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# Musical perceptual skills, but not neural auditory processing, are associated with better reading ability in childhood

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ABSTRACT

Musical activities have been suggested to be beneficial for language development in childhood. Randomised controlled trials using music have indicated that musical interventions can be used to support language skills in children with developmental language difficulties. However, it is not entirely clear how beneficial music activities are for normally developing children or how the effects mediated via music are transmitted. To investigate these questions, the present study used structural equation models to assess how musical training, perceptual musical skills, and auditory processing in the brain are associated with reading proficiency and each other. Perceptual musical skills were assessed using musicality tests while auditory processing in the brain was measured using mismatch negativity responses to pitch, duration, and phoneme length contrasts. Our participants were a community sample of 64 8–11-year-old typically developing children with and without musical training, recruited from four classes in four elementary schools in Finland. Approximately half of children had music as a hobby. Our results suggest that performance in tests of musical perceptual skills is directly linked with reading proficiency instead of being mediated via auditory processing in the brain. Auditory processing in the brain in itself seems not to be strongly linked with reading proficiency in these children. Our results support the view that musical perceptual skills are associated with reading skills regardless of musical training.

## 1. Introduction

Musical practice is associated with improved cognitive development in many domains across the life span (for a review, see e.g. Tervaniemi, 2017). As language and music share many common features, multiple studies have focused on investigating whether language development benefits from musical training via improved sensory-level auditory skills and/or by enhanced higher-level musical expertise, both being effects of musical training (for a review, see Dumont et al., 2017). In order to determine whether musical training or perceptual musical skills are associated with language skills (Dumont et al., 2017), studies on school children is warranted since the effect of music training might be most apparent in them. In comparison with cognitive demands in earlier developmental stages, school requires that children attend classes and learn complex subject matter that is primarily taught using language in spoken and written forms.

Especially reading, or written language comprehension, seems to have long-term effects on children's development. For example, Duncan and others (2007) used data from several longitudinal studies and named reading skills as one of the three crucial skills in school, along with math and attention skills that are most robustly associated with later academic achievement. Other studies have corroborated the long-term effects of reading skills on achievement level. For example, Lesnick et al. (2010) report that reading skills in the third grade are associated with educational attainment in high school and college. In short, the ability to read fluently can be considered a prerequisite for understanding more complex subject matters at school, and pupils with less advanced reading skills may not perform on the level of their

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advanced-reading peers. Over time, these differences in performance may increase and lead to poorer educational attainment in children with less advanced reading skills.

Indeed, several researchers have proposed using musical training to improve reading skills and language skills in general (e.g. Tierney and Kraus, 2013) with the hope that musical training could provide an effective low-cost educational approach that could benefit all children. For example, a two-year follow-up study by François et al. (2013) showed that musical training in eight-year-old children was linked with improved auditory non-word segmentation, suggesting that musical activities can affect more complex language skills. In this study, children were pseudo-randomly divided into either music or painting training, and their ability to learn and recognise novel non-words was assessed both one and two years after random group assessment. Test performance improved more in the music group than in the painting group and was seen as both improved behavioural performance and enhanced electrophysiological responses to familiar vs unfamiliar non-words.

Although positive effects of music training on reading and other measures of language processing or proficiency have been obtained, the effects may not differ from other types of approaches (e.g. Bhide et al., 2013). At least in some cases, language training programmes may provide similar benefits as music training does (Tervaniemi et al., 2021). Furthermore, the results of musical activities for facilitating reading have not always been promising, particularly if music training is provided as a group-based activity in the school setting (Cogo-Moreira et al., 2013). Yet, recent meta-analysis suggests that even though methods, participants and outcome measures are highly varied across studies, music training seems to improve both phonological awareness and development of reading skills (Eccles, van der Linde, Le Roux, Swanepoel, MacCutcheon & Ljung, 2021).

However, several studies have questioned whether musical training results in improved language outcomes or if the beneficial effects of musical training are due to other underlying factors. For example, Swaminathan, and Schellenberg (2020) showed that pre-existing perceptual musical skills have a larger effect on language skills than musical training. Most recent evidence also shows that associations between perceptual musical skills and language skills are not one-directional. For example, the results of Tervaniemi and others (2021) indicate that foreign language learning can facilitate neural processing of musical information, supporting the views about the interplay between music and language functions (e.g. White et al., 2013). Consistent with this, recent studies suggest that many benefits attributed to musical training might also arise from inherently efficient auditory skills. For example, Mankel and Bidelman (2018) show that adult non-musicians who are nevertheless adept in many musical perception tasks perform better in discrimination of speech in noise than non-musicians who perform poorly in musical perception tasks. As some non-musicians can also show similar advantages as musically trained individuals, many advantages attributed to musically trained individuals probably result from both nature and nurture (see, e.g. Schellenberg, 2019).

Studies testing the associations between perceptual skills and reading skills have shown that low-level perceptual abilities (pitch and rhythm discrimination, e.g. Douglas and Willatss, 1994; pitch and interval duration discrimination, Banai and Ahissar, 2013; pitch order discrimination, Putkinen et al., 2019) in children are associated with better performance on reading and spelling tests. Other studies have implicated that especially rhythmic discrimination could be strongly associated with language processing. For example, Gordon and others (2015a) showed that rhythmic discrimination was strongly associated with important pre-reading skills (phonological awareness and expressive grammatical abilities) in 6 year old children.

Several models have been developed to explain how either innate or obtained perceptual musical skills might influence language skills, including reading. The bottom-up viewpoint suggests that musical activities improve low-level perceptual abilities such as pitch, timing and timbre discrimination (for a review, see Kraus and Chandrasekaran, 2010; see also Tierney and Kraus, 2013), and these improved perceptual skills benefit discrimination of both musical and speech stimuli. Improved perceptual skills would then improve language outcomes also in more complex language skills, such as reading. For example, Patel's (e.g. 2014) OPERA hypothesis proposes that the beneficial effects of music arise from improved low-level perceptual abilities that, because of cross-modal plasticity, improve neural processing of both speech and non-speech sounds.

More nuanced models have strived to explain the associations between low-level perceptual abilities, perceptual musical skills and reading. Some of the most popular models propose that perceptual musical skills improve phonological processing and help children develop their phonological awareness or map the phonological units in their language to the orthography. While the association between phonological awareness and reading skills is robust and large (Bus & Van IJzendoorn, 1999), the perceptual musical skills might be associated with reading skills in other ways as well. For example, Anwari, Trainor, Woodside, and Levy (2002) showed that while perceptual musical skills did correlate with both phonological awareness and reading skills, perceptual musical skills were associated with reading skills even when the effect of phonological awareness was partialed out.

Later research and theories have attempted to elucidate whether low-level processing skills, other than phonological awareness, are linked with either language processing or reading (e.g. Poeppel et al., 2008; Zhang and McBride-Chang, 2010; Goswami, 2019). For example, Poeppel and others (2008) suggest that there are separate neuronal networks that process speech at the segmental level (for example, individual phonemes or phoneme order) and suprasegmental level (such as syllable), and both processes are needed for the development of accurate phonological representations. Also Zhang and McBride-Chang (2010) propose that both suprasegmental and segmental neural processing contribute to more complex skills (verbal short-term memory, phonological awareness, rapid automatised naming, morphological awareness), which in turn contribute to reading skills.

Although links between low-level perceptual abilities, higher-order skills and reading skills seem plausible, they may not be causal. A meta-analysis by Gordon, Fehd and McCandliss (2015b) suggests that although music interventions report beneficial effects on phonological awareness, very few randomised controlled studies have been conducted. Data are even sparser for interventions attempting to improve reading skills via musical training. Gordon and others (2015b) comment that, at the time of their publication, few studies had looked at direct effects of music interventions on reading fluency, and based on their data, no statistically significant direct effect of music interventions on reading fluency could be found. Furthermore, recent broad meta-analyses have not yielded unequivocal support for the transfer effects of music on other cognitive skills in child development (Sala and Gobet, 2020). However, some researchers have also challenged the analyses of Sala and Gobet (2020). For example, Bigand and Tillman (2021) argue that the finding of Sala and Gobet (2020) is partly due to failed differentiation between near and far transfer effects. Indeed, Bigand and Tillman (2021), reanalysing the data used by Sala and Gobet (2020) suggest that musical training provides far transfer effects, or small but significant effects on cognitive skills in children, such as reading.

It is also possible that musical training influences language or reading through means other than improvements in low-level perceptual abilities. Studies show that the effects of perceptual musical skills or musical training are positively correlated with many cognitive abilities, such as attention (e.g. Roden et al., 2014), working memory and executive functions (Moreno et al., 2011; Putkinen et al., 2021; for a review, see Besson et al., 2011). Musical training also includes structured teaching, which might influence children's executive functions (Diamond and Lee, 2011). If true, then improvements in executive functions, in turn, could help children perform better in almost any cognitive task.

It is even possible that formal musical training helps children learn how to do tests and tasks, which in turn could help test performance in various behavioural tests of perceptual abilities in comparison to children without musical training, even in the absence of underlying differences in low-level perceptual abilities. Alternatively, children who find music easy, pleasant and enjoyable, or children for whom test taking is easy and natural, may take up music. Thus, possible beneficial effects of music on any cognitive task might partly be due to pre-existing differences instead of music itself (Schellenberg, 2015 & 2016). Consistent with this viewpoint, Swaminathan et al. (2018) report in their study in adults that the positive association between musical training and reading skills were found only when cognitive skills (verbal short-term and working memory, and nonverbal intelligence) were not controlled for. Their finding suggests that underlying and pre-existing differences may in part explain how and why musical activities seem to benefit language skills.

Thus, it may be that perceptual musical skills are more strongly associated with various cognitive skills, such as reading, than length of musical training. For example, Swaminathan and Schellenberg (2020) assessed if perceptual musical skills or length of musical training was a better predictor of non-native phoneme discrimination or native grammar understanding in 6–9 year old children. They found that perceptual musical skills rather than length of musical training were positively associated with their measures of language aptitude (Swaminathan and Schellenberg, 2020). In similar vein, Kragness, Swaminathan, Cirelli and Schellenberg (2020) found that perceptual musical skills predicted later abilities while the improvement in musical ability did not.

To assess these questions further, the present study investigated how musical training, perceptual musical skills and low-level perceptual skills are associated with reading skills. In particular, we addressed whether musical training influences the links among these skills. If reading skills were influenced by neural auditory processing skills, then the links between these automatic auditory responses and measures of reading skills would be robust. However, if performance in behavioural tests of perceptual musical skills were linked with reading skills, then the associations between perceptual music test performance and reading skills would be strong. If some aspect of the musical training not captured by our model predicted reading skills, then reading ability would be strongly associated with the length of musical training regardless of auditory processing skills or performance in tests of musical perception. Finally, if we were able to find signs that the link between automatic auditory processing of the brain and reading skills or musical perceptual skills and reading skills was not similar for musicians and non-musicians, it could suggest that musicians' and non-musicians' reading fluency is influenced by partly different abilities.

We assessed musical perceptual abilities using several broadly used tests of musicality while auditory processing was measured using Mismatch Negativity (MMN), a component of the event-related potentials (ERPs) that represents bottom-up discrimination abilities but also taps into long-term memory. In brief, the MMN is elicited when an auditory stimulus violates the expectation of incoming input and is seen as a negative deflection approximately 200 ms from the onset of the deviance in an unexpected stimulus (e.g. Näätänen et al., 2011; Winkler, 2007). However, the MMN is not only a response that represents expectancy violations or bottom-up processing, but it also represents the activation of neural memory traces for words and phonemes. For example, the MMN responses to syllables are larger when they complete a word than a pseudo-word (Pulvermüller et al., 2001), supporting the notion that memory representations of linguistic elements can be probed with the MMN. Furthermore, the MMN response strength has been associated with phoneme-processing ability in children (e.g. Linnavalli, Putkinen, Huotilainen & Tervaniemi, 2018), and musical and phonetic training has previously been shown to increase the MMN responses along with learning (e.g. Putkinen, Tervaniemi, Saarikivi, Ojala & Huotilainen, 2014a; Ylinen et al., 2010; Junttila et al., 2020). The MMN is also associated with behavioural perceptual accuracy for pitch (Tiitinen et al., 1994) and duration (Amenedo and Escera, 2000).

## 2. Methods

### 2.1. Participants

Sixty-four children in four classes without a special emphasis on music education or any other subject from four separate elementary schools in the Turku area in Finland participated in the experiment (22 boys). The mean age of the children was 9 years 6 months (range: 8 years 1 months–11 years 2 months). Fifty-five of the children were right-handed, while four reported being left-handed and three children reported being ambidextrous. Data on handedness from two children were not obtained. All children who wanted to enroll in the study gave their written consent, as did their parents. The study plan was approved by the ethical committee of the University of Turku and conducted according to the Declaration of Helsinki.

Out of the 64 children, 31 children used to have music as a hobby at some stage of their childhood, 31 did not, and data on the history of music as a hobby were missing from two children. 27 of the 31 children that used to have music as a hobby still had music as a hobby at the time when the study was conducted. Information about the length of music as a hobby was missing from one child, but the rest of the 30 children had practiced music for an average of 1.88 years (range: 0.25–5 years). These 31 children formed the music group while the children with no history of music formed the non-music group. Children, whose data on the history of music as a hobby were missing, were not included in either group for analyses on differences between the groups but included in other analyses. The children were not randomised into music and non-music groups; the sample of children was a community sample and children were divided into groups after the data were collected.

Adequacy of the sample size was assessed using G*Power software (Faul et al., 2007). For assessing differences in ERP responses between music and non-music groups, data from similar studies (e.g. Virtala et al., 2012; Putkinen, Tervaniemi, Saarikivi, de Vent & Huotilainen, 2014b) suggested using a total sample size of at least 18 or 44 participants, respectively. Regarding associations between ERPs and musical perceptual skills tests, previous research into associations between perceptual musical skills and reading skills suggests a minimum sample size of 49 participants (based on the smallest correlation reported in Anvari et al., 2002). Based on these studies, we considered our sample size adequate.

### 2.2. Behavioural tests

The outcome variables, or reading skills, were assessed using ALLU, a standardised Finnish reading test for elementary school children (**AL**a-asteen **LU**kutesti, which translates to reading test for comprehensive school grades 1–6; Lindeman, 1998), out of which two subtests (ALLU-T4A and ALLU-T5B) were chosen. ALLU-T4A measured sentence comprehension, where the child had to pair a correct picture out of four options with the presented sentence. ALLU-T5B measured reading fluency, where the children were presented with letter strings without spaces, and they had to segment them into words within a specific time limit (e.g. cathousephone). Data from three children were missing for the ALLU-T4A subtest, and data from two children were missing for the ALLU-T5B subtest. As these tests are routinely done in a school setting by a teacher, we do not know why data from ALLU tests were missing from these five children.

Perceptual musical skills were evaluated using three subtests from Seashore Tests of Musical Ability (Seashore et al., 1960a, 1960b, 2003) and one subtest from the Montreal Battery of Evaluation of Amusia (MBEA; based on the theoretical model of Peretz and Coltheart, 2003). Each test subtest took approximately 5 min to administer and children had a break after each subtest. The testing of perceptual musical skills took approximately 45 min. Seashore tests were used because they have been standardised, and thus, their psychometric properties were known (Seashore et al., 1960b). While the MBEA is designed as a screening tool, it has good psychometric properties and its scores are correlated with Gordon's Musical Aptitude Profile tests (Peretz et al., 2003). Pitch (measuring pitch perception), duration (testing duration discrimination) and tonal memory (assessing ability to discriminate deviations in melodies) were used from the Seashore Tests of Musical Ability. Data of two children were missing for each of the Seashore subtests. The scale subtest from the MBEA was used, which tests the ability to tell apart two melodies, in which the altered melody violates the key to the melody while keeping the overall melodic contour intact (data from two children were missing). As the children were of the same age and educational status, raw scores were used in the analyses for the MBEA and Seashore tests.

In addition, we expected verbal IQ to influence reading skills and measured it using the similarities, vocabulary, information, arithmetic and comprehension subtests of the Wechsler's Intelligence Scale for Children, 3rd edition (WISC-III). Test scores for verbal IQ were missing from three children. Missing values were not replaced.

Whether the values were missing completely at random (MCAR) or at random (MAR) or whether patterns in missing values were explained by other factors, Little's MCAR test was conducted for all the variables used in the analysis and using Sex (male, female), Handedness (left, right, ambidextrous) and Group (music, non-music) as factors. No distinctive pattern was found ($\chi^2$ (27) = 34.514, p = 0.152), and the data were assumed to be missing completely at random.

### 2.3. Electrophysiological recordings

Electrophysiological recordings were used to assess the participants' neural auditory processing abilities. The EEG was recorded in the former Centre for Cognitive Neuroscience laboratories, University of Turku, Finland. EEG recording took approximately 20–25 min and was conducted on a different day than the testing of perceptual musical skills. During the experimental paradigms the children sat in a chair and watched a silent movie of their choosing. To tap into auditory processing, we used two MMN paradigms. The first paradigm (BeatBit paradigm; stimuli from Iverson and Evans, 2007) assessed minimum pair discrimination in English, using/bɪt/('*bit*') as a frequently repeating standard sound and/biːt/('*beat*') as an infrequent deviant (see Ylinen et al., 2010). Both stimuli were 410 ms in duration with matched onsets and offsets. Stimulus onset asynchrony (SOA) of 750 ms was used, and the stimuli were divided into blocks of 434 stimuli (65 deviants). Two to three blocks were presented for each child depending on fatigue of the child. The stimuli were pseudo-randomly presented so that at least two standards were presented after each deviant and the sequence started with 13 repetitions of the standard stimulus. Two standard sounds immediately following a deviant were excluded from further analysis.

The second paradigm was a multi-feature MMN paradigm using harmonic tones, consisting of three harmonic partials, originally used in the study of Pakarinen et al. (2007), where every other sound is a standard tone and the other sounds are one of several deviants, differing from the standard based on one auditory feature only (Näätänen et al., 2004). The multi-feature paradigm used a 75-ms long tone (523 Hz) as a standard while the deviants were changes in duration (from 75 ms to 27 ms), intensity (70 dB -> 55 dB), location (from binaural to either coming from left or right ear only; both were averaged together) or pitch (either change from 523 to 609 Hz or from 523 to 450 Hz, both averaged together). SOA of 350 ms was used. The multi-feature paradigm was presented in two blocks starting with 10 repetitions of the standard tone, and 130 repetitions of each deviant were presented in total. Presentation software (Neurobehavioural Systems Ltd., Berkeley, CA, USA) was used to present the stimuli to the participants at approximately 70 dB (, sound pressure level, SPL) via headphones. Only pitch and duration MMNs that theoretically could be associated with reading skills were included for further analysis. Location and intensity MMNs were excluded post hoc and originally recorded as they were an integral part of the paradigm of Pakarinen and others (2007). Phoneme discrimination (measured by the BeatBit paradigm) could be associated with phonological awareness and was thus analysed further. In addition, a previous study by Ylinen et al. (2019) has suggested that the MMN responses to second-language words (here, BeatBit) are correlated with reading skills in children with the same age range. Pitch discrimination skills are important for vowel discrimination, as vowel identity is determined by its first two formants, or harmonics. Also, duration discrimination is relevant for Finnish, where differences between short and long vowels or consonants denote differences in meaning (e.g. tuli: fire; tuuli: wind; tulli: customs). However, MMN responses to location and intensity deviants were excluded from further analysis because of their low response strength and not being linguistically relevant in Finnish.

The EEG data were recorded with an active electrode cap (ActiCap; Brain Products GmbH) from 32 electrodes according to the international 10/20 system. Vertical eye movements were recorded using an additional electrode based on the outside of the canthus of the right eye. We used the QuickAmp amplifier and the recording software BrainVision Recorder. The data were sampled at a rate of 500 Hz and lowpass filtered online with 100 Hz as the cut-off frequency. During the recording, the data were referenced to the FCz electrode. The data were further analysed in Matlab (version 2018b; MathWorks, 2018) and EEGlab (v2019.0; Delorme and Makeig, 2004). First, we lowpass filtered the data using a 40-Hz cut-off frequency and interpolated any broken channels (range 0–3). After this, parts of the EEG signal with extensive artefacts arising from movement or external sources were removed by hand, after which independent component decomposition was conducted (using FastICA algorithm; Hyvärinen, 1999, or in six rare cases where FastICA did not converge, EEGlab's runica-function was used instead), and ICA components judged to be associated with horizontal and vertical eye movements on the basis of visual inspection were removed from the data (1–3 components; median 2). Then, the data were filtered using a FIR (linear finite impulse response) filter using 0.5 and 25 Hz as cut-off frequencies (EEGlab's eegfiltnew-function) and divided into epochs (from 50 ms prior to stimulus onset to 350 ms for multi-feature and 100 ms prior to stimulus onset to 700 ms for BeatBit paradigm). Any epochs where the EEG amplitude exceeded two standard deviations from the mean of all epochs on any of the channels of interest (F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, C3, Cz, C4, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8) were excluded. After artefact rejection, the participants had an average of 102 accepted trials (range: 57–139) for the BeatBit paradigm. For the multi-feature paradigm, pitch deviants had an average of 82 (range: 35–111) and duration deviants 82 (range: 29–100) accepted trials. Finally, the data were re-referenced to the average of P7 and P8 electrodes.

MMN waveforms for all stimulus types in both paradigms were calculated by subtracting the response to the repeating standard stimulus from that of the deviant stimulus, separately for each participant. Grand mean ERP and MMN waveforms were then formed by averaging the responses from all participants together, separately for each stimulus type. The MMN response latency was then determined as the latency of the most prominent peak in the grand mean MMN waveform between 100 and 250 ms from stimulus onset, separately for each stimulus type. The MMN amplitudes for the individual participants were calculated as mean waveform amplitude in a 40 ms window, centered at the MMN response latency determined from the grand mean MMN waveforms. As the MMN is mostly apparent in the frontal and central electrode channels and its polarity is inverted at mastoid sites (e.g. Alho et al., 1993), the MMN responses from F3, Fz, F4, C3, Cz and C4 electrodes were averaged together. The averaging was done to optimise the MMN amplitude while minimising noise and to reduce the number of input variables in the statistical models.

### 2.4. Statistical analyses

The statistical significance of the MMN was tested using two-tailed t-tests comparing the mean amplitude to zero using the data from all participants ($N = 64$). Differences in MMN amplitudes between the groups were tested with two separate ANOVAs, one for BeatBit and one for a multi-feature paradigm. In the ANOVAs, Group (music group, $N = 31$; non-music group, $N = 31$) was used as a between-subjects factor. The ANOVA for the multi-feature paradigm used Stimulus (pitch, location, intensity, duration) as a within-subject factor, while the ANOVA for the BeatBit paradigm did not include the Stimulus factor. The Greenhouse-Geisser correction was used when sphericity was violated (uncorrected degrees of freedom are reported). Partial eta squared ($\eta^2$) and Cohen's *d* were used to measure effect size. To test differences between groups in tests of perceptual musical skills and verbal IQ, two-tailed t-tests were used. Equality of variances was tested using Levene's test, and corrected values are used when appropriate (uncorrected degrees of freedom are reported). Normality of residuals for ANOVAs was assessed visually using Q-Q plots and standardised residual histograms.

To test the interplay between auditory processing and perceptual musical skills and their effects on reading skills, we used the structural equation modelling (SEM) approach (see, e.g., Russell et al., 1998) for the data of all participants ($N = 64$). SEM models investigate how the observed variables are indicative of the underlying latent variables and how these latent variables in turn are associated with each other and the predicted variables. The SEM can be characterised as a combination of factor analysis (how the observed variables are associated with the underlying latent variables) and regression analysis (how the underlying latent variables are associated with one another). The SEM was done using R software (version 4.0.2.; R Core Team, 2020) and the lavaan toolbox (Rosseel, 2012). Multivariate normality was tested using Mardia's test, and data were multinormal in terms of both skewness ($p = 0.499$) and kurtosis ($p = 0.194$). Model fit was evaluated using the comparative fit index (CFI; good fit $\geq$0.95) and root mean square error of approximation (RMSEA; good fit $\leq$0.06).

In the SEM analysis, we tested a model with three latent variables only as the sample size was small. We chose to use perceptual musical skills (measured using an MBEA-scale subtest and Seashore's pitch, time and tonal memory subtests), auditory processing (assessed with the MMN responses from BeatBit paradigm and duration, intensity, location and pitch change MMNs from the multi-feature paradigm) and reading skills (ALLU-T4A and ALLU-T5B) as latent variables in the model. Regarding the relationships between the variables, we set reading skills to be regressed by both auditory processing and perceptual musical skills. Two other factors were set to regress with reading skills. First, reading skills were regressed by verbal IQ as previous studies have shown that verbal IQ is positively associated with performance in various reading-related tasks (e.g. Ferrer et al., 2007). Second, reading skills were regressed by the length of musical training. As exact associations between musical training and reading skills are not known, we thought that extracurricular formal training and independent practice associated with musical training might provide benefits to reading skills through avenues other than improved performance in tests of perceptual musical skills, such as via improved social skills (Ritblatt et al., 2013).

As perceptual musical skills are influenced by musical training, the perceptual musical skill variable in our model was regressed also by length of musical training. Musical training has repeatedly been shown to improve auditory skills in children (e.g. Milovanov et al., 2009; Chobert et al., 2014), and some of the children had musical training that would influence our perceptual musical skills variable. In similar vein, auditory processing was regressed by musical training as several studies have reported these associations (e.g. Putkinen et al., 2014b). The auditory skills variable was regressed by the perceptual musical skills variable.

As data included missing values and values were missing completely at random (MCAR), pairwise case selection (cases excluded only from the analyses where the value is missing, not from all analyses) was used for the SEM model. For the SEM model, the MMN response polarity is reversed for easier interpretation of the results. As the MMN is a negative response, more negative MMN responses are considered larger and indicative of better discrimination ability. However, when regressed with other variables where larger positive values represent better performance, the regression coefficient becomes negative even though it represents, for example, better discrimination ability being associated with better performance in tests of musical aptitude. By reversing the MMN response polarity, the regression coefficients are easier to interpret.

We also tested whether similar associations between the variables are seen in both children with and without musical training. As sample size was not adequate to test the SEM separately for children with and without musical training, the association between perceptual musical skills variables, auditory skills variables and reading skills variables were tested using Pearson's correlations for all children and separately for both music and non-music groups. We also tested associations between length of musical training and MMN amplitudes using Spearman correlation.

## 3. Results

### 3.1. Behavioural data: perceptual musical skills, reading skills and verbal IQ

Table 1 shows test scores for children, separately for children in the music and non-music groups. Regarding test scores for perceptual musical skills, children in the music group scored higher than children in the non-music group for the MBEA-scale subtest ($t(60) = -2.742$, $p = 0.008$), Seashore's pitch subtest ($t(60) = -3.854$, $p < 0.001$) and Seashore's tonal memory subtest ($t(60) = -4.186$, $p = 0.001$). The groups did not differ in performance in the Seashore's time subtest performance ($t(60) = -0.826$, $p = 0.412$).

Children in the music group had higher scores than children in the non-music group in the ALLU subtests (ALLU-T4A: $t(59) = -2.611$, $p = 0.011$; ALLU-T5B: $t(60) = -3.755$, $p < 0.001$).

Verbal IQ scores were larger in the music than the non-music group ($t(59) = -2.395$, $p = 0.020$).

### 3.2. MMN data: auditory skills

For the BeatBit paradigm, the MMN responses were significantly different from zero ($t(63) = -10.14$, $p < 0.001$). See Fig. 1 for the ERP waveforms and Fig. 2 for the MMN waveforms, shown separately for music and non-music groups. The MMN response amplitudes did not

**Table 1**
Test scores for perceptual musical skills, reading skills, and verbal IQ, separately for music and non-music groups. Mean and standard error of the mean are reported.

| Measure | Music group | Non-music group | Difference between the groups |
|---|---|---|---|
| Verbal IQ | 108.23 (3.290) | 98.87 (2.054) | $p = 0.020$ |
| ALLU-T4A | 13.20 (0.471) | 11.29 (0.557) | $p = 0.011$ |
| ALLU-T5B | 95.58 (6.505) | 63.35 (5.599) | $p < 0.001$ |
| MBEA scale | 22.23 (0.674) | 19.29 (0.891) | $p = 0.008$ |
| Seashore pitch | 63.48 (5.333) | 37.32 (4.200) | $p < 0.001$ |
| Seashore duration | 67.94 (4.721) | 61.94 (5.522) | $p = 0.412$ |
| Seashore tonal memory | 69.16 (4.507) | 38.61 (5.741) | $p < 0.001$ |

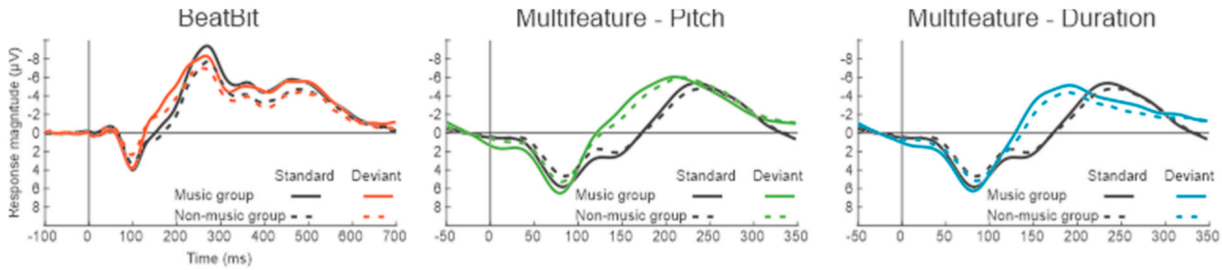


**Fig. 1.** ERP waveforms for both BeatBit and multi-feature paradigms averaged over six fronto-central electrodes (F3, Fz, F4, C3, Cz and C4). Solid lines represent the music group (N = 31), and dashed lines denote the non-music group (N = 31). Note the different timescale (x-axis) for BeatBit and multi-feature paradigm ERP figures.

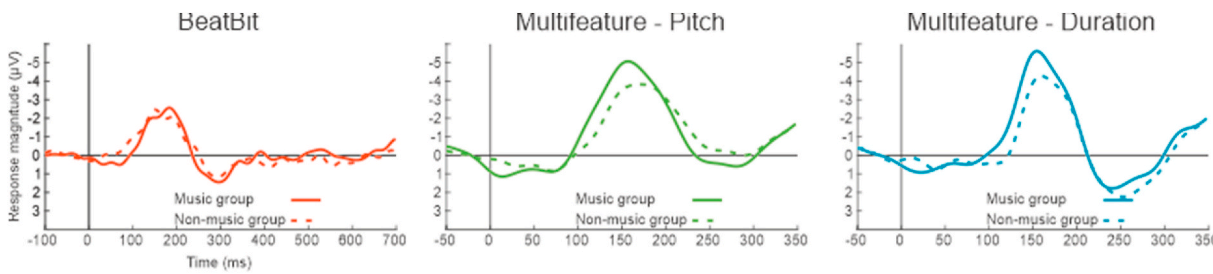


**Fig. 2.** MMN waveforms for both BeatBit and multi-feature paradigms averaged over six electrodes (F3, Fz, F4, C3, Cz and C4). MMN responses did not differ between the groups for the BeatBit paradigm, but the music group had larger MMN responses than the non-music group in the multi-feature paradigm. Solid lines indicate the music group (N = 31), and dashed lines denote the non-music group (N = 31). Note the different timescale (x-axis) for BeatBit and multi-feature paradigm MMN figures.

differ significantly between the music and non-music groups ($F(1,61) = 0.05$, $p = 0.82$, $\eta^2 = 0.001$, Cohen's $d = 0.05$).

In the multi-feature paradigm, statistically significant MMN responses were found for both pitch and duration (pitch: $t(63) = -11.82$, $p < 0.001$; duration: $t(63) = -13.99$, $p < 0.001$). These MMN responses of the music group were larger than those of the non-music group (main effect of Group, $F(1,60) = 5.26$, $p = 0.025$, $\eta^2 = 0.081$; Cohen's $d$ for pitch and duration were 0.43 and 0.62, respectively). This MMN response enhancement in the music group was general instead of stimulus-specific, as the Group * Stimulus interaction was not significant ($F(1,60) = 0.10$, $p = 0.75$, $\eta^2 = 0.002$). See Fig. 2 for the MMN responses for both the music and non-music groups.

MMN responses for duration ($\rho = -0.357$, $p = 0.005$) and pitch ($\rho = -0.307$, $p = 0.016$) were modulated by the length of musical training while the MMN for the BeatBit was not ($\rho = -0.102$, $p = 0.433$).

### 3.3. SEM for auditory processing, perceptual musical skills and reading skills

The SEM (see Fig. 3; for alternative models, see Supplementary

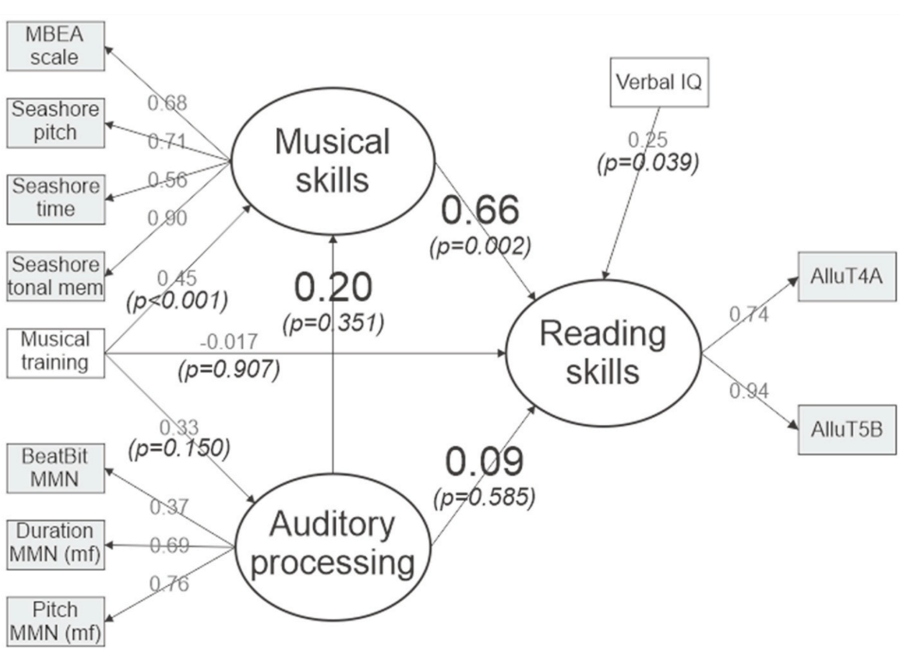


**Fig. 3.** Structural equation model of the interplay of perceptual musical skills, auditory processing skills and reading skills. For the observed variables (grey boxes) forming the latent variables (white ovals), the numbers signify standardised parameter values, or how strongly the variables are associated with the latent variable. For other variables in the model, the values are standardised regression coefficients where the p-value denotes significance of the regression coefficient from zero. The model indicates that the reading skills are significantly associated with verbal IQ and perceptual musical skills but not with auditory processing. The relationship between perceptual musical skills and auditory processing approached statistical significance, and the effect of musical training on perceptual musical skills is significant. Tonal mem: tonal memory subtest. mf: MMN responses from the multi-feature paradigm. Please note that for easier interpretation of the SEM, MMN response polarity is reversed.

Material) parameters indicated an adequate fit (CFI: 0.986; RMSEA: 0.034). With the exception of the ALLU-T5B score (p = 0.558), all other estimated intercepts were statistically significant from zero. In a similar vein, with the exception of the ALLU-T5B score (p = 0.344) and auditory skills (p = 0.222), all other estimated variances differed significantly from zero. The estimated loadings of all the observed variables on the latent variables differed significantly from zero (p < 0.030). The SEM indicated that while perceptual musical skills were positively associated with reading skills, auditory processing was not significantly associated with reading skills. Also, neither auditory processing nor reading skills were not associated with length of musical training while perceptual musical skills were.

Correlational analyses conducted separately for both the music and non-music groups indicated that MMN responses were at best sparsely associated with reading skills (see Table 2). For either group, no correlations were statistically significant, whereas for the whole group duration and pitch MMNs were associated with ALLU-T5B scores. Slightly different patterns emerged for the music and non-music groups in analyses of perceptual musical skills. For the music group, statistically significant associations or associations approaching statistical significance were found for all tests of perceptual musical skills with at least one of the tests of reading skills. For the non-music group, performance in tests of pitch discrimination was not associated with performance in tests of reading skills, even though non-music groups' performance in other tests was associated with at least one of the tests of reading skills (see Table 3). Correlations between the tests of perceptual musical skills and MMN amplitudes are reported in Table 4.

## 4. Discussion

The present study assessed how musical skills test scores and auditory processing, as studied using the MMN, are associated with reading ability in children between 8 and 11 years of age and, further, how musical training influences this association. Our results indicate that in the SEM model, higher scores in musical skills tests were associated with better performance on standardised tests for reading ability whereas auditory processing as measured by the MMN was not. In addition, while musical training was not directly associated with reading ability, its association with reading ability was mediated by perceptual music skills. These findings are discussed in detail below.

Our results suggest that performance in tests of perceptual musical skills is directly linked with reading skills in 8–11-year-old children instead of being mediated via improvements in low-level auditory discrimination skills, as assessed by the MMN. This link was robust, as evidenced by the large regression coefficient, and was highly statistically significant. In addition, the overall associations between perceptual musical skills and reading skills performances were statistically significant for all comparisons, but not always when separated to music and non-music groups.

While our results show slightly different patterns in individual correlations of the musicality test scores with performance in tests of reading for both children with and without music training, this finding does not necessarily imply that the differences in correlation patterns between the groups are statistically significant. In studies with small samples, such as ours, differences in correlation patterns are likely to arise by chance. This is not to say that slightly different abilities might benefit reading in different groups (such as improved pitch processing in musically trained children, which might benefit reading via improved phonological awareness; Bolduc and Montésinos-Gelet, 2005; Sun et al., 2017; Bus & Van IJzendoorn, 1999), but our results do not support this

**Table 2**
Correlations between ALLU reading test scores and MMN response amplitudes for the whole group and separately for the music and non-music groups. In each cell, results from the whole group are reported first. M denotes results on the music group while NM refers to the non-music group. In these analyses, the sign of the MMN response is not flipped; thus, larger negative correlation denotes larger (=more negative) MMN responses being correlated with higher scores in tests of reading. Statistically significant correlations are marked in bold. *: p < 0.05; **: p < 0.01.

| | ALLU-T4A | ALLU-T5B |
|---|---|---|
| BeatBit MMN | r = −0.055, p = 0.675<br>M: r = −0.151, p = 0.462<br>NM: r = −0.036, p = 0.838 | r = −0.189, p = 0.141<br>M: r = −0.280, p = 0.258<br>NM: r = −0.177, p = 0.309 |
| Duration MMN | r = −0.064, p = 0.623<br>M: r = 0.119, p = 0.561<br>NM: r = −0.024, p = 0.890 | **r = -0.302, p = 0.017***<br>M: r = −0.163, p = 0.417<br>NM: r = −0.272, p = 0.115 |
| Pitch MMN | r = −0.189, p = 0.144<br>M: r = −0.026, p = 0.900<br>NM: r = −0.134, p = 0.443 | **r = -0.358, p = 0.004**<br>M: r = −0.143, p = 0.476<br>NM: r = −0.223, p = 0.197 |

**Table 3**
Correlations between tests of perceptual musical skills and ALLU reading test scores for the whole group and separately for the music and non-music groups. In each cell, results from the whole group are reported first. M denotes results on the music group while NM refers to the non-music group. Statistically significant correlations are marked in **bold**. #: p < 0.1; *: p < 0.05; **: p < 0.01.

| | ALLU-T4A | ALLU-T5B |
|---|---|---|
| MBEA scale | **r = 0.435, p < 0.001****<br>M: r = 0.071, p = 0.730<br>NM: **r = 0.513, p = 0.002**** | **r = 0.451, p < 0.001****<br>M: r = 0.351, p = 0.073#<br>NM: **r = 0.419, p = 0.012*** |
| Seashore pitch | **r = 0.319, p = 0.012***<br>M: r = 0.081, p = 0.695<br>NM: r = 0.193, p = 0.268 | **r = 0.514, p < 0.001****<br>M: **r = 0.439, p = 0.022***<br>NM: r = 0.261, p = 0.129 |
| Seashore duration | **r = 0.262, p = 0.041**<br>M: r = 0.115, p = 0.578<br>NM: r = 0.310, p = 0.070# | **r = 0.362, p = 0.004**<br>M: r = 0.371, p = 0.057#<br>NM: **r = 0.379, p = 0.025*** |
| Seashore tonal memory | **r = 0.477, p < 0.001****<br>M: r = 0.134, p = 0.513<br>NM: **r = 0.489, p = 0.003**** | **r = 0.580, p < 0.001****<br>M: **r = 0.513, p = 0.006****<br>NM: **r = 0.447, p = 0.007**** |

**Table 4**
Correlations between tests of perceptual musical skills and MMN response amplitudes for the whole group and separately for the music and non-music groups. In each cell, results from the whole group are reported first. M denotes results on the music group while NM refers to the non-music group. In these analyses, the sign of the MMN response is not flipped; thus, larger negative correlation denotes larger (=more negative) MMN responses being correlated with higher scores in tests of perceptual musical skills. Statistically significant correlations are marked in **bold**. #: p < 0.1; *: p < 0.05; **: p < 0.01.

| | MBEA scale | Seashore pitch | Seashore duration | Seashore tonal memory |
|---|---|---|---|---|
| BeatBit MMN | r = −0.165, p = 0.201<br>M: r = −0.306, p = 0.121<br>NM: r = −0.098, p = 0.576 | r = −0.147, p = 0.254<br>M: r = −0.171, p = 0.393<br>NM: r = −0.182, p = 0.296 | r = −0.129, p = 0.316<br>M: r = 0.152, p = 0.451<br>NM: r = −0.312, p = 0.068 | r = 0.030, p = 0.820<br>M: r = −0.033, p = 0.869<br>NM: r = 0.068, p = 0.698 |
| Duration MMN | r = −0.177, p = 0.169<br>M: r = −0.317, p = 0.108<br>NM: r = 0.010, p = 0.956 | r = −0.240, p = 0.060#<br>M: **r = -0.387, p = 0.046***<br>NM: r = 0.105, p = 0.549 | r = −0.207, p = 0.106<br>M: **r = -0.441, p = 0.021***<br>NM: r = 0.003, p = 0.988 | r = −0.183, p = 0.153<br>M: r = −0.374, p = 0.054#<br>NM: r = 0.120, p = 0.491 |
| Pitch MMN | **r = -0.284, p = 0.025***<br>M: r = −0.303, p = 0.125<br>NM: r = −0.207, p = 0.232 | **r = -0.335, p = 0.008****<br>M: r = −0.231, p = 0.256<br>NM: r = −0.280, p = 0.103 | **r = -0.305, p = 0.016***<br>M: r = −0.262, p = 0.186<br>NM: r = −0.317, p = 0.063 | r = −0.222, p = 0.083#<br>M: r = −0.354, p = 0.070#<br>NM: r = −0.020, p = 0.907 |

interpretation. To answer these questions, further studies should be conducted separately for children with and without musical training. Such analysis would help assess, which expertise effects, if any, carry over to reading both in children with and without training in music.

While our results suggest that reading skills were mostly facilitated by the cognitive abilities required to perform well in tests of perceptual musical skills, we cannot fully discount the possibility that the association between perceptual musical skills and reading may be mediated by other factors not captured by our model. Some of the tests of musicality require good working memory skills (e.g. Seashore's tonal memory subtest; MBEA subtest for scale), and, in parallel, working memory processes are highly important for development of fluent reading (e.g. Gathercole et al., 2006; de Jong, 1998). Working memory also plays a small role in measures of verbal intelligence in our study. Verbal IQ measure includes a test of arithmetic (as is standard in WISC-III used in this study), whereas in WISC-IV, it is part of the working memory index. However, it seems unlikely that other factors could fully explain the results obtained in the current study. For example, the Seashore's time and pitch subtests, which demand less working memory, showed clear associations with reading skills. Thus, it seems unlikely that the association between perceptual musical skills and reading found in our study is fully explained by working memory skills.

However, we failed to find a robust association between auditory processing skills, as measured by the MMN, and measures of reading. Individual comparisons between variables suggested merely that auditory pitch and duration discrimination could be linked to written word segmentation (ALLU-T5B) but even then, only at the whole group level. While previous studies have found associations between low-level perception and discrimination abilities and reading skills (e.g. Douglas and Willats, 1994; Banai and Ahissar, 2013), our results did not fully agree with the previous studies. This may be because of different tests used to measure reading skills in different studies. Furthermore, it should be noted that even though similar cognitive processes predict reading skills in many different languages, different orthographic systems put different demands on reading acquisition and may affect the strengths of the associations between cognitive processes and reading skills (Caravolas et al., 2012).

Thus, while previous studies have reported robust associations between measures of basic auditory processing and reading skills, our results are not fully in line with these earlier findings. For example, the study of Kuppen et al. (2014) showed that sound rise time, sound duration, frequency and intensity discrimination abilities were associated with development of reading and phonological awareness in low-IQ children who were poor readers. There are several ways to interpret our results. First, it could be that basic auditory processing is a bottleneck for development of phonological awareness and reading skills only when the auditory processing abilities fall under a certain threshold. Until then, the auditory processing skills are 'good enough' for typical phonological processing or reading development (however, see Van Zuijen and others, 2012). This interpretation is consistent with the previous work of Banai and Ahissar (2013), who found associations with auditory processing and reading-related skills only in children without musical training, who also had poorer auditory processing skills than the musically trained children in their study. Applying this interpretation to our results, it could be that we did not see an association between the MMN and reading skills as all children had adequate auditory skills for normal reading or phonological processing. Even though the children in the music group elicited larger MMNs than children in the non-music to pitch and duration changes, consistent with previous studies (e.g. Moreno et al., 2009; Magne et al., 2006), it could be that this did not provide any additional benefit to reading skills because all children already had appropriate auditory processing skills to facilitate typical reading. Importantly, no group differences were found in the MMNs to the BeatBit phonetic contrast measuring phonological discrimination, which is an important aspect of phonological awareness and strongly associated with reading skills. Although phonological processing is only one of many abilities linked with fluent reading, our result suggests that the music group did not have a large and widespread advantage in auditory processing skills over the non-music group.

The second possible interpretation is that associations between auditory processing and reading are not broad but instead specific. For example, Goswami (2019) and Zhang and McBride-Chang (2010) argue that specific auditory processing skills (e.g. rise time processing, segmental and suprasegmental processing) are highly relevant for speech processing, and more general auditory processes assessed in our study may not be essential for development of abilities needed for reading skills. However, this explanation may be unlikely, as phonological abilities should be strongly associated with reading, but the discrimination of phonetic contrast in our study was not linked with either measure of reading skills. It could be that active phonological abilities may not be tightly linked with phonetic contrast discrimination, and thus, this association is not seen in our study (however, see Smith et al., 2021). Alternatively, it may be that in normally developing children, many general auditory processing abilities are already adequate for reading, and improvements in skills that are required to perform well in tests of musical skills may further benefit reading skills.

The third possible interpretation of our results is that associations between auditory processing and reading skills depend on how reading is operationalised. In many studies, reading is studied using measures of reading speed or accuracy, such as spelling accuracy (Douglas and Willats, 1994), accuracy of pronouncing printed words (Kuppen et al., 2014) or other reading-related abilities (verbal memory, phonological awareness; Banai and Ahissar, 2013). The tests used in the present study measure reading comprehension and word segmentation, which may measure somewhat different processes related to fluent reading than other studies. Future studies should utilise a broader battery of reading tests, including those assessing reading accuracy and speed (e.g. non-word reading and repetition), segmentation and reading comprehension.

Importantly, observed links between perceptual musical skills and reading skills naturally depend on the tests used when operationalising these skills. For example, some tests of musical skills may rely on working memory, especially if the listener has to keep two melodies in their working memory and compare them. As mentioned previously, some of the Seashore's tests rely on good working memory skills, but not, for example, pitch and duration subtests, which rely on short-term and sensory memory. Hence, we argue that our current results are unlikely to stem from possible working memory processes only. However, various tests, including Seashore's tests, have received valid criticism (see, e.g., Law and Zentner, 2012). While more adequate tests of perceptual musical skills have been developed recently (e.g. PROMS, Law and Zentner, 2012; MET, Wallentin et al., 2010), they were not available when planning the current project (data were recorded in 2010). So, when the current data were collected, only commonly used alternatives to Seashore's test would have been AMMA (Advanced Measures of Music Audiation) (Gordon, 1989) or Karma's test (Karma, 2007). While Karma's test is recommended and often used at least in the music education field with children and in academic research with adults (Tervaniemi et al., 2011; Tervaniemi et al., 1997), we considered it to be too long for the current purposes. In a similar vein, AMMA is too difficult for children and requires the children to discriminate between melodic and rhythmic. Child-oriented versions of AMMA (called PMMP and IMMA; Gordon, 1979 and Gordon, 1982, respectively), in turn, would have prolonged the testing so much that two testing sessions on separate dates would have been necessary. In the case of the current study protocol, this was not feasible due to practical reasons (the parents could not be asked to transport their children to the testing site twice in a short interval). Thus, these tests or their derivates would not have been applicable for the 8–11-year-old children in our study.

Finally, it is important to consider that findings based on the correlational analyses could be unreliable in the current study due to the large number of correlation analyses done. Even though these were conducted mostly post-hoc to assess what variables could explain the observed relationships between the latent variables in the SEM model, there is a risk of false positives. This is partly due to the fact that while the SEM model does not include the group factor, the correlational analyses do. Future studies should consider conducting separate SEM models for music and non-music groups to assess whether similar latent variables explain the associations between perceptual musical skills and reading skills.

To summarise, our results suggest that musical training in children is associated with larger MMN responses to changes in basic auditory features, consistent with previous studies. However, broadly analysed, auditory processing as measured by the MMN in typically developing children was not associated with reading skills in our study. Instead, reading skills were associated with musical perceptual skills or with skills that are enhanced by musical training and improve performance in tests of perceptual musical skills. It is possible that reading skills may be associated only with very specific auditory skills and only in children whose auditory skills are deficient because of developmental disorders, such as dyslexia. In contrast, typically developing children's reading proficiency could be mediated by more complex cognitive skills that are required to perform well in perceptual music tests.

## CRediT statement

**Eino Partanen**: Investigation, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Riia Kivimäki**: Conceptualization, Methodology, Funding acquisition, Investigation, Project administration, Writing – original draft, Writing – review & editing. **Minna Huotilainen**: Conceptualization, Writing – review & editing. **Sari Ylinen**: Methodology, Writing – review & editing. **Mari Tervaniemi**: Conceptualization, Methodology , Funding acquisition, Investigation, Project administration, Writing – original draft, Writing – review & editing.

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## Appendix A. Supplementary data

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