC, 1-up 1-down adaptive testing method. The stimuli consisted of digitally synthesized, complex piano tones at three base frequencies: 262 Hz (C4), 330 Hz (E4), and 392 Hz (G4). Two tones were presented consecutively, a base frequency, and an initial interval presented at 12 semitones (one octave), in random order. Participants were instructed to select the tone that was higher in pitch (i.e., the first or second tone). A correct response would yield a smaller subsequent pitch interval, whereas an incorrect response would yield a larger subsequent pitch interval (at that base frequency). The largest interval size was 12 semitones, the lowest interval size was 1 semitone, and the step size was 1 semitone. When a participant answered a 1-semitone interval correctly, this was treated as a reversal at zero to create an accurate psychometric function. The participant's pitch discrimination thresholds were calculated using the last six of eight reversals at each base frequency, and their final pitch discrimination threshold was calculated as an average of all three base frequencies.

The use of a 1-up 1-down adaptive testing method has been criticized as it estimates the chance-level point of the psychometric function. However, studies have confirmed its empirical utility and reliability, with Kang et al. (2009) finding this subtest to be highly reliable (Cronbach's alpha = .91). A study by Won et al. (2010) also utilized a technique that estimated a higher point on the psychometric function (75% correct) and found a strong correlation with pitch thresholds derived through the standard testing technique ($r = .97$). Intended for rapid, clinical use, its utility as a widely adopted test that allows for comparisons against multiple studies and its suitability for this study's participants outweigh its theoretical weaknesses. A detailed discussion justifying this test method can be found in Drennan et al. (2015).

The timbre recognition task was an 8-AFC task. The stimuli comprised eight live-recorded musical instruments that spanned four major classes: strings (violin and cello), brass (saxophone and trumpet), woodwinds (flute and clarinet), and percussion (guitar and piano). All instruments played an identical five-note melody (C4-A4-F4-G4-C5) at 82 beats per minute, which were level-matched and played with the same articulation and phrasing. Each instrument was played three times in random order, and participants were tasked with selecting the instrument they heard. Scores were calculated as percent correct.

Formal Music Experience

The Role of Music in Families Questionnaire (RMFQ) was developed to evaluate the role of music in families of children with hearing loss and their general attitudes and level of engagement with music (Looi et al., 2019, 2018). The RMFQ consists of seven broad sections: General Demographic Information, Childhood Music Participation and Experiences, Attitudes and Reactions to Music, Resources for Child Regarding Music, Overall Importance of Music in Your Household and Family, Child's Music Listening Preferences, and Future Perspective. One section of the RMFQ (Childhood Music Participation and Experiences) was used in this study to appraise the level of formal music participation and experience each participant had received prior to commencement of this study. A score was calculated on the basis of duration (in terms of years), multiplied by its frequency (1 = *less often than monthly,* 2 = *once a month,* 3 = *2–3 times a month,* 4 = *once a week,* 5 = *4–6 times a week,* 6 = *2–3 times a week,* and 7 = *daily*), divided by the total number of categories ($n = 6$) that assessed activities: music lessons, singing groups, instrumental groups, special children's programs, dance classes, and group-based music classes. As an example, 1 year of weekly piano lessons equates to: 1 (year) × 4 (frequency, weekly) ÷ 6 (categories) = 0.7.

Music Appreciation

A music appreciation questionnaire developed by Looi, King, and Kelly-Campbell (2012) for adults with hearing loss was adapted for use in this study. Changes in music appreciation were measured after music training was completed. Questionnaires were child and parent reported, requiring a response (depending on context) of "much better/more," "a little better/more," "no change," "a little worse/more," or "much worse/more" with assigned values of +2, +1, 0, −1, and −2, respectively. Scores were averaged across parent and child. The questions asked were: Has the music program…

1. changed your enjoyment of music?
2. made music sound more pleasant?
3. made music sound more natural?
4. changed your ability to identify instruments?
5. changed your ability to recognize melodies?
6. changed your ability to learn new songs?
7. changed how much music you listen to?
8. changed how much you want to continue learning/exploring music?
9. changed your overall interest in music?
10. changed how much you want to learn an instrument/continue learning an instrument?

Procedure

Testing

All testing occurred in an acoustically treated sound booth. The test battery was administered using a laptop computer with the following peripheral connections: Audio output was through a loudspeaker (Genelec 8020C) connected to an external sound card (Yamaha AUDIOGRAM 3). Test battery responses were displayed and inputted by the child on a touchscreen monitor. The presentation level of test materials was calibrated to 65 dBA with a Digitech QM1592 sound-level meter measured at the participants' position, located 1 m directly in front of the loudspeaker. The exception was the MBEP, as each emotion varied with intensity; as such, the happy sentences were used for level calibration.

The test battery took approximately 1 hr to complete. All perceptual test materials were presented in randomized order. Testing was shared between three experimenters (the first author and two research assistants); as such, approximately half of all test sessions were blinded. Participants could have a break at any time and were prompted by the experimenter if they would like a break halfway through the test session. Questionnaires were paper based, with demographic information and the RMFQ completed by a parent in the first baseline test session. The music appreciation questionnaire was completed by participants in the post-training test session, with the experimenter reading aloud each questionnaire item to the child who could ask for clarification at any time. Children responded either verbally or by pointing to their selection. Honest responses were emphasized, and children were not allowed to consult or discuss their responses with their parents. Feedback and encouragement were provided for the first three tokens of each perceptual test or for the duration of the practice trials. A token gift such as a sticker was provided halfway through the testing to maintain motivation and at the end of the test session.

Training

Music training was provided over 12 weeks, with a focus on maximizing access to a broad range of musical skills and activities. The curriculum consisted of weekly, 40-min, face-to-face group-based (four to five children per class) music therapy sessions facilitated by a registered music therapist at Macquarie University on a Saturday morning. The curriculum was created by the registered music therapist, based on the Nordoff–Robbins (or Creative Music Therapy) approach that emphasizes active music making between therapists and their clients (Nordoff et al., 2007). Input was provided from the first two authors to adapt the activities for children with SNHL. Participants were also expected to complete a series of activities three times a week (approximately 15–30 min, depending on ability) with MusicFirst Junior (Music Sales Group, 2018)—an online-based suite of music apps designed for children aged between 6 and 12 years that is compatible for PC/Mac/smart devices that included Morton Subotnick's Music Academy and Groovy Music. The app curriculum was developed by the first author, with input from the music therapist to match the goals at each week. Parents were encouraged to set aside a regular time for app use, which was regarded as homework. MusicFirst Junior allows for a rudimentary logging of activity (not completed, partially completed, or completed activity), and app use and compliance were discussed at each Saturday morning session with the parents. Examples of music therapy activities include drumming, singing, dancing, and improvisation. Examples of the music apps include "drawing" and creating compositions and identification of high, low, fast, or slow sounds. While group-based activities are ecologically valid and have the advantage of social engagement, they lack the level of control that computer-based approaches allow for, which also have the additional benefit of data logging the activities. Thus, this hybrid approach of face-to-face group-based activities, supplemented by online-based apps, was used to provide a broad range of musical activities and tasks during a limited time frame. The music therapy curriculum can be found in the Appendix.

Results

Statistical Analyses

IBM SPSS Statistics (Version 22) was used to perform main hypothesis testing using linear mixed models with restricted maximum likelihood. A significant advantage to linear mixed models is that it can accommodate missing data; hence, all data from participants can be used for analysis even for those that did not complete the entirety of the music training ($n = 2$). An independent-samples t test was used for comparisons between children with SNHL and TH, and Bonferroni-corrected p values are reported; concordance between parent and child responses on music appreciation was examined using Cohen's kappa statistical test and a nonparametric Wilcoxon signed-ranks test for the appreciation questionnaire responses. Visual inspection of Q–Q plots at baseline for all variables did not reveal any obvious deviations from expected normal distributions. The criterion for statistical significance was fixed at $p = .05$.

For the double baseline analyses of the children with SNHL ($n = 14$), the following fixed effects were entered: time (Baseline 1 and Baseline 2), group (1-week retest and 12-week retest/wait-listed cohort), Time × Group (interaction term), device configuration (CI, bimodal, and HA), formal music experience, and hearing age (chronological age − age at fitting/implantation). It should be noted that hearing age was used to simplify the model and avoid overparameterization (due to the small sample size) by accounting for both chronological age and age at fitting/implantation as one variable. Accounting for formal music experience and hearing age in analyses is recommended by Gfeller (2016) for music training studies. For the double baseline analyses of the TH children ($n = 16$), the following fixed effects were entered: time (Baseline 1 and Baseline 2), formal music experience, and chronological age. For the music training analyses of the children with SNHL ($n = 11$), the following fixed effects were entered: time (pre—their Baseline 2 scores, mid, post, and follow-up), device configuration (CI, bimodal, HA), formal music experience, and hearing age.

For the training analyses of the children with SNHL, participants were entered as random effects with random intercepts (random slopes were of interest, but they failed to converge); however, due to a lack of variability primarily from ceiling effects, the TH children were entered as random effects without random intercepts. These models were used to predict the following outcome measures: SIN, spectral resolution, pitch, timbre, emotional prosody, and question/statement prosody performance over time—controlling for device configuration, hearing age/chronological age (for TH children), and formal music experience.

Double Baseline Measures

For the children with SNHL, no statistically significant differences were found for the main effect of time or the interaction between time and group (i.e., either 1-week or 12-week retest) for any measure, with the exception of emotional prosody that improved significantly by 6.7% from Baseline 1 to Baseline 2, *F*(1, 13) = −2.746, *p* = .017, driven primarily by the wait-listed group. Hearing age was a statistically significant factor for pitch, timbre, emotional prosody, and question/statement prosody: *F*(1, 8) = −4.75, *p* = .001; *F*(1, 8) = 4.41, *p* = .002; *F*(1, 8) = 4.83, *p* = .001; *F*(1, 8) = 2.33, *p* = .048, respectively—underscoring the importance of hearing age (and more broadly, natural development) as a parameter of interest. Device configuration was only statistically significant for the spectral resolution task; HA users' spectral resolution (*M* = 5.0 rpo) was significantly better than that of CI recipients, *M* = 2.68 rpo, *F*(2, 8) = −2.68, *p* = .029, and bimodal users, *M* = 2.5 rpo, *F*(2, 7) = −2.69, *p* = .031. Formal music experience was trending toward significance for pitch perception, *F*(1, 8) = −2.22, *p* = .057. The estimated marginal means for the baseline results can be observed in Table 3.

For the TH children, no statistically significant differences were found for the effect of time. Chronological age was a statistically significant factor for pitch, spectral resolution, emotional prosody, and trending toward significance for SIN: *F*(1, 28) = −2.78, *p* = .010; *F*(1, 26) = 2.93, *p* = .007; *F*(1, 19) = 2.21, *p* = .040; *F*(1, 27) = −2.04, *p* = .052, respectively. Formal music experience was a statistically significant factor for question/statement prosody, *F*(1, 27) = 2.36, *p* = .026.

As the majority of the double baseline measurements were not statistically significant, the data from the participants with a retest of 1 week suggest that there was no learning or practice effect of the test materials, while the data from the participants with a retest of 12 weeks suggest there was no effect of natural maturation and development. Thus, any subsequent improvement in outcome measures was likely the result of the music training itself.

Attendance and Compliance

Attendance was generally high, ranging from 67% to 100% attendance rate (*M* = 83%, *SD* = 10%) across the 12 weeks of music therapy sessions, with most absences due to illness or family obligations. Participants were expected to complete the assigned apps three times a week. The use of apps was more variable with one participant not using the app at all (the parent-reported time constraints). With the removal of this outlier, music app compliance ranged from 39% to 83% (*M* = 64%, *SD* = 13%) over 12 weeks. Additionally, one participant also left the study in Week 8 due to a surgical procedure.

Perceptual Measures

Table 4 summarizes all outcome measures across time points for the children with SNHL. Mean estimates of each outcome measure across time with a TH comparison can be observed in Figure 2. The following results are estimated marginal means relative to performance at the pretraining measurement; comparisons to TH children are made in respect to raw Baseline 2 measures (as the models to calculate each group's estimated marginal means are not equivalent).

SIN

A statistically significant improvement was observed for SIN at the posttraining point with a mean SRT decrease of 1.1 dB, *F*(3, 11) = −2.40, *p* = .036, which was essentially retained at the follow-up point with a decrease of 1 dB, *F*(3, 15) = −2.17, *p* = .046. On average, TH children's SRTs were 3.8 dB lower, 95% CI [−5.6, −2.0], than those of children with SNHL, *t*(12) = −4.55, *p* = .004.

Spectral Resolution

A statistically significant improvement was observed for spectral resolution at the posttraining point with a mean increase of 2 rpo, *F*(3, 12) = 4.89, *p* ≤ .001, and this was retained at the follow-up point with an improvement of 1.7 rpo, *F*(3, 9) = 3.76, *p* = .005. On average, TH children's spectral resolution was 4.5 rpo higher than that of children with SNHL, *t*(25) = 6.66, 95% CI [3.1, 5.8], *p* < .001.

Emotional Prosody

No statistically significant improvement for emotional prosody was observed for any time point. However, performance was generally excellent at pretraining (82% correct), suggesting a task that was too easy, with four participants scoring above 95% at the pretraining time point, indicating a ceiling effect. On average, TH children's perception of emotional prosody was 13 percentage points higher than that of children with SNHL, though this was not statistically significant, *t*(13) = 2.95, 95% CI [4, 23], *p* = .07.

Question/Statement Prosody

A statistically significant improvement was observed for question/statement prosody at the posttraining point

Table 3. Baseline results (estimated marginal means) for children with sensorineural hearing loss.

Group	Time	SIN (dB)	Spectral resolution (rpo)	Pitch (semitones)	Timbre (%)	Emotional prosody (%)	Question/statement prosody (%)
1-week retest	Baseline 1	4.2	3.7	5.9	31.3	78.9	78.3
	Baseline 2	3.7	4.1	5.1	29.5	82.0	78.2
12-week retest	Baseline 1	2.5	2.7	4.6	22.8	77.2	60.0
	Baseline 2	2.8	3.1	3.9	18.2	83.9	67.7

Note. SIN = speech-in-noise.

Table 4. Results from the linear mixed models for perceptual measures across time points.

				95% CI	
Parameter	**Estimate (*M, SE*)**	***t***	***p***	**Lower**	**Upper**
Speech-in-noise (SRT, dB)					
Pre	3.4 (0.6)	.	.	2.1	4.8
Mid	2.9 (0.6)	−1.04	.314	1.5	4.2
Post	2.3 (0.6)	−2.40	.036*	1.0	3.6
Follow-up	2.4 (0.6)	−2.17	.046*	0.9	3.8
Spectral resolution (rpo)					
Pre	3.6 (0.5)	.	.	2.5	4.7
Mid	4.7 (0.6)	1.94	.076	3.3	6.1
Post	5.6 (0.5)	4.89	< .001*	4.5	6.8
Follow-up	5.3 (0.5)	3.76	.005*	4.1	6.6
Emotional prosody (%)					
Pre	82.2 (2.0)	.	.	77.7	86.6
Mid	85.2 (2.1)	1.23	.239	80.6	89.7
Post	85.3 (1.8)	1.40	.191	81.0	89.6
Follow-up	85.3 (1.6)	1.58	.138	81.1	89.5
Question/statement prosody (%)					
Pre	70.8 (5.8)	.	.	57.9	83.7
Mid	77.8 (5.9)	1.40	.181	64.8	90.9
Post	84.4 (4.9)	3.61	.004*	72.1	96.8
Follow-up	79.1 (5.3)	1.99	.069	65.7	92.5
Pitch (threshold, semitones)					
Pre	4.3 (0.5)	.	.	3.1	5.4
Mid	3.6 (0.5)	−1.30	.216	2.3	5.0
Post	3.8 (0.9)	−0.59	.571	1.7	5.8
Follow-up	4.0 (0.6)	−0.61	.566	2.6	5.3
Timbre (%)					
Pre	24.3 (3.1)	.	.	16.2	32.4
Mid	30.6 (3.2)	2.46	.028*	23.1	38.1
Post	32.4 (3.8)	2.44	.032*	23.9	40.8
Follow-up	29.6 (4.3)	1.41	.227	19.2	40.0

Note. SRT = speech reception threshold.

*$p \leq .05$, relative to pretraining measurement.

with a mean increase of 14 percentage points, $F(3, 12) = 3.61$, $p = .004$, although this benefit was not fully retained at the follow-up point with an improvement of 8 percentage points, $F(3, 13) = 1.99$, $p = .069$. On average, TH children's perception of question/statement prosody was 10 percentage points higher than that of children with SNHL; however, this was not statistically different, $t(25) = 1.32$, 95% CI [−6, 26], $p = 1.18$.

Pitch

No statistically significant improvement for pitch threshold was observed over any time point. Surprisingly, TH children's pitch thresholds were not significantly different to those of the children with SNHL. On average, TH children's mean thresholds were 2.1 semitones lower, $t(25) = 1.80$, 95% CI [−4.4, 0.3], $p = .500$.

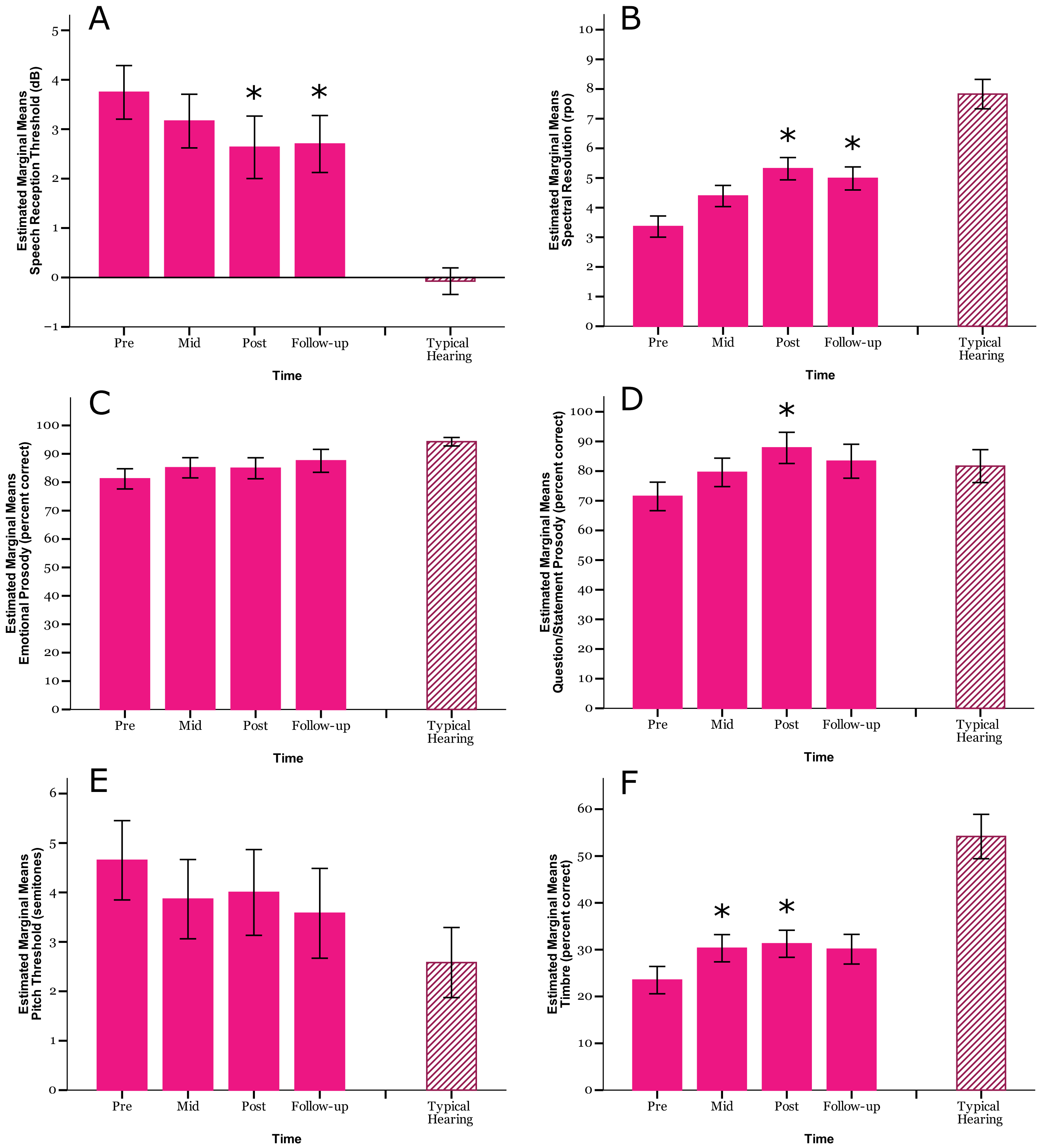
Timbre

A statistically significant improvement was observed at the midtraining point with timbre perception increasing by 6 percentage points, $F(3, 12) = 2.46$, $p = .028$, and at the posttraining point with an increase of 8 percentage points, $F(3, 12) = 2.44$, $p = .032$. However, this was not retained at the follow-up point with an improvement of 5 percentage points, $F(3, 4) = 1.41$, $p = .227$. On average, TH children's timbre perception was 31 percentage points higher than that of children with SNHL, $t(23) = 5.56$, 95% CI [19, 42], $p < .001$.

Device Configuration, Hearing Age, and Formal Music Experience

Generally, device configuration, hearing age, and formal music experience were not significant factors for most outcome measures in the statistical model. Considering that hearing age was a significant factor for pitch, timbre, and prosodic tasks and device configuration was a significant factor for spectral resolution at baseline measures, it suggests that the effect of training was greater than the effect of hearing age or device configuration. Device configuration and formal music experience were not significant factors in any of the measures with music training. However, hearing age was a significant factor for emotional prosody and pitch perception, $F(1, 6) = 6.2$, $p < .001$; $F(1, 5) = -3.2$, $p = .022$, respectively—reiterating the importance of including hearing age as a parameter of interest,

Figure 2. Bar graphs of estimated marginal means across time with a comparison of typical-hearing children's performance: (A) speech-in-noise, (B) spectral resolution, (C) emotional prosody, (D) question/statement prosody, (E) pitch, and (F) timbre. Error bars: ± 1 *SE*. **p* ≤ .05 compared to pre time point.



particularly for pitch-based tasks. A scatter plot of hearing age with pitch and emotional prosody (averaged across all time points) can be observed in Figure 3.

Mechanisms for SIN Enhancement

Post hoc analyses explored possible mechanisms for SIN enhancement. As both spectral resolution and timbre perception improved significantly, bivariate correlations between these and SIN were analyzed (measures were averaged over all time points). As shown in Figure 4, a moderate correlation was found between timbre perception and SIN, Pearson's $r = .611$, $p = .046$; although correlation does not equate to causation, this finding provides evidence to further explore this relationship as a potential mechanism. No correlation was found between spectral resolution and SIN, Pearson's $r = -\ .149$, $p = .662$.

Music Appreciation

Interrater reliability was examined between parent and child responses for music appreciation. For most measures, Cohen's kappa agreement was poor (−.67 to .17), except questions asking if the music program had (a) affected the child's ability to identify instruments and (b) affected the child's motivation to learn or continue learning an instrument (.44 = moderate agreement). Music appreciation was evaluated with a Wilcoxon signed-ranks test, with a hypothesized median of interest set to 0 = *no change*. Table 5 indicates that, after music training, a statistically significant improvement was observed for the vast majority of parent-reported observations, while children-reported music sounded more pleasant, that it improved their ability to identify instruments and that they wanted to learn or continue to learn an instrument.

Discussion

After a 12-week music training program, outcomes for SIN, spectral resolution, timbre, and question/statement prosody were improved for children with prelingual, moderate-to-profound SNHL. While improvement to question/statement results broadly corroborate prosodic benefits found in other studies (Good et al., 2017; Lo et al., 2015), the enhancement of SIN, spectral resolution, and timbre perception are novel, and to the authors' best knowledge, this is the first time such an effect has been observed after a music-based intervention for children with hearing loss. The trajectory of benefit was specific to each outcome variable, with question/statement prosody only improving at the posttraining point, timbre perception improving at midtraining and posttraining time points, and SIN and spectral resolution improving at the posttraining and follow-up points. It is difficult to ascertain whether these differences of trajectory are due to auditory development or the specificity of the curriculum provided. Additionally, it should be noted that, by the follow-up time point, the number of participants was reduced by two, leading to a reduction of power for all measures at this point. Despite this, the observation that SIN and spectral resolution benefits were maintained at follow-up indicates a fairly robust effect. As expected, children with SNHL performed more poorly than their TH peers in a range of measures: SIN, spectral resolution, and timbre perception. However, pitch and both prosodic tasks were not significantly different, which will be discussed at a later stage in this article.

Double baseline results for all groups (children with SNHL over 1-week or 12-week retest and a TH comparison) were nonsignificant, except for emotional prosody for the wait-listed group, which improved significantly. Collectively, the results indicate that all tests were not subject to practice effects and had suitable test–retest reliability and

Figure 3. Scatter plot of estimated marginal means for hearing age with emotional prosody (left) and hearing age with pitch (right).

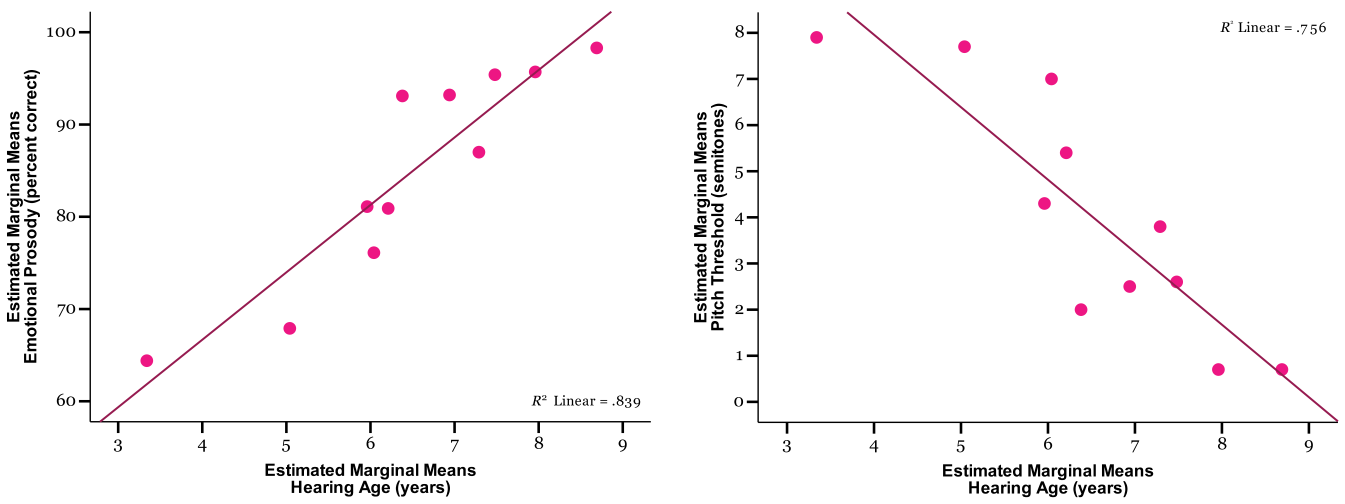
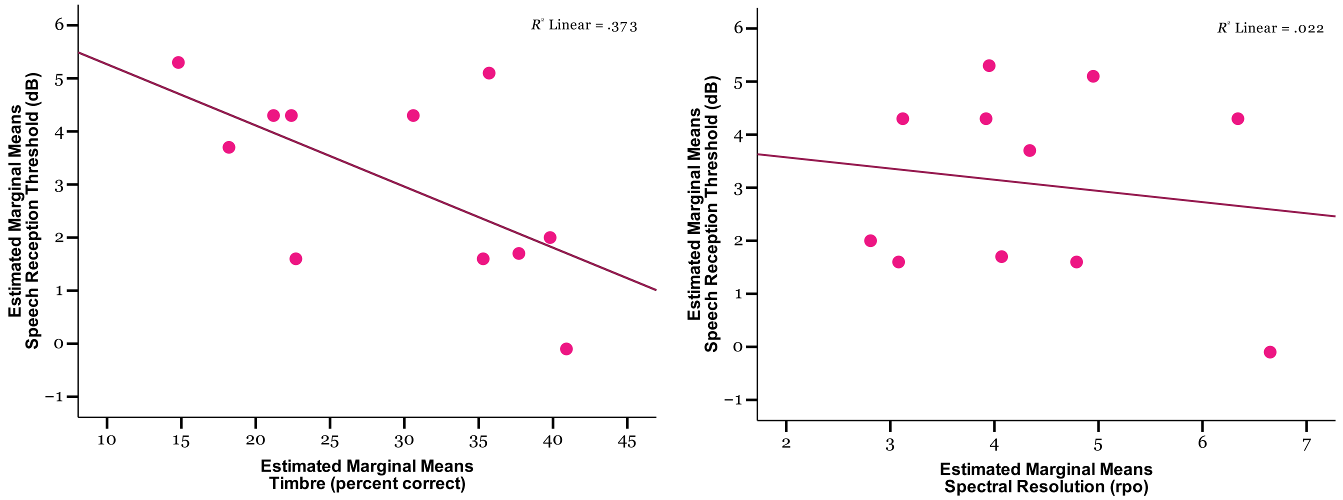


Figure 4. Scatter plot of estimated marginal means for timbre with speech-in-noise (left) and spectral resolution with speech-in-noise (right).



that natural development and maturation over a 12-week period are insufficient to generate a significant change for the vast majority of outcomes measured. Additionally, the near-ceiling performance on most tasks for the TH group indicated measures were developmentally appropriate for the age range of the children in the current study. While it was possible that some of the children with SNHL may have had a slight delay in their development of skills such as language, this likelihood was reduced by the widespread adoption of effective early intervention principles within Australia (Ching, 2015) and the fact that the children in this study were prelingually implanted/aided. There were no significant differences in age or formal music experience between the children with SNHL and TH. Hence, any change in outcome is likely attributable to the music intervention itself.

SIN enhancement is of considerable interest for habilitation as children require a greater SNR than adults to attain similar speech intelligibility in noisy environments (Neuman et al., 2010; Schafer et al., 2012). Children with hearing loss are disproportionately affected by poor classroom acoustics (Valente et al., 2012), so it is unsurprising that SIN remains a commonly reported problem (Davies et al., 2001; Schafer & Thibodeau, 2006). It is also assumed that speech perception affects overall quality of life—although this is not well established empirically (Schorr et al., 2009). SIN can be conceptualized as a higher order auditory task, which is likely supported by top-down processes, which are in turn activated, developed, and organized through auditory input (Kral & Eggermont, 2007). The results of this study are encouraging and suggest that, even with a short duration of music training, SIN enhancement is potentially attainable for children with hearing loss, likely driven by experience-based neuroplastic fine tuning of the auditory system. However, while the overall benefit for SIN was statistically significant, the effect size is relatively small with a mean improvement of 1.1 dB for SRTs. This value is

Table 5. Wilcoxon signed-ranks test of music appreciation and interrater reliability.

	Parent report (*n* = 10)			**Child report (*n* = 10)**			
Has the music training program…	***Z* (*SE*)**	***Mdn***	***p***	***Z* (*SE*)**	***Mdn***	***p***	**Kappa**
1. changed your enjoyment of music?	45 (8.2)	1	.006*	6 (1.8)	0	.102	.09
2. made music sound more pleasant?	10 (2.5)	0	.046*	10 (2.5)	1	.046*	.09
3. made music sound more natural?	10 (2.6)	0	.059	7 (2.7)	0	.458	.00
4. changed your ability to identify instruments?	28 (5.8)	1	.015*	15 (3.6)	1	.038*	.44
5. changed your ability to recognize melodies?	45 (8.2)	2	.006*	10 (2.6)	1	.059	.17
6. changed your ability to learn new songs?	28 (5.8)	1	.015*	6 (1.8)	0	.102	−.67
7. changed how much music you listen to?	28 (5.8)	1	.015*	9 (2.6)	0	.131	.15
8. changed how much you want to continue learning/exploring music?	28 (5.8)	1	.015*	6 (1.7)	0	.083	.00
9. changed your overall interest in music?	28 (5.7)	2	.014*	13 (3.6)	1	.129	−.04
10. changed how much you want to learn an instrument/continue learning an instrument?	28 (5.8)	1	.015*	15 (3.5)	2	.034*	.44

*$p \leq .05$, relative to a hypothesized median = 0 (no change).

close to the test–retest reliability of the AuSTIN (0.99 dB) for adult CI recipients (Dawson et al., 2013). However, the longitudinal nature of the study, the use of a double baseline, in conjunction with the maintenance of SIN improvement at the follow-up point, supports the assertion that this is a reliable effect.

Timbre perception significantly improved at the mid- and posttraining time points but was not retained when measured at the follow-up time point, due in part to a reduction of statistical power with two participants absent at this time point. This perceptual finding was supported by a music appreciation question that directly probed whether participants believed they were better able to identify instruments after training. Unlike previous adult hearing loss studies that have found qualitative/subjective appraisals do not necessarily correlate with perceptual outcomes (Gfeller et al., 2008; Looi et al., 2007), this study provides some evidence that, while parents and children were generally in poor agreement with each other for the music appreciation measures, there was consistency with the qualitative and behavioral results of timbre/instrument identification. Improved identification of instruments was also one of the few music appreciation measures that had a moderate level of agreement between parent and child reports. It should also be noted that the instruments in the Clinical Assessment of Music Perception timbre test were generally different to the instruments used in training (of the eight instruments in the test battery, only piano and guitar were used consistently in training). Interestingly, post hoc analyses showed a moderate correlation between timbre and SIN perception and no correlation between spectral resolution and SIN. The relationship between timbre and SIN in CI adult studies is mixed, with Kang et al. (2009) finding a positive association, while Gfeller et al. (1998), albeit from a much older CI study, did not. Furthermore, the relationship between speech and musical timbre in pediatric populations with hearing loss has not been previously explored. While our findings are correlational and unable to account for any causal effect, it suggests two interpretations for future consideration. First, while SIN and timbre are often described in terms of discrete spectral or temporal cues, it is important to note that spectrotemporal modulations are more representative of natural speech (Santoro et al., 2014) and provide a more dynamic perspective of timbre (Patil et al., 2012). As such, the results suggest the possibility that an underlying shared process (such as enhancement of temporal cues or spectrotemporal modulations) led to gains, improving performance for both SIN and timbre perception. Second, the benefit may be conceptualized as a direct consequence of better timbre perception skills improving the perceptual organization of auditory objects relevant for auditory scene analysis (Bregman, 1994; Ding & Simon, 2012; Kraus & Chandrasekaran, 2010). That is, the timbre task required the identification of instruments; improvement may have transferred specifically to the SIN task, in terms of better identification of the target (single female speaker) from masker signals (four-talker babble) that differ in spectrotemporal modulations.

The large improvement in spectral resolution is noteworthy. Previous investigations have found that TH adults and children improve their spectral resolution as a function of age, whereas children with CIs mature at around 7 years old (Horn et al., 2017) and do not seem to improve as a function of age (Landsberger et al., 2017). Better spectral resolution is also associated with better SIN performance in postlingually implanted adults (Lawler et al., 2017; Won et al., 2007) and prelingually implanted children (Jung et al., 2012). However, post hoc analyses from this study investigating correlations between spectral resolution and SIN find no evidence to support this relationship. This is in line with suggestions by Horn et al. (2017) and Landsberger et al. (2017), who argue that the auditory development of prelingually implanted children is fundamentally different to that of postlingual adults, with a greater weighting of temporal cues over spectral cues. The discrepancy between SIN and spectral resolution correlations in prelingually implanted children, as reported by Jung et al. (2012), could be due to the small sample size, difference in age (8–16 years), and the difference in test material. Spectral discrimination assessed in spectral ripple tests is often confounded by factors such as loudness, spectral centroid, and changes to spectral edges (Azadpour & McKay, 2012). The SMRT (which was used in this study) was designed to avoid these confounding factors and may be a more accurate measure of spectral resolution (Aronoff & Landsberger, 2013).

Additionally, a study by Nittrouer et al. (2014) investigated perceptual weighting strategies in 8-year-old children with and without CIs. Based on their findings, they proposed that limited access to spectral cues diminished the development of language and perceptual weighting strategies. However, key to their argument was that this was independent to auditory sensitivity and that enhancing sensitivity was not optimal for phonemic (i.e., language-based) learning. As such, improvement to spectral resolution is likely to yield benefits, but in the longer term context of language development. A final consideration is that learning effects have been noted in tests of spectral resolution. Tested at multiple time points, de Jong et al. (2017) found the maximum mean improvement of 1.6 rpo was noted after 4 weeks. However, as suggested by de Jong et al., the use of a double baseline as well as test time points that are beyond a “carryover” period—an effect or ability that carries over from one test to another—is recommended. As there was no significant difference for any baseline measures, our results are likely indicative of actual improvement resulting from the intervention that avoids a carryover effect. Taken together, the results from this study are both novel and encouraging and open opportunities to the utility of music as a means of enhancing spectral resolution for children who have SNHL that otherwise does not appear to develop over time. However, benefits for music and speech outcomes as a result of improved spectral resolution for prelingual children with hearing loss would likely require a longer time frame to develop (White-Schwoch et al., 2013).

Contrary to findings by Chen et al. (2010), pitch perception did not improve in this study. This was likely due to differences in training protocol, study design, and age of cohort; Chen et al. (2010) provided 13 CI recipients aged between 5 and 14 years with Yamaha Music School classes, which likely had a greater focus on traditional music pedagogy that involved score reading and instrument playing. Additionally, their findings were based on a study design that provided 2–36 ($M = 13.2$) months of music training to participants, as opposed to this study in which all participants essentially received 12 weeks of training. As such, their findings are based on a correlation between duration of training and pitch perception, as opposed to whether perceptual abilities were significantly different to baseline or control performance. The curriculum of this study had a broad range of musical activities that initially focused on rhythm-, then timbre-, and then pitch-related tasks; therefore, the amount of pitch-based training may not have been sufficient for changes to occur. Interestingly, in this study, pitch perception performance was not significantly different between children with SNHL and those with TH. This is likely due to the age of the cohort, as the development of pitch has been estimated to not be fully matured until 11 years in TH children (Lamont, 1998). This interpretation is also supported by the significant factor of hearing age for pitch perception and emotional prosody in statistical modeling, which is shown in Figure 3. While there is a lack of data regarding the perceptual development of pitch perception as a function of age in children with SNHL, it is reasonable to expect that maturation would be delayed, given delayed access to auditory input, as well as early intervention programs focusing extensively on speech and language development.

Two prosodic tasks were used in this study. While the sentence-based emotional prosody tasks did not significantly improve, the single-word question/statement task did. Unlike the study by Good et al. (2017) that used a 4-AFC task and found significant benefit to emotional prosody after music training, this study used a 2-AFC task differentiated by difficulty, with happy/sad (easier condition) and angry/scared (harder condition). As such, the emotional prosody task was likely hampered by ceiling effects with five participants scoring above 95% ($M = 96\%$) at the pretest session with both conditions averaged and with four participants scoring above 90% ($M = 95\%$) at the pretest even for the harder condition. On the other hand, question/statement prosody improved significantly. As pitch intonation is the primary cue for both prosodic tasks, this finding was not expected. However, the intonation curves were approximately 12 semitones (or an octave) in width, which is well within the participant's pitch thresholds, and these naturalistic utterances are also within the expected range for rising intonation utterances in studies with more controlled stimuli that extend as high as 15 semitones (Chatterjee & Peng, 2008; Holt & McDermott, 2013). Additionally, pitch was only tested using a discrete pitch direction task, and it is possible that broader measures of continuous pitch changes such as in the Montréal Battery for Evaluation of Musical Activities or a melodic contour identification task as developed by Galvin et al. (2007) may be more suitable for measuring pitch-based improvements for children with hearing loss, as they are similar to pitch intonations found in natural speech.

While the music appreciation results showed little concordance between parent and child responses, results indicated an overall positive change to music appreciation. The lack of concordance between the parents and children is not entirely surprising, given the vast difference in perceptual abilities and expectations from the study. Borrowing from quality of life literature that has long examined interrater reliability between TH child and parent-proxy reports—without consistent evidence as to which is more reliable, it is preferable to consider that each rater provides a contribution from a different perspective (Eiser & Morse, 2001; Jokovic et al., 2004). Overall, the parents reported widespread benefits across the vast majority of music appreciation measures, while responses from the children were more conservative. It is possible the parents' responses were subject to participant bias, with the expectation that enrolling their children into the music program would result in positive outcomes. After training, children reported music as sounding more pleasant and had an improved ability to identify instruments, which corresponds to the measured improvement in timbre perception. Interestingly, while there was no significant change in general interest toward music, likely as the children had a high level of engagement and interest in music to begin with (Chen-Hafteck & Schraer-Joiner, 2011), they specifically wanted to learn or continue learning an instrument. A study by MacKenzie (1991) investigated the motivations for wanting to learn an instrument in 48 TH children aged between 7 and 11 years. Their findings suggest that they are primarily self-motivated, followed by the influence of a teacher. As even the children who were learning an instrument wanted to continue, it is highly likely the music therapist was also influential in this study. Anecdotally, many parents discussed instrumental training with the music therapist at the end of the 12-week music training session.

Compared to findings in postlingually implanted adults that found music more natural sounding after training (Looi, King, & Kelly-Campbell, 2012), this was not the case in this study, which makes sense in the context of prelingually implanted/aided children who have no point of reference as to what "natural" should be, other than their own subjective experience. There was no change in how much music (more/less) participants wanted to listen to. While we did not explicitly ask how much music they were already listening to prior to training, it was likely not different to their TH peers. This is supported by findings that the hours spent listening to music for children aged between 2 and 5 years is similar, irrespective of hearing loss (Looi et al., 2019, 2018).

Compliance and general enjoyment of the group-based face-to-face music therapy sessions were high. A Wilcoxon signed-ranks test, $Z = 21$, $p = .023$, indicated high levels of enjoyment as reported by the children. However, the use of apps was, at times, hampered by technical issues. Difficulties arose primarily as the app required an online connection, and a few parents expressed frustration at the slow load times and some compatibility issues on a range of devices. For the children that did not have technical problems, anecdotal evidence suggested overall enjoyment of the apps was high, but a Wilcoxon signed-ranks test, $Z = 19$, $p = .068$, was not significant, indicating a neutral appraisal of the apps in general. As stated by one of the parents:

> The app concept was great but let down by delivery over the Internet. Too slow and lots of waiting. The loading time made it hard to engage with the activities and had problems with logging in on a few occasions. (Parent of HL12)

As an off-the-shelf product with a purported wide range of hardware compatibility, one limitation is that participants' engagement with the apps was flexible and not controlled. Parents reported greatest levels of success on tablet-like devices (compared to desktop computers), which was likely preferred as they are both mobile and allow for tactile engagement. Overall, the hybrid approach of face-to-face classes complemented by online apps was one means of maximizing the amount of music training provided in a limited time. Parents were also asked to provide feedback after the music training program:

> We would like to continue with the music program, as our son has made significant progress in the 12 weeks, and we would love for him to go further again! We have noticed that he has become quicker to identify songs on the radio, and even more astounding is that he has suddenly developed some intonation and tune to his singing along, which was previously nonexistent. In addition, his music teacher at school has commented on his improvement, as have his clarinet teacher and band leader. (Parent of HL3)

This study was limited by a small sample size, lack of an active control group, and an unbalanced number of children using CI/bimodal/HA configurations. It should be noted that no analysis has been made to make any distinction between these configurations. While each device configuration is clearly distinct, the lack of statistical power and balance within the groups does not allow for analysis. Instead, we have treated the cohort as a broader group of children with moderate-to-profound SNHL. Furthermore, device configuration was a factor in the statistical model, and the use of a repeated-measures design helps mitigate any potential differences this may entail. Nonetheless, the strengths of this study include the use of double baselines, a relatively well-constrained age range compared to most studies of this nature, additional controlling for age effects by including hearing age as a factor in statistical modeling—which was a significant factor for pitch and prosodic tasks, and the use of a follow-up test point to measure retention. While the findings of this study indicate multiple benefits of music training for children with SNHL, it also more broadly supports a causal link between music training and perceptual skills, beyond inherent preexisting abilities. The use of a nonlinguistic spectral resolution task was also novel, as was the measurement of both music appreciation and perceptual accuracy. Musical activities and benefits were maximized by using a multimodal training protocol that combined group-based music therapy with the flexible use of apps. While this pedagogical approach makes implementation of music therapy for children with hearing loss viable with minimum modification to a standard curriculum, it potentially makes generalization and replication more variable and difficult than a highly structured computer-based approach (Gfeller, 2016). Replication of the present findings with larger sample sizes across a range of ages will be required to reinforce the efficacy of music training for children with hearing loss, and the results and interpretations of this study should not be considered definitive given the numerous limitations. Furthermore, highly structured training protocols targeting specific areas of music perception and utilizing various pedagogical approaches (e.g., pitch, timbre, rhythm; instrumental or vocal learning; face-to-face, individual, group, or computer-based approaches) may help with understanding the various auditory processes and speech transfer mechanisms.

Overall, the findings from this study provide preliminary evidence that music training benefits tasks beyond music skills, such as SIN, timbre, spectral resolution, and question/statement prosody during and after a 12-week music training program for children with SNHL. Much of the efficacy is likely derived from the multimodal approach of the music training in conjunction with high levels of enjoyment that music provides. This study considered mechanisms and benefit primarily from a perceptual basis; nonetheless, there are a great many possible mechanisms and areas of inquiry that are worthwhile considerations for future studies, including statistical learning (Mandikal Vasuki et al., 2017), cognitive factors such as working memory and attention (George & Coch, 2011; Torppa et al., 2014), language (Linnavalli et al., 2018), and the development of musical production skills (Xu et al., 2009). In conclusion, the findings lend support to previous studies indicating transfer effects to speech perception and add to a growing body of evidence that supports the use of music as an effective and complementary means of habilitation.

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Music Training for Children With Sensorineural Hearing Loss Improves Speech-in-Noise Perception

Week 1—Music therapy

Activities	Equipment	Goals
Hello	Guitar	• Social skill (acknowledge the members) • Singing (pitch, rhythm)
Drum • raindrop to thunder		• Explore dynamics • Creative expressions (modes of playing) • Working as a team
• Patterns (rhythm + modes)		• Auditory memory
“Shake” • Choices of instruments • Position • Body parts		• Choices of contrasting sounds • Concepts (auditory): start/stop, position, body parts • Listen for single-step instructions with music • Creative movement (dance)
“I have a sound”		• Confidence • Explore vocal sounds • Expand range of vocal sounds • Leader–follower • Relationship
Aeroplane	Paper plane	• Creative vocal expressions • Confidence in leading in a group
Parachute		• Auditory discrimination (fast/slow, loud/soft) • Teamwork
“It’s time to go now”		• Singing • Pitch and rhythm discrimination • Relating as a group—social skills

Week 2—Music therapy

Activities	Equipment	Goals
Hello	Guitar	• Social skill (acknowledge the members) • Singing (pitch, rhythm)
Drum • Recap raindrop to thunder • Pass round the circle (2 directions) • Pass with eyes closed		• Explore dynamics • Creative expressions (modes of playing) • Working as a team • Directional sounds
“Shake” • Choices of instruments • Position • Body parts • (eyes closed) • Listen for single-step instructions with music (from MT and peers)		• Choices of contrasting sounds • Concepts (auditory): start/stop • Position (up/down, right/left, front/back) • Body parts • Creative movement (dance)
“I have a sound” (with mic)		• Confidence • Explore vocal sounds • Expand range of vocal sounds • Leader–follower • Relationship
Aeroplane	Paper plane	• Creative vocal expressions • Confidence in leading in a group
Parachute		• Auditory discrimination (fast/slow, loud/soft)
“It’s time to go now”		• Singing • Pitch and rhythm discrimination • Call–response • Relating as a group—social skills

Week 3—Music therapy

Activities	Equipment	Goals
Hello	Guitar	• Social skill (acknowledge the members) • Singing (pitch, rhythm) • Volume increase
Drum • 'I like …' • Recall others' likings • Pass round the circle (2 directions) • Pass with eyes closed		• Explore speech rhythms • Creative expressions (modes of playing) • Working as a team • Directional sounds
"Shake" • Guess what instrument • Choices of instruments • Position • Body parts • Loud/soft highlight	3 pairs: Shaker Cabasa Castanet Clapper Jingle stick Bells	• Sound discrimination • Concepts (auditory): start/stop • Position (up/down, right/left, front/back, side to side) • Body parts • Listen for single-step instructions with music (from MT and peers)
"I have a sound" (with mic)	Long/short sounds High/low sounds taught	• Confidence • Explore vocal sounds • Expand range of vocal sounds • Leader–follower • Relationship
Parachute • Rotate seats when music stops	Range of pitches	• Auditory discrimination (fast/slow, loud/soft) • Teamwork • Add high/low movement correspond with pitch
"It's time to go now"		• Pitch and rhythm discrimination • Call–response • Volume increase

Week 4—Music therapy

Activities	Equipment	Goals
Hello (reposition)	Guitar Pitch chart Horn	• Social skill (acknowledge the members) • Singing (pitch, rhythm)
"Shake" • Choices of instruments • Position • Body parts	Guess the sound bag Discuss qualities	• Choices of contrasting sounds • Concepts (auditory): start/stop, position, body parts • Listen for single-step instructions with music
• Drum • Speech pattern "I like…" • Pattern up to 3–4 sounds (rhythms, modes)	Group 2 with noise	• Auditory memory • Rhythm • Social
Movement with pitch (up and down) "It's time to go now"	Strings	• Pitch perception • Singing • Pitch and rhythm discrimination • Relating as a group—social skills

Week 5—Music therapy

Activities	Equipment	Goals
Hello (reposition) 3 horns each	Guitar Pitch chart Horns	• Social skill (acknowledge the members) • Singing (pitch, rhythm)
Drum • Speech pattern about what they did in holidays • Pattern up to 3–4 sounds (rhythms, modes)	L/S F/S Sounds of different emotions	• Auditory memory • Rhythm • Social
"Shake" • Choices of instruments • Position • Body parts • No visual cue	Discuss about the sound Blindfold	• Choices of contrasting sounds • Concepts (auditory): start/stop, position, body parts • Listen for single-step instructions with music
Movement with pitch (up and down)	Strings Keyboard • Octaves • 6ths	• Pitch perception
Emotions sing "If you are…"	Puppet or instruments	
"It's time to go now"		• Singing • Pitch and rhythm discrimination • Relating as a group—social skills

Week 6—Music therapy

Activities	Equipment	Goals
Hello (reposition)	Guitar Pitch chart Horns	• Social skill (acknowledge the members) • Singing (pitch, rhythm)
Drum • Speech pattern "I like…" over drum beat	Bongos	• Auditory • Sharing/team • Rhythm
"Shake" • Choices of instruments Position Body parts No visual cue	Discuss about the sound Blindfold	• Contrasting sounds • Concepts (auditory): start/stop, position, body parts • Listen for single-step instructions with music
"I can sing" (with mic)		• Long/short sounds • High/low sounds—increase awareness and execution of pitch range • Leader–follower relationship
Movement with pitch (up and down) 5ths and 3rds	Strings Keyboard/vocal—continuous sound	• Pitch perception
"It's time to go now"		• Singing • Pitch and rhythm discrimination • Relating as a group—social skills

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Music Training for Children With Sensorineural Hearing Loss Improves Speech-in-Noise Perception

Week 7—Music therapy

Activities	Equipment	Goals
Hello (reposition)	Guitar Pitch chart Horns	• Social skill (acknowledge the members) • Singing (pitch, rhythm)
Movement with pitch (up and down) 5ths, 3rds, and 2nds	Strings Keyboard/vocal—continuous sound	• Pitch perception
Drum • Speech pattern “activities during the week” over drum beat • “Scared” sounds	Bongos	• Auditory • Sharing/team (pairs) • Rhythm
Percussions location	Discuss about the sound Blindfold	• Distinguish sounds • Listen for directs
Feelings song: “If you are happy/sad/surprised” • Pretend sounds	Puppets	• Sing • Sing with different tone of voice/speed
Keyboard improvisation with emotions—happy		• Creative expressions • Others match sounds with percussion
“It’s time to go now”	With gesture cues	• Singing • Pitch and rhythm discrimination • Relating as a group—social skills

Week 8—Music therapy

Activities	Equipment	Goals
Hello (reposition)	Pitch chart No guitar Horns	• Social skill (acknowledge the members) • “Same” pitch
Movement with pitch (up and down) 5ths, 3rds, same, (2nds) • Each SINGS for others	Strings Keyboard/vocal—continuous sound	• Pitch perception • Lead the singing
Drum • Speech pattern “What makes you…” over drum beat	Bongos	• Auditory • Sharing/team • Rhythm
Percussions location • 2 instruments	Blindfold	• Distinguish sounds • Listen for directs
Feelings song: “There are times…” (new song) Say the sentence “This is a stick”	Puppets	• Sing • Sing with different tone of voice/speed • Say the sentence “This is a stick” in various emotions
Keyboard improvisation with emotions (sad)		• Creative expressions • Others match sounds with vocals/percussion
“It’s time to go now”		• Singing • Pitch and rhythm discrimination • Relating as a group—social skills

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Music Training for Children With Sensorineural Hearing Loss Improves Speech-in-Noise Perception

Week 9—Music therapy

Activities	Equipment	Goals
Hello (reposition)	Pitch chart	• Social skill (acknowledge the members)
	No guitar	• “Same” pitch
	Horns	
Movement with pitch (up and down) 5ths, 3rds, same, (2nds)	Strings	• Pitch perception
• Each SINGS for others	Vocal	• Lead the singing
Drum	Bongos	• Auditory speech over sound
• With “feelings” pic		• Sharing/team
Percussions location	Blindfold	• Distinguish sounds
2 instruments		• Listen for directs
Feelings song: “There are times…”	Puppets	• Sing
Say the sentence “This is a stick” in various emotional context		• Sing with different tone of voice/speed
Keyboard improvisation with emotions		• Creative expressions
		• Others match sounds with percussion
“It’s time to go now”		• Singing
		• Pitch and rhythm discrimination
		• Relating as a group—social skills

Week 10—Music therapy

Activities	Equipment	Goals
Hello (reposition)	Pitch chart	• Social skill (acknowledge the members)
	No guitar	• “Same” pitch
	Horns	
Aeroplane point up/down	Vocal	• Pitch perception
Sing “hello” descending or ascending		• Sing the perceived ascending/descending interval
Drum	Bongos	• Auditory–speech over sound
• I feel… when I…	Feelings cards	• Sharing/team
		• Feelings
Percussions location	Blindfold	• Distinguish sounds
• Cymbal/ratchet/tambourine/2-tone block		• Listen for directs
Feelings song: “There are times…”	Puppets	• Sing
• Say the sentence “This is a stick” with various emotions		• Sing with different tone of voice/speed/
Keyboard improvisation with emotions (scared)		• Creative expressions
		• Others match sounds with vocals/percussion
Do Re Mi	Bells	• Teamwork
		• Sing
“It’s time to go now”		• Singing
		• Pitch and rhythm discrimination
		• Relating as a group—social skills

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Music Training for Children With Sensorineural Hearing Loss Improves Speech-in-Noise Perception

Week 11—Music therapy

Activities	Equipment	Goals
Hello (reposition)	Pitch chart No guitar Horns	• Social skill (acknowledge the members) • "Same" pitch
Aeroplane point up/down	Vocal	• Pitch perception
Sing "hello" descending or ascending		• Sing the perceived ascending/descending interval
Drum	Feelings cards	• Sharing/team
Express and guess		• Feelings
Feelings song: "There are times…"	Puppets	• Sing
• Say the sentence "This is a stick" with various emotions		• Sing with different tone of voice/speed/
Keyboard improvisation with emotions (choice)		• Creative expressions • Others match sounds with percussion
Do Re Mi	Bells	• Teamwork • Pitch
"It's time to go now"		• Singing • Pitch and rhythm discrimination • Relating as a group—social skills

Week 12—Music therapy

Activities	Equipment	Goals
Hello	Pitch chart No guitar Horns (random allocation)	• Team work • "Same" pitch
Aeroplane point up/down	Vocal	• Pitch perception
Sing "hello" descending or ascending		• Sing the perceived ascending/descending interval
Choice of instruments improvisation with emotions (choice)		• Creative expressions • Others match sounds with percussion
Do Re Mi	Bells	• Teamwork • Pitch
"It's time to go now"		• Singing • Pitch and rhythm discrimination • Relating as a group—social skills