# Longitudinal associations between melodic auditory-visual integration and reading precursor skills in beginning readers

Borbála Lukács[a,b] (lukacs.borbala@ttk.hu)

Kata Asztalos[c] (kata.asztalos@gmail.com)

Ferenc Honbolygó[a,d] (honbolygo.ferenc@ttk.hu)

[a]: Brain Imaging Centre, Research Centre for Natural Sciences, Budapest, Hungary

[b]: Doctoral School of Psychology, ELTE Eötvös Loránd University, Budapest, Hungary

[c]: Kodály Institute, Liszt Ferenc Academy of Music, Budapest, Hungary

[d]: Institute of Psychology, ELTE Eötvös Loránd University, Budapest, Hungary

## Author Note

Correspondence concerning this article should be addressed to Borbála Lukács, Brain Imaging Centre, Research Centre for Natural Sciences; Magyar tudósok körútja 2., H-1117, Budapest, Hungary. E-mail: lukacs.borbala@ttk.hu

Author contributions: Borbála Lukács: Conceptualization, Methodology, Software, Data curation, Formal analysis, Investigation, Visualization, Writing – Original draft preparation. Kata Asztalos: Conceptualization, Supervision, Writing – Original draft preparation. Ferenc Honbolygó: Conceptualization, Funding acquisition, Resources, Supervision, Validation, Writing – Original draft preparation.

Declaration of interest: none.

## Abstract

The present study explored longitudinal relations between musical abilities (discrimination, auditory-visual connection) and precursor skills of reading (phonemic awareness, rapid naming, phonological memory, phonemic fluency) in 6–7-year-old children starting primary school. Eighty-five participants were assessed twice over the first school year to estimate the extent to which longitudinal changes in musical and phonological processing are related at the initial stages of formal reading and music instruction. Results of the repeated measures correlation analyses revealed specific longitudinal associations among enhancements in auditory-visual connection skills, pitch discrimination, and components of phonological processing. Moreover, the development of melodic auditory-visual integration appeared to be a relevant indicator of improvements in reading precursor skills. These findings might point to shared integration mechanisms underlying musical and reading development in young readers, which possibly originate in the emergent capability of prosodic reading.

*Keywords*: music education, musical abilities, precursors of reading, auditory-visual integration, repeated measures correlation.

# Longitudinal associations between melodic auditory-visual integration and reading precursor skills in beginning readers

Comparative studies on music-language relations are grounded in the notion that both language and music rely on a complex set of auditory and cognitive functions, which allow the encoding of basic acoustic parameters (i.e., duration, frequency, intensity, timbre) of sounds and the integration of discrete sound units into hierarchical sequences according to syntactic rules (Besson et al., 2011; Kraus & Chandrasekaran, 2010; Patel, 2003). Based on the acoustic similarities of the two domains, it has been suggested that the processing of music and speech draw on shared basic auditory mechanisms (Besson et al., 2011; Peretz & Coltheart, 2003). Beyond music perception, the ability to process temporal and spectral auditory information appears to be crucial for speech perception. Precise perception of rapid temporal and frequency changes in the auditory stream enables the differentiation between distinct phoneme categories as well as the segmentation of the speech stream into smaller perceptual units, such as words, syllables, and phonemes (Corriveau et al., 2010; Ziegler et al., 2012). Despite the large body of research with preschoolers and school-aged children, the role of domain-general auditory mechanisms in the connection between music processing and phonological processes involved in reading is still not clear. Moreover, little focus has been placed so far on examining how the development of musical and phonological processing are linked in children starting formal reading and music instruction. In the present study, we investigated the association between musical abilities and phonological processing skills in 6−7-year-old children to better understand the commonalities between music and language over the course of learning to read, with the ultimate aim to unravel parallels between training of musical abilities and the development of linguistic skills.

A considerable amount of studies imply that components of musical abilities and phonological processing skills (primarily phonological awareness) are connected in typically developing preschoolers and school-aged children. These correlational studies, however, provided diverse findings regarding the nature of relations, revealing global associations (Anvari et al., 2002; Degé et al., 2015; Steinbrink et al., 2019) or specific relations of phonological processing skills to either pitch-related (e.g., Bolduc & Montésinos-Gelet, 2005; Lamb & Gregory, 1993; Lukács & Honbolygó, 2019) or rhythm-related musical abilities (e.g., David et al., 2007; Holliman et al., 2010; Moritz et al., 2013; Ozernov-Palchik et al., 2018). There is also evidence for longitudinal links between training musical abilities and language development in children. It has been argued that long-term engagement with music enhances low-level auditory mechanisms in the music domain, including sensitivity to spectral and temporal parameters, that are also relevant for the extraction of acoustic information from speech sound sequences (Besson et al., 2011; McMullen & Saffran, 2004; Patel, 2008). It is plausible that enhancement in these domain-general auditory mechanisms may further influence language development at the cognitive level, leading to domain-specific improvements in phonological processing skills (Besson et al., 2011; Moreno & Bidelman, 2014). Results of longitudinal studies indicate that children participating in diverse music interventions demonstrate enhanced phonological awareness, rapid naming skills (Degé & Schwarzer, 2011; Herrera et al., 2011; Linnavalli et al., 2018; Patscheke et al., 2019), and verbal short-term/working memory capacity (Bolduc & Lefebvre, 2012; Kaviani et al., 2014). The extent of the overall gain of music learning, however, varies considerably across studies, suggesting that music instruction might have the potential to enhance only specific aspects of phonological processing (Gordon, Fehd, et al., 2015).

Based on the common auditory mechanisms underlying musical and phonological processing, it has been proposed that phonological processing skills might mediate the association between basic auditory processing and reading development (Corriveau et al., 2010; Ozernov-Palchik et al., 2018). Phonological processing skills, such as phonological awareness, rapid automatized naming, and phonological memory, are identified as robust indicators of progress in reading acquisition (Melby-Lervåg et al., 2012). Given the relevance of both pitch pattern processing (Foxton et al., 2003; Ziegler et al., 2012) and auditory rhythm perception, especially rise time sensitivity (Corriveau & Goswami, 2009; Goswami, 2011), for segmentation and discrimination processes, basic auditory mechanisms might support the development of the explicit awareness of the phonological structure (syllables, onsets, rhymes) and the manipulation of speech sound units at the initial stages of word decoding. Therefore, training auditory processing in the music domain may indirectly influence reading through promoting the learning of the mappings between speech sounds and visual symbols as well as the efficient access to phonological and lexical information in beginning readers (Gathercole & Baddeley, 1993; Torgesen et al., 1994; Wagner & Torgesen, 1987; Wolf & Bowers, 1999).

Beyond the converging evidence for the mediatory role of phonological processing in the connection between music processing and reading, there is also a line of research suggesting that temporal and tonal auditory processing may be related to the development of fluent reading through the acquisition of reading prosody. Reading prosody refers to the ability to read with proper phrasing, intonation, and expression (Kuhn et al., 2010). Phrasing is mostly linked to the rhythm of oral reading, i.e., the duration of syllables/words and pauses, enabling the segmentation and grouping of the text into syntactically meaningful sequences (Cowie et al., 2002; Kuhn et al., 2010). Intonation and expressivity are associated with the pitch modulations and melody contour of the voice but involve other acoustic parameters, such as intensity and timbre, to emphasize phrase boundaries and convey additional implicit meaning about the text (Godde et al., 2020). To define how the development of certain prosodic features is linked to children's emerging reading fluency, Miller and Schwanenflugel (2008) investigated reading prosody development from first to second grade. Their results showed that beyond the achievement of word decoding skills, the development of appropriate intonation contour appeared as a robust indicator of later reading fluency. The placing of pauses did not predict significantly fluent reading in third grade. Similar connections have been observed in other studies (Clay & Imlach, 1971; Cowie et al., 2002; Schwanenflugel et al., 2004), suggesting that the early development of reading intonation may be particularly important for the acquisition of later fluent reading. However, it has been highlighted that children should achieve decoding skills and fluency to a certain extent to allocate cognitive capacities to the appropriate prosodic reading of texts (Schwanenflugel et al., 2004). It seems possible, therefore, that not only prosodic development affects later reading fluency, but there might be reciprocal associations between the acquisition of fluent and prosodic oral reading in schoolchildren.

Because empirical evidence stems from different age groups, the question arises whether the relation of musical abilities to precursors of reading depends on children's current stage of musical, phonological, and reading development. The developmental aspect of music-language associations is somewhat neglected in the literature, despite the fact that both music processing and phonological awareness show accelerated development during the middle childhood years. Besides the emerging sensitivity to larger phonological units (syllables, rhymes; Ziegler & Goswami, 2005), children show considerable improvements in temporal and tonal auditory skills (Gembris, 2006; Gooding & Standley, 2011) and increased sensitivity to tonality (Kenney, 1997) and to the key and harmony structure of music without any formal instruction (Corrigall & Trainor, 2009). Other phonological processing skills, such as the awareness of phonemes

(Wimmer et al., 1991) and alphanumeric RAN relying on letter and digit knowledge (Torgesen et al., 1994), are typically acquired through formal reading instruction. The ability to associate musical notes with corresponding visual symbols may also begin to develop through formal education (Miyamoto, 2007). Given that the development of certain abilities depends on explicit instruction, it is possible that the associations between the different aspects of musical ability and phonological processing might gain strength with reading and musical experience, leading to developmental parallels at specific stages of their acquisition.

Research has been seldom conducted on whether the relationship between musical and phonological development varies with children's reading and musical experience. A study by Forgeard et al. (2008) demonstrated that improvement in tonal processing and improvement in phonemic processing were associated more in 6- to 7-year-old normal-reading children who received 31 months of instrumental music training than children who received no training. However, further evidence for such correlations at the initial stages of learning to read is still lacking. Hence, the present study aimed at contributing to the current understanding of longitudinal music-language associations by exploring potential parallels in the development of musical abilities and reading-related skills in young readers receiving formal music instruction. To address this issue, we examined how improvements in a set of musical abilities (discrimination, auditory-visual connection) and several phonological processing skills (phonemic awareness, RAN, phonological memory, phonemic fluency) are associated in children aged 6–7 years who started their first year at primary school. We focused on first-grade students to measure the development of phonological skills from the beginning of formal reading and music instruction. Measurements were carried out at the beginning and end of the school year with the same test battery to assess the strength of associations longitudinally over six months of schooling. Participants received school music lessons according to the solfeggio-based Kodály curriculum. According to the findings of Forgeard et al (2008) about the parallels in the development of musical and phonological processing skills and results regarding the importance of melody contour development in the acquisition of reading fluency, we predicted that specific longitudinal associations would be observed between the improvement in pitch-related but not rhythm-related musical abilities and the improvement in phonological processing skills in young readers.

## Materials and methods

This study is part of an ongoing four-year longitudinal research project (title: Active Music Learning with singing and movement: methods and the investigation of their effects) conducted in Hungary, which aimed to develop and implement two music pedagogical models in primary school education (Lukács et al., 2018) and follow children's cognitive and neural development from first to third grade (Maróti et al., 2018; Maróti, Honbolygó, & Weiss, 2019). The study was performed in accordance with the Declaration of Helsinki and the study protocol was approved by the United Ethical Review Committee for Research in Psychology (EPKEB) in Hungary (approval number: 2016/062).

### Participants

Initially, 103 children were recruited from four first-grade classes of three public primary schools located in Budapest (capital city) and Győr (county seat in the north-western region), Hungary. Data of 18 children were excluded: six children changed school after the first assessment, one child withdrew the consent from participation, and 11 children had missing data on more than two measures in either the first or the second measurements. The final sample consisted of 85 children (45 boys, 40 girls). Mean age at the first assessment was 6;11 and at the second assessment was 7;5. All participants were native Hungarian speakers of which two children were bilingual with Spanish, two children with Russian, and one child with English as their second language. Concerning parental education, 94.8% of mothers and 80.3% of fathers graduated from university, 2.4% of mothers and 5.3% of fathers graduated from post-secondary tertiary education, and 2.6% of mothers and 14.4% of fathers graduated from secondary education (matriculation). With respect to participants' musical background, 54.1% of the children had no music lessons, 23.7% had less than one year, and 11.6% had more than one year of private music lessons prior to school music instruction.

All participants received classroom music lessons as part of general school education. In Hungarian primary schools, the traditional practice of music instruction follows the pedagogical concepts of Zoltán Kodály. Emphasizing the fundamental role of folk songs of the native culture, music classes apply singing as the main instrument in vocal and rhythmic activities to support the development of musical hearing, musical reading and writing, and music comprehension. The Kodály concept implements relative solmization which associates syllable names and hand signs with specific degrees of musical scales and applies rhythmic syllables which represent rhythmic patterns with different duration values.

School music instruction started at the beginning of the school year. Professionally trained music teachers gave music lessons to the whole class (20–30 children per group) in 45-minute sessions. Until the posttraining measurements were conducted in April, participants received music lessons for 27 weeks (excluding holidays).

**Measures**

Age, gender, musical background, and socioeconomic status (SES) were assessed as potential confounding variables with a background questionnaire. Children were tested twice during the first school year using identical measures. Phonemic awareness, rapid automatized naming, phonological short-term memory, and phonemic fluency were measured as precursors of reading. Further, musical abilities were assessed with discrimination and auditory-visual connection subtests.

***Background measures***

A background questionnaire was applied to assess age, gender, and musical background of participants as well as parental education at the beginning of the study. Parents were asked to share information about the participants' musical background, which was defined by the duration of formal music instruction children engaged in prior to school music education. The questionnaire was also used to acquire information about the highest level of education of both parents. Mothers' and fathers' responses were coded separately on a 9-point scale (1 = No graduation, 2 = Primary education, 3 = Technical school, 4 = Vocational high school, 5 = Matriculation (Secondary school graduation), 6 = Post-secondary tertiary education, professional qualification, 7 = Bachelor degree, 8 = Master degree, 9 = Doctoral degree). A final SES score was calculated either as the mean of both parents' scores in intact families and the single parent's score in single-parent families. Parents of 9 participants did not provide information about their highest education and children's musical background; therefore, we used data of only 76 participants regarding musical background and SES in statistical analyses.

IQ was assessed with one verbal (Vocabulary) and one nonverbal (Block Design) subtest of the Hungarian adaptation of WISC-IV (Nagyné Réz, Lányiné Engelmayer, Kuncz, Mészáros, & Mlinkó, 2008; Wechsler, 2003). Block Design was administered to estimate nonverbal IQ and visuo-spatial skills. Pictures were presented to children showing red and white designs with increasing complexity, and their task was to recreate each design with red and white blocks. Accurately constructed items were scored based on the amount of time used for designing. We measured verbal IQ with the Vocabulary subtest. Children were presented words with increasing difficulty and were asked to define the meaning of each item. Scoring was based on the sophistication of explanation. We used raw scores in statistical analyses to estimate changes in performance within the same age group.

***Measures of the precursors of reading***

Phonemic awareness (PA) and rapid naming skills were tested using two subtests of the Hungarian version of Dyslexia Differential Diagnosis Maastricht (3DM-H; Blomert & Vaessen, 2009; Tóth, Csépe, Vaessen, & Blomert, 2014). The short version of the Phoneme Deletion subtest was administered to measure phonemic awareness. In this task, children were presented one-syllable CVC pseudo-words (e.g., 'cák' without 'k' [=cá]) and asked to delete the initial or the last speech sound, then to pronounce the remaining sound sequence. The subtest comprised two practice items and four test items. Instructions and items were presented via the headphone. We calculated an accuracy score based on the proportion of correct answers and a speed score based on the time (seconds) to pronounce the sound sequence. Scores were transformed and corrected by the parameters of hierarchic item response theory models; therefore, the mean of score was 0 and standard deviation was 1.

Rapid automatized naming (RAN) skills were measured by two tasks. Children were presented first matrices of digits (i.e., 1, 4, 5, 6, 8), then matrices of pictures of simple objects (i.e., fish, chair, pear, scissors, dog), and they had to sequentially name the items as quickly as they could. After five items were displayed as practice in each task, two blocks of each item type were presented. Arranged in a 3×5 matrix within each block, the 15 items appeared in a pseudo-random order. Instructions were presented on the computer screen and via headphone simultaneously. We calculated a speed score for digits and pictures separately by averaging the number of items named correctly in a second.

Verbal short-term memory (STM) was tested with Digit Span forward subtest from the Hungarian version of WISC-IV (Nagyné Réz et al., 2008; Wechsler, 2003). Children heard sequences of digits presented orally by the experimenter and their task was to repeat the sequence in the same order. By summing the longest correctly repeated sequence, we computed a short-term memory span score.

Phonemic fluency was assessed with a letter fluency subtest described by Mészáros, Kónya, and Kas (2011). A wide range of cognitive skills related to executive control can be measured by the test: it requires access to the mental lexicon based on a given phonemic category; generation and use of strategies; search for task-relevant items, inhibition of task-irrelevant items; updating information; flexible shifting between task conditions (Matute et al., 2004). In this test, children were asked to name as many words beginning with the same phoneme as they could in 60 seconds. After one practice task, three tasks were presented to children, which required the generation of words starting with *k*, *t*, and *s* phonemes, respectively. After excluding repetitions and out-of-category items, a phonemic fluency score was defined by the total number of correct words listed in the three conditions.

***Measures of musical abilities***

Musical abilities were assessed with an online test based on the measure of Asztalos and Csapó (2017). Participants completed the musical tests at their own pace via the eDia (Electronic Diagnostic Assessment; Csapó & Molnár, 2019) system, which provided a child-friendly, easy-to-use online platform for data collection. Children heard the instructions, the explanations for musical terms, and test stimuli via headphones. The online battery comprised six subtests of which five measured musical discrimination and one measured auditory-visual connection skills.

Discrimination subtests were applied to evaluate children’s ability to memorize and differentiate musical patterns. Each subtest comprised 15 items. Children were presented pairs of musical stimuli and were asked to indicate whether the consecutive stimuli were the same or different by clicking on the green check mark in case of identical stimuli or clicking on the red cross in case of difference. In the Melody Discrimination subtest, melodies included two or four bars. Rhythmic context was simple, the excerpts contained only quarters, eighth notes, and quarter rests. The changed note was one second or third higher or lower than the original one, which did not modify the contour or the tonality of the initial melody. The Pitch Discrimination subtest comprised pairs of notes for which the possible pitch difference was one semitone. The Rhythm Discrimination subtest presented children six- or eight-beat-long rhythmic sequences which included simple (quarter, eighth notes, quarter rests) and complex rhythmic patterns (syncopation, sixteens, dotted quarters, triplets). In case of difference, the number of the notes has not changed. The Harmony Discrimination subtest contained pairs of triads (chords of three notes) which could differ only in one note. The interval difference between the initial and changed note was either a minor or a major second. In the Tempo Discrimination subtest, children heard two identical melodies successively, or the second one was 10-, 15-, 20-, or 30-bpm (beats per minute) faster or slower than the first one.

In addition to music perception subtests, auditory-visual connection tasks were administered to assess children's ability to associate musical auditory (melodic and rhythmic) patterns with their visual representations. In the Melody Connection tasks, short melodies were presented, and children had to choose one out of the three pictures that represented the contour of the melody heard. In the Rhythm Connection tasks, short rhythmic sequences were presented. Quarter notes were illustrated by big drums, whereas eighth notes were illustrated by small drums in the pictures. Children had to decide which one out of the three pictures of drums represented the rhythmic pattern heard. The auditory-visual connection subtest included 15 items of which 10 items were related to melody and 5 items were related to rhythm. Because the two connection tasks measured different aspects of auditory-visual connection ability, Melody connection and

Rhythm connection were included as separate variables in statistical analyses. For each musical subtest, an accuracy score was defined by the number of correct answers.

### Procedure

Parents provided written informed consent and children provided verbal assent before participation in the study. Assessments were carried out in a quiet room during school hours. The authors and trained assistants administered the tests in three sessions. Participants were tested individually on the measures of IQ, working memory, and verbal fluency tasks in one session. Computer-based tests measuring phonological awareness and rapid naming were performed in another session. The order of the two individual sessions was counterbalanced across participants. After the individual testing sessions, musical abilities were assessed in groups of 10 to 15. Using computers in the school lab, participants completed the online musical tests on their own, while research assistants provided technical support and monitored children's progress. The order of the musical measures was fixed at both testing points. All children completed the musical subtests in the same order: each testing session started with the five discrimination subtests (melody, pitch, rhythm, harmony, and tempo discrimination) and ended with the auditory-visual connection subtest (melody and rhythm connection).

First measurements were conducted at the beginning of the first school year (*pretraining*), and second measurements were carried out six months later at the end of the school year (*posttraining*). No compensation was provided for participating in the study.

## Results

### Preliminary analyses

Preliminary analyses were conducted with JASP software (version 0.9.2.0, JASP Team, 2018). Since the Phoneme Deletion test was completed by only a subset of participants at baseline ($N$ = 56), we included only data of this subsample in analyses examining the relation of PA Accuracy and PA Speed to other variables. A few missing data occurred for the measures of RAN and auditory-visual connection at either testing point; therefore, the number of observations differed slightly across the tests. Pre- and posttraining mean values and standard deviations for age and the measures of IQ, precursors of reading, and musical abilities are shown in **Table 1**.

**Table 1**

*Descriptive statistics of the whole sample*

| | Pretraining | | Posttraining | |
|---|---|---|---|---|
| Measures | *M* | *SD* | *M* | *SD* |
| Age (years) | 6.96 | 0.34 | 7.48 | 0.35 |
| Nonverbal IQ | 24.31 | 10.17 | 28.34 | 10.48 |
| Verbal IQ | 24.61 | 5.76 | 29.69 | 6.86 |
| PA Accuracy [a] | -1.19 | 0.90 | -0.11 | 0.56 |
| PA Speed [a] | -1.37 | 1.11 | -0.58 | 0.95 |
| RAN Digits | 1.15 | 0.32 | 1.55 | 0.28 |
| RAN Pictures | 0.95 | 0.21 | 1.09 | 0.20 |
| Phonemic Fluency | 9.85 | 6.38 | 17.45 | 7.95 |
| Verbal STM | 6.98 | 1.62 | 7.55 | 1.42 |
| Melody Discrimination | 6.87 | 2.22 | 6.81 | 2.05 |
| Pitch Discrimination | 7.95 | 3.51 | 8.97 | 3.64 |
| Rhythm Discrimination | 7.39 | 2.49 | 7.25 | 2.82 |
| Harmony Discrimination | 7.35 | 2.53 | 7.99 | 2.73 |
| Tempo Discrimination | 7.88 | 2.69 | 8.07 | 2.62 |
| Melody Connection | 4.72 | 2.55 | 6.46 | 2.60 |
| Rhythm Connection | 2.36 | 1.50 | 2.73 | 1.44 |

*Note*. PA = phonemic awareness (3DM-H Phoneme Deletion); RAN = rapid automatized naming (3DM-H subtests); STM = short-term memory (WISC-IV Digit Span).

[a] Means and standard deviations are shown only for the subsample of participants who managed to perform the subtest at pretraining ($N$ = 56).

Because Verbal IQ was significantly related to Phonemic Fluency at both measurement points and Nonverbal IQ was significantly related to multiple components of musical skills (see **Supplementary Table 1** and **Table 2**), both IQ measures were controlled for when calculating partial Spearman correlations between precursors of reading and musical abilities separately for each measurement point with the ppcor package (Kim, 2015) in the statistical software R (version 3.6.2; R Core Team, 2019). Results of partial correlation analyses regarding the relations among musical abilities and precursors of reading are summarized for pretraining assessments in **Supplementary Table 3** and for posttraining assessments in **Supplementary Table 4**. After the Benjamini-Hochberg method was applied to control for the false discovery rate (i.e., the proportion of mistakenly rejected null hypotheses, or Type I error; Benjamini & Hochberg, 1995), none of the pretraining or posttraining partial correlations remained significant.

**Repeated measures correlations**

To evaluate the possible longitudinal associations between precursors of reading and musical abilities, we computed repeated measures correlations with the rmcorr package (Bakdash & Marusich, 2018) in R software. Rmcorr calculates the common within-participants correlation between paired measures, relying on corresponding tests completed by each participant at least twice. The overall within-participants association between two continuous variables is determined by a special version of analysis of covariance (ANCOVA), which takes one measure as the outcome variable with participant as the factor level, while using the second measure as the covariate to control for the effect of within-participants variance. Rmcorr estimates the best linear fit based on paired data of each participant, resulting in individual regression lines showing a common slope but varying intercepts. Ranging between –1 and 1, the rmcorr coefficient ($r_{rm}$) reflects the strength of relation between an increase in one test and an increase in another test within the participant (Bland & Altman, 1994; Bland & Altman, 1995). In the present study, rmcorr was applied to assess how pre- to posttraining longitudinal changes in reading-related skills and musical abilities were associated, i.e., the degree to which the development of precursor skills were related to the development of musical discrimination and auditory-visual connection. For all repeated measures correlations, 95% confidence intervals were estimated using bootstrapping. Confidence intervals around zero indicate a linear relationship that shows a great variability across participants, whereas narrow confidence intervals indicate good fit and no considerable heterogeneity across participants (Bakdash & Marusich, 2017). The assumptions of normally distributed residuals and homoscedasticity were met for the analyses.

Results of the longitudinal correlation analyses between precursors of reading and musical abilities are reported in **Table 2**. We report only significant correlations that survived Benjamini-Hochberg correction for multiple comparisons in details below.

**Table 2**

*Repeated measures correlations between the precursors of reading and musical abilities*

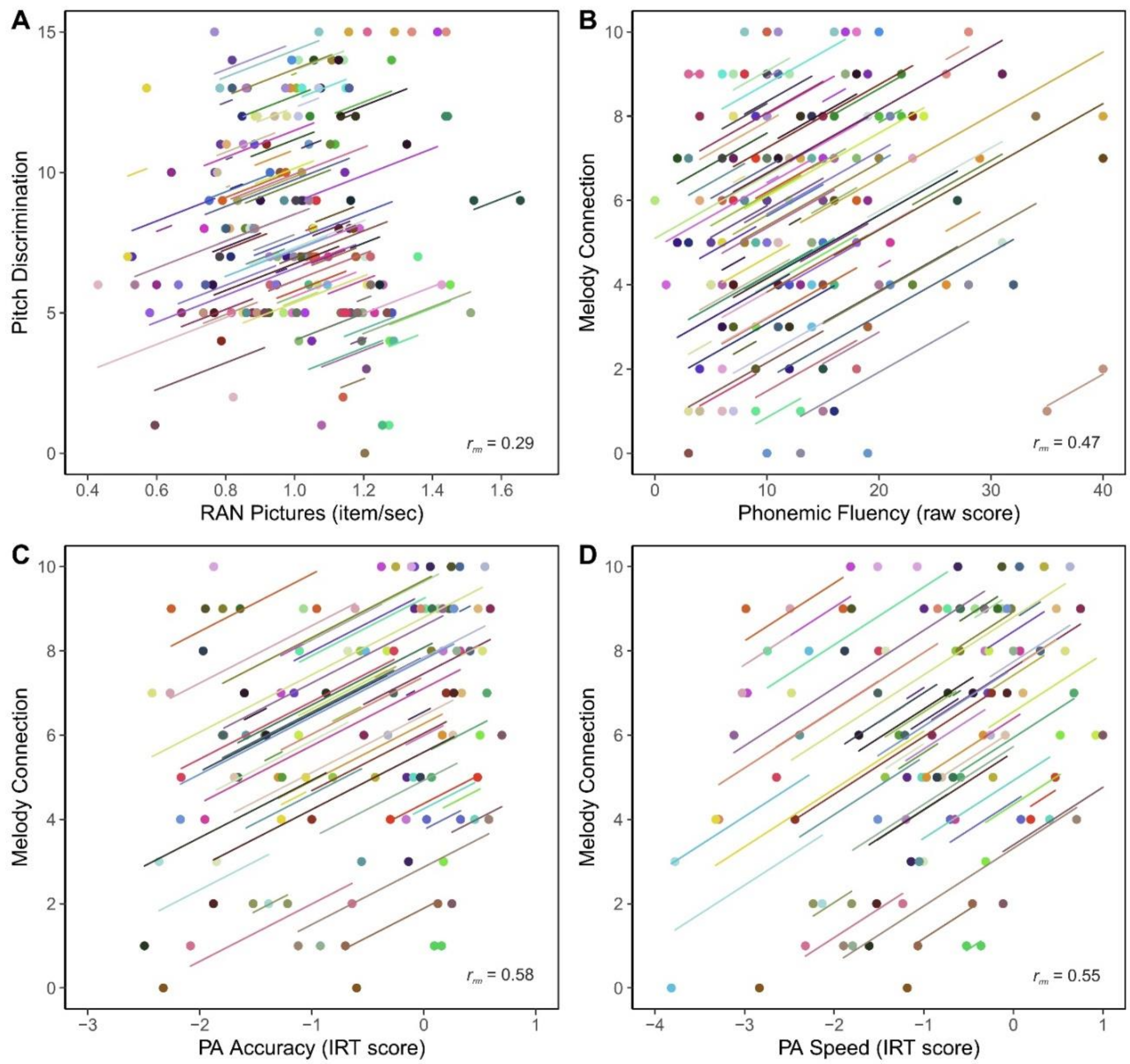
| Measures | Musical abilities | | | | | | |
|---|---|---|---|---|---|---|---|
| | Discrimination | | | | | Auditory-Visual Connection | |
| | Melody | Pitch | Rhythm | Harmony | Tempo | Melody | Rhythm |
| PA Accuracy | -0.01 | 0.19 | -0.13 | 0.24 | 0.01 | **0.58*** ** | 0.19 |
| PA Speed | -0.13 | 0.17 | 0.05 | 0.09 | -0.17 | **0.55*** ** | 0.20 |
| RAN Digits | -0.05 | 0.27* | 0.04 | 0.12 | 0.06 | **0.55*** ** | 0.26* |
| RAN Pictures | 0.08 | **0.29** ** | 0.11 | 0.21* | 0.20 | **0.39*** ** | **0.34** ** |
| Phonemic Fluency | 0.03 | 0.24* | 0.04 | 0.14 | 0.03 | **0.47*** ** | 0.19 |
| Verbal STM | 0.13 | 0.24* | 0.10 | -0.13 | -0.08 | 0.09 | 0.13 |

*Note*. PA = phonemic awareness (3DM-H Phoneme Deletion); RAN = rapid automatized naming (3DM-H subtests); STM = short-term memory (WISC-IV Digit Span). Correlations that remained significant after the Benjamini-Hochberg correction are written in bold.

*$p < .05$, **$p < .01$, ***$p < .001$.

From among music discrimination skills, only one significant correlation emerged between Pitch Discrimination and RAN Pictures, $r_{rm}$ (84) = 0.29, 95% CI [0.05, 0.50], $p = 0.006$, as illustrated in **Figure 1A**. Rmcorr plots represent the pretraining and posttraining correlations simultaneously between paired measures that were collected on the same participant at two repeated measurements. Two dots with the same color show two measurements from the same participant. Colored lines depict rmcorr regression lines fit for each participant, with the common slope indicating the common association between the improvements on the two measures. The length of individual regression lines illustrates the magnitude of longitudinal change in each participant. Accordingly, the repeated measures correlation between Pitch Discrimination and

RAN Pictures suggests that greater increases in pitch perception were related to larger improvements in rapid naming of pictures.

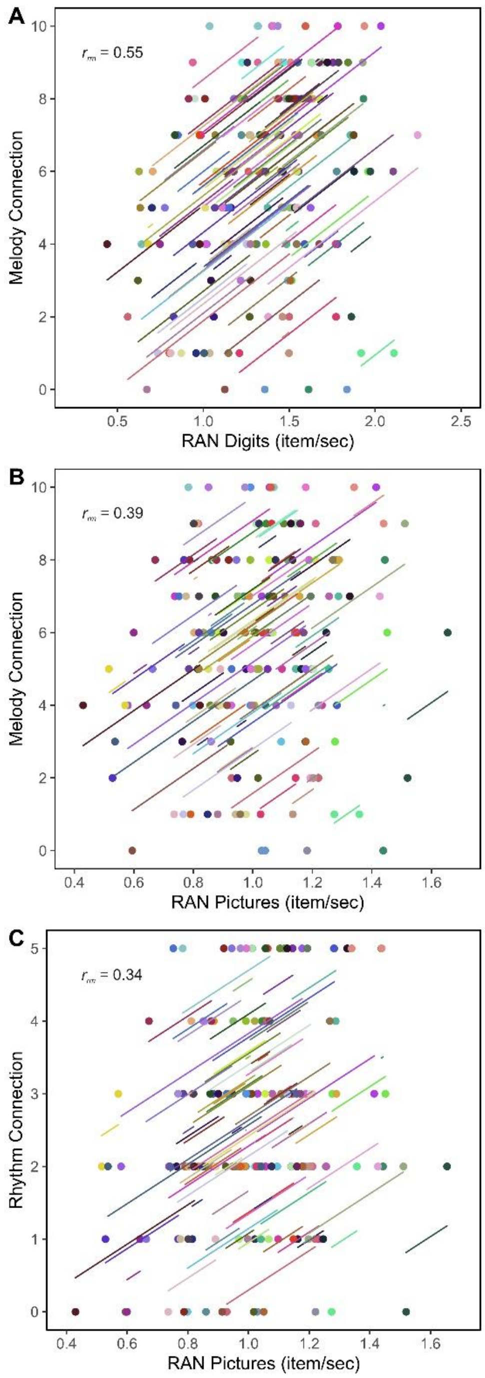



(Double-column fitting image)

**Figure 1**. Scatterplots showing significant repeated measures correlations among Pitch Discrimination and RAN Pictures (**A**), and the significant longitudinal relations of Melody Connection to Phonemic Fluency (**B**), PA Accuracy (**C**), and PA Speed (**D**). *Note*. For the musical measures, the number of correct responses is displayed.

Repeated measures correlations between auditory-visual connection skills and predictors of reading revealed several significant associations. Except for Verbal STM, the melodic subtest was significantly correlated with all precursors of reading. Performance on the melodic subtest was significantly associated with Phonemic Fluency, $r_{rm}$ (82) = 0.47, 95% CI [0.31, 0.60], $p = 7.215 \times 10^{-6}$ (**Figure 1B**). Additionally, significant associations were found between Melody Connection and PA Accuracy, $r_{rm}$ (53) = 0.58, 95% CI [0.41, 0.73], $p = 3.187 \times 10^{-6}$ (**Figure 1C**), and PA Speed, $r_{rm}$ (53) = 0.55, 95% CI [0.37, 0.68], $p = 1.260 \times 10^{-5}$ (**Figure 1D**). Melody Connection was also significantly correlated with RAN Digits, $r_{rm}$ (81) = 0.55, 95% CI [0.37, 0.69], $p = 7.420 \times 10^{-8}$ (**Figure 2A**), and RAN Pictures, $r_{rm}$ (82) = 0.39, 95% CI [0.21, 0.56], $p$ = 0.0002 (**Figure 2B**). These longitudinal correlations indicate that greater improvements in reading-related skills were associated with larger increases in melodic auditory-visual connection.

Concerning the rhythmic subtest, analyses revealed a significant correlation with RAN Pictures, $r_{rm}$ (82) = 0.34, 95% CI [0.16, 0.53], $p$ = 0.001 (**Figure 2C**). It suggests that greater improvement in rhythmic auditory-visual connection was associated specifically with larger increases in rapid naming of pictures.




(Single column fitting image)

**Figure 2**. Scatterplots showing significant repeated measures correlations between Melody Connection and RAN Digits (**A**), Melody Connection and RAN Pictures (**B**), and Rhythm Connection and RAN Pictures (**C**). *Note*. For Melody and Rhythm Connection, the number of correct responses is displayed.

To further examine the extent to which improvements in melodic and rhythmic auditory-visual connection skills predict the development of each precursor of reading, we conducted linear mixed-effects regression analyses using the lmer function via the lme4 package (Bates et al., 2015) in the R environment. We fitted a random-intercept regression model for each precursor of reading (dependent variables), including Melody and Rhythm Connection separately as fixed effects, allowing the intercept to vary for each level of the random effect, i.e., for each participant, and keeping the slope constant among individuals. For parameter estimation, the REML (restricted maximum likelihood) criterion was used.

The results of regression analyses are presented in **Table 3**. Except for Verbal STM, all precursors of reading were significantly predicted by the advancements in Melody Connection. Improvements in the Rhythm Connection subtest predicted only the increases in the RAN Pictures task.These findings strengthen the results of the rmcorr analyses, indicating that the development of melodic auditory-visual connection is the best predictor of the enhancements in reading-related skills. Moreover, improvements in rhythmic auditory-visual connection seem to be predictive of the development of picture naming skills specifically.

**Table 3**

*Results of the linear mixed-effects regression analyses predicting the development of reading precursors*

| Effect | | | 95% CI | | *t* | *p* |
|---|---|---|---|---|---|---|
| | | | *LL* | *UL* | | |
| | | PA Accuracy | | | | |
| Fixed effects | Estimate | *SE* | | | | |
| Intercept | -1.375 | 0.225 | -1.850 | -0.914 | -6.11 | < .001 |
| Melody Connection | 0.086 | 0.034 | 0.015 | 0.160 | 2.57 | .012 |
| Rhythm Connection | 0.076 | 0.067 | -0.056 | 0.208 | 1.13 | .263 |
| Random effects | Variance | *SD* | | | | |
| Intercept (participant) | 0.047 | 0.217 | | | | |
| Residual | 0.744 | 0.863 | | | | |
| | | PA Speed | | | | |
| Fixed effects | Estimate | *SE* | | | | |
| Intercept | -1.955 | 0.276 | -2.513 | -1.399 | -7.10 | < .001 |
| Melody Connection | 0.146 | 0.038 | 0.068 | 0.221 | 3.89 | < .001 |
| Rhythm Connection | 0.044 | 0.074 | -0.101 | 0.188 | 0.60 | .552 |
| Random effects | Variance | *SD* | | | | |
| Intercept (participant) | 0.545 | 0.738 | | | | |
| Residual | 0.611 | 0.782 | | | | |
| | | RAN Digits | | | | |
| Fixed effects | Estimate | *SE* | | | | |
| Intercept | 1.016 | 0.071 | 0.867 | 1.164 | 14.28 | < .001 |
| Melody Connection | 0.044 | 0.011 | 0.021 | 0.066 | 4.14 | < .001 |
| Rhythm Connection | 0.033 | 0.019 | -0.006 | 0.070 | 1.67 | .098 |
| Random effect | Variance | *SD* | | | | |
| Intercept (participant) | 0.042 | 0.205 | | | | |
| Residual | 0.078 | 0.280 | | | | |
| | | RAN Pictures | | | | |
| Fixed effects | Estimate | *SE* | | | | |
| Intercept | 0.856 | 0.042 | 0.772 | 0.941 | 20.46 | < .001 |
| Melody Connection | 0.015 | 0.006 | 0.003 | 0.026 | 2.57 | .011 |
| Rhythm Connection | 0.030 | 0.011 | 0.009 | 0.050 | 2.84 | .005 |
| Random effect | Variance | *SD* | | | | |
| Intercept (participant) | 0.028 | 0.167 | | | | |
| Residual | 0.018 | 0.135 | | | | |
| | | Phonemic Fluency | | | | |
| Fixed effects | Estimate | *SE* | | | | |
| Intercept | 8.230 | 1.623 | 4.896 | 11.546 | 5.07 | < .001 |
| Melody Connection | 0.694 | 0.240 | 0.183 | 1.189 | 2.89 | .004 |
| Rhythm Connection | 0.514 | 0.439 | -0.344 | 1.372 | 1.17 | .244 |
| Random effect | Variance | *SD* | | | | |
| Intercept (participant) | 25.43 | 5.043 | | | | |
| Residual | 32.28 | 6.187 | | | | |
| | | Verbal STM | | | | |
| Fixed effects | Estimate | *SE* | | | | |
| Intercept | 6.561 | 0.303 | 5.969 | 7.153 | 21.69 | < .001 |
| Melody Connection | 0.055 | 0.044 | -0.030 | 0.140 | 1.26 | .212 |
| Rhythm Connection | 0.141 | 0.080 | -0.014 | 0.298 | 1.77 | .078 |
| Random effect | Variance | *SD* | | | | |
| Intercept (participant) | 1.081 | 1.040 | | | | |
| Residual | 1.173 | 1.083 | | | | |

*Note*. CI = confidence interval; *LL* = lower limit; *UL* = upper limit; PA = phonemic awareness (3DM-H Phoneme Deletion); RAN = rapid automatized naming (3DM-H subtests); STM = short-term memory (WISC-IV Digit Span).

# Discussion

The present study examined longitudinal associations among musical abilities and precursors of reading in 6−7-year-old children starting primary school. We tested music discrimination, auditory-visual connection, and phonological processing skills (phonemic awareness, rapid automatized naming, phonological memory, phonemic fluency) twice during the first school year to evaluate the extent to which longitudinal changes in these processes are related at the very beginning of formal reading and music instruction. We attempted to identify potential parallels in the development of musical and phonological processing as indicators that these longitudinal associations coincide with the initial stages of learning to read and explicit musical experience.

## Associations between musical processing and phonological processing skills

Although cross-sectional correlations were not of direct interest in the current study, it is important to note that we did not observe any significant correlation between musical abilities and precursors of reading neither at the beginning of schooling nor at the end of the school year. Hence, our findings contradict prior evidence that indicated associations among phonological processing skills and tonal and/or rhythmic musical abilities (e.g., Degé et al., 2015; Lamb & Gregory, 1993; Moritz et al., 2013). We suppose that the discrepancies between the current and previous findings might be attributed to the differences of the difficulty and cognitive demands of the measures administered. Conflicting results in this field possibly suggest that the diverse relations among musical abilities and phonological processing skills reflect specific task-dependent mechanisms, and not necessarily domain-general processes.

**Longitudinal associations between the development of musical abilities and precursor skills of reading**

To better understand the longitudinal nature of associations in beginning readers taking classroom music lessons, we assessed the degree to which baseline to end-of-year performance changes in the tests of musical and phonological processing were related. The advantage of the repeated measures correlation method applied here was that by accounting for within-participants variance, we were able to evaluate longitudinal associations among the development of musical abilities and precursor skills based on individual developmental trajectories.

With respect to the relationships between the development of music discrimination and precursor skills, only improvements in rapid naming of pictures and pitch discrimination were correlated. This longitudinal correlation suggests a strong relationship between the development of pitch perception and the development of nonalphabetic RAN, i.e., the access of the phonological representations of simple non-linguistic visual symbols. Contrary to our expectations, improvement in phonemic awareness was not significantly associated with improvement in pitch or harmony discrimination, which contradicts the results by Forgeard et al. (2008), showing a specific relationship between improvement in tonal music perception and improvement in phonological awareness.

The lack of associations between the development of temporal discrimination skills (rhythm and tempo perception) and the enhancement of phonological processing skills may also seem surprising as previous studies pointed to the importance of basic temporal auditory skills in the development of phonological processing skills (Holliman et al., 2010; Moritz et al., 2013; Ozernov-Palchik et al., 2018). A few researches with school-age children, however, have recently indicated that temporal discrimination ability is associated especially with grammar skills. Examining typically developing 6-year-olds, Gordon, Shivers et al. (2015) found that rhythm perception was particularly related to expressive grammar (i.e., the production of morpho-syntactic sequences) but not to phonological awareness. When testing the relations of rhythm and melody perception to grammar skills separately, only rhythm discrimination turned out to be predictive of receptive grammar (i.e., the understanding of syntactically complex sentences) in children aged between 6 and 9 years (Swaminathan & Schellenberg, 2020). Moreover, the positive association between syntax processing and rhythm discrimination has been proved to become more robust with age (Lee, Ahn, Holt, & Schellenberg, 2020). Since the abovementioned studies revealed that music training has weak or no effect on the development of grammar skills, formal musical experience seems to be not necessary for the emergence of longitudinal associations between the development of musical rhythm skills and syntactic acquisition in school-age children. It further supports the notion that music instruction itself has a low potential to facilitate language development, including reading-related processes (Gordon, Fehd, et al., 2015), and that the relation of music training to reading development might be mediated by cognitive abilities and not music perception (Swaminathan et al., 2018).

For auditory-visual connection skills, results revealed that development in melodic auditory-visual connection was significantly related to the development of phonemic awareness, rapid naming skills, and phonemic fluency, but not to the development of phonological memory. Furthermore, rhythmic auditory-visual connection showed a significant longitudinal relation to rapid naming of pictures. These longitudinal relations might indicate parallels between the developmental trajectories of tonal auditory-visual connection and phonological processing skills (excluding phonological memory) as well as between temporal auditory-visual connection and nonalphabetic RAN. We assume that both formal reading and music instruction might account for the appearance of these longitudinal associations, presumably driven by the increasing efficacy of multimodal integration skills during the first months of schooling.

In beginning readers, word decoding critically relies on the efficacy of integration of visual and verbal information (i.e., the mappings of phonemes to their orthographic correspondents; Bryant et al., 1990; Mann & Liberman, 1984) and phonological lexical retrieval (i.e., rapid naming skills; Moll et al., 2014). At the early stages of reading acquisition, both lexical retrieval and visual-verbal integration mechanisms improve rapidly and become more efficient and automatized through practice (Froyen et al., 2009; Wagner & Torgesen, 1987). Simultaneously, the learning of grapheme-phoneme correspondences increase the explicit knowledge of and sensitivity to phonemes (Goswami, 2002). Enhancements in these language-specific processes might influence the development of domain-general multimodal integration and auditory discrimination skills, which might be relevant for music processing. On the other hand, taking classroom music lessons also affects the progress in auditory processing and multimodal integration skills through various musical activities, including learning music notation. Based on the mappings of musical sounds to written notes, music notation also demands multimodal integration mechanisms. Studies comparing adults with different musical expertise have shown that long-term music training including music notation enhances the processing of auditory-visual pairings (Nichols & Grahn, 2016; Paraskevopoulos et al., 2012), which may be transferred to the language domain (Behne et al., 2013; H. Lee & Noppeney, 2014). It is therefore possible that even a six-month long music instruction and experience with music notation could have a positive impact on the development of multisensory integration skills, leading to enhancements in both musical auditory-visual integration and phonological processing in beginning readers.

It is important to note that the developmental course of reading-related skills paralleled especially with the enhancements of melodic multimodal integration. The results of mixed effects regression provided further evidence that tonal auditory-visual connection predicted significantly the progress in phonological processing skills at this stage of learning to read. It was only pictorial RAN in which rhythmic auditory-visual connection significantly predicted improvements above and beyond melodic auditory-visual connection. These findings suggest that the tonal and temporal aspects of multisensory integration might be separable and associated with distinct phonological processing skills in first-grade children.

The relevance of temporal and melodic auditory features in the development of fluent reading may provide further support for the current results. Despite the still unclear construct of reading fluency, the development of appropriate oral reading prosody, based on the temporal organization and intonation of texts, is generally considered as a key marker of the achievement of future fluency in reading (Godde et al., 2020). Following primary school children's acquisition of prosodic reading, Miller and Schwanenflugel (2008) found that the fewer irrelevant pausing in first grade were associated with a more mature intonation contour in second grade. Nonetheless, besides the progress in word reading, only the development of appropriate pitch contour production appeared as a robust indicator of later reading fluency. These results are in accordance with the outcomes of prior studies conducted with young readers that also indicated the importance of pitch-related prosodic development in achieving fluency in oral reading (Clay & Imlach, 1971; Cowie et al., 2002; Schwanenflugel et al., 2004). The tonal and temporal aspects of reading prosody may play a different role even in the development of reading comprehension since the strength of the connection between reading prosody and reading comprehension seems to vary as a function of prosody features (for a recent meta-analysis, see Wolters, Kim, & Szura, 2020). The current findings may further imply that in this specific period of reading acquisition, the longitudinal correlation between intonation and oral reading skills might not be limited to pitch contour production but extend to the integration of melody contour processing in multiple modalities.

The current study did not include any reading measures, which hinders the possibility to draw conclusions about the developmental parallels of music processing and fluent reading itself. Our findings contribute to the literature on music-language associations by revealing simultaneous improvements in tonal auditory-visual integration and specific indicators of reading in the early stages of reading acquisition. Future research should attempt to examine both the phonological-orthographic and the prosodic particularities of reading development that might affect the associations between musical and reading development in children with emerging literacy. Also, there is need for more studies to measure multisensory integration skills in both the music and language domain to better understand the role of multimodal integration processes at this specific stage of musical and reading development.

**Limitations**

The results of the present study may be affected by some methodological issues. The major limitation of the current findings involved the measures we applied. The online measure of musical abilities was not a standardized test, which challenges the validity and reliability of the current results. Except for rapid naming, precursor skills were assessed by only one task. To control for the occurrence of potential task-dependent associations, future studies should apply test batteries that span the main components of phonological processing skills and musical abilities. Previous evidence suggests that precursors of reading are strongly related to music production, especially rhythm reproduction (e.g., Degé et al., 2015; Steinbrink et al., 2019). Therefore, it is recommended to measure music production along with music perception in further studies. Moreover, despite that phonemic awareness has been shown to be a stronger precursor of reading acquisition than rhyme awareness in school-aged children (Melby-Lervåg et al., 2012), only a subsample of participants were able to complete the phoneme deletion task we applied. Using tests that are more appropriately suited for assessing phonemic awareness in beginning readers would increase the reliability of results and enable larger sample sizes by decreasing the amount of missing data.

## Conclusion

In summary, the current research revealed specific longitudinal associations among enhancements in auditory-visual connection skills, pitch discrimination, and components of phonological processing. The present work could broaden our understanding of music-language associations by showing that the development of melodic auditory-visual integration might be a particularly relevant predictor of the increases in phonological processing skills. At the same time, our findings point to the intertwined progress of these skills in the early stages of reading acquisition. The strong relation of tonal auditory-visual connection to phonological processing skills highlights the potential for common integration processes in musical and oral reading development, possibly mediated by early prosodic reading. Concerning that auditory-visual integration might build a basis of the connection between music and reading, it would be important to design more multimodal music education programs to unravel how the training of musical integration processes may support the development of fluent reading in schoolchildren.

## Acknowledgments

This study was supported by the Content Pedagogy Research Program of the Hungarian Academy of Sciences (SZ-009/2016) and the János Bolyai Research Fellowship awarded to F.H. We are grateful to all children and parents for their participation in this study, the primary school teachers for their support, and research assistants (Tamara Biró, Dorottya Denke, Márta Lőrincz-

Fazekas, Bernadett Ferencz, Borbála German, Sarolt Pintér, and Petra Prjevara) for their help with data collection. We would like to thank our colleagues at the MTA-LFZE Research Group on Active Music Learning, Emese Maróti, Edina Barabás, Borbála Szirányi, Gabriella Deszpot, Tamara Farnadi, and László Norbert Nemes, for their help with the development of the research.

**References**

Anvari, S. H., Trainor, L. J., Woodside, J., & Levy, B. A. (2002). Relations among musical skills, phonological processing, and early reading ability in preschool children. *Journal of Experimental Child Psychology*, *83*(2), 111–130. https://doi.org/10.1016/S0022-0965(02)00124-8

Asztalos, K., & Csapó, B. (2017). Development of musical abilities: Cross-sectional computer-based assessments in educational contexts. *Psychology of Music*, *45*(5), 682–698. https://doi.org/10.1177/0305735616678055

Bakdash, J. Z., & Marusich, L. (2017). Repeated Measures Correlation. *Frontiers in Psychology*, *8:456*. https://doi.org/10.2139/ssrn.2833824

Bakdash, J. Z., & Marusich, L. R. (2018). *rmcorr: Repeated Measures Correlation. R package version 0.3.0*. https://doi.org/10.3389/fpsyg.2017.00456

Bates, D., Mächler, M., Bolker, B. M., & Walker, S. C. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Behne, D., Alm, M., Berg, A., Engell, T., Foyn, C., Johnsen, C., Srigaran, T., & Torsdottir, A. E. (2013). Effects of musical experience on perception of audiovisual synchrony for speech and music. *Proceedings of Meetings on Acoustics*, *19*, 1–6. https://doi.org/10.1121/1.4801060

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society. Series B (Methodological)*, *57*(1), 289–300. https://doi.org/10.2307/2346101

Besson, M., Chobert, J., & Marie, C. (2011). Transfer of training between music and speech: Common processing, attention, and memory. *Frontiers in Psychology*, *2:94*. https://doi.org/10.3389/fpsyg.2011.00094

Bland, J. M., & Altman, D. G. (1994). Correlation, regression, and repeated data. *BMJ*, *308*, 896. https://doi.org/10.1136/bmj.308.6933.896

Bland, J. M., & Altman, D. G. (1995). Calculating correlation coefficients with repeated observations: Part 1 - correlation within subjects. *BMJ*, *310*, 446. https://doi.org/10.1136/bmj.310.6977.446

Blomert, L., & Vaessen, A. (2009). *Differentiaal Diagnostiek van Dyslexie: Cognitieve analyse van lezen en spellen [Dyslexia Differential Diagnosis: Cognitive analysis of reading and spelling]*. Boom Test.

Bolduc, J., & Lefebvre, P. (2012). Using Nursery Rhymes to Foster Phonological and Musical Processing Skills in Kindergarteners. *Scientific Research*, *3*(4), 495–502. https://doi.org/10.4236/ce.2012.34075

Bolduc, J., & Montésinos-Gelet, I. (2005). Pitch Processing and Phonological Awareness. *Psychomusicology: A Journal of Research in Music Cognition*, *19*(1), 3–14. https://doi.org/10.1037/h0094043

Bryant, P. E., Maclean, M., Bradley, L. L., & Crossland. (1990). Rhyme and Alliteration, Phoneme Detection, and Learning to Read. *Developmental Psychology*, *26*(3), 429–438. https://doi.org/10.1037/0012-1649.26.3.429

Clay, M. M., & Imlach, R. H. (1971). Juncture, pitch, and stress as reading behavior variables. *Journal of Verbal Learning and Verbal Behavior*, *10*(2), 133–139. https://doi.org/10.1016/S0022-5371(71)80004-X

Corrigall, K. A., & Trainor, L. J. (2009). Effects of musical training on key and harmony perception. *Annals of the New York Academy of Sciences*, *1169*, 164–168. https://doi.org/10.1111/j.1749-6632.2009.04769.x

Corriveau, K. H., & Goswami, U. (2009). Rhythmic motor entrainment in children with speech and language impairments: Tapping to the beat. *Cortex*, *45*(1), 119–130. https://doi.org/10.1016/j.cortex.2007.09.008

Corriveau, K. H., Goswami, U., & Thomson, J. M. (2010). Auditory processing and early literacy skills in a preschool and kindergarten population. *Journal of Learning Disabilities*, *43*(4), 369–382. https://doi.org/10.1177/0022219410369071

Cowie, R., Douglas-Cowie, E., & Wichmann, A. (2002). Prosodic characteristics of skilled reading: Fluency and expressiveness in 8-10-year-old readers. *Language and Speech*, *45*(1), 47–82. https://doi.org/10.1177/00238309020450010301

Csapó, B., & Molnár, G. (2019). Online diagnostic assessment in support of personalized teaching and learning: The eDia system. *Frontiers in Psychology*, *10:1522*. https://doi.org/10.3389/fpsyg.2019.01522

David, D., Wade-Woolley, L., Kirby, J. R., & Smithrim, K. (2007). Rhythm and reading development in school-age children: A longitudinal study. *Journal of Research in Reading*, *30*(2), 169–183. https://doi.org/10.1111/j.1467-9817.2006.00323.x

Degé, F., Kubicek, C., & Schwarzer, G. (2015). Associations between musical abilities and precursors of reading in preschool aged children. *Frontiers in Psychology*, *6:1220*. https://doi.org/10.3389/fpsyg.2015.01220

Degé, F., & Schwarzer, G. (2011). The effect of a music program on phonological awareness in preschoolers. *Frontiers in Psychology*, *2:124*. https://doi.org/10.1177/0022429405053000302

Forgeard, M., Schlaug, G., Norton, A., Rosam, C., Iyengar, U., & Winner, E. (2008). The Relation Between Music and Phonological Processing in Normal-Reading Children and Children With Dyslexia. *Music Perception: An Interdisciplinary Journal*, *25*(4), 383–390. https://doi.org/10.1525/mp.2008.25.4.383

Foxton, J. M., Talcott, J. B., Witton, C., Brace, H., McIntyre, F., & Griffiths, T. D. (2003). Reading skills are related to global, but not local, acoustic pattern perception. *Nature Neuroscience*, *6*(4), 343–344. https://doi.org/10.1038/nn1035

Froyen, D., Bonte, M., Van Atteveldt, N., & Blomert, L. (2009). The long road to automation: Neurocognitive development of letter-speech sound processing. *Journal of Cognitive Neuroscience*, *21*(3), 567–580. https://doi.org/10.1162/jocn.2009.21061

Gathercole, S. E., & Baddeley, A. D. (1993). *Working memory and language*. Erlbaum.

Gembris, H. (2006). The development of musical abilities. In R. Colwell (Ed.), *MENC handbook of musical cognition and development* (pp. 124–164). Oxford University Press.

Godde, E., Bosse, M. L., & Bailly, G. (2020). A review of reading prosody acquisition and development. *Reading and Writing*, *33*(2), 399–426. https://doi.org/10.1007/s11145-019-09968-1

Gooding, L., & Standley, J. M. (2011). Musical Development and Learning Characteristics of Students: A Compilation of Key Points From the Research Literature Organized by Age. *Update: Applications of Research in Music Education*, *30*(1), 32–45. https://doi.org/10.1177/8755123311418481

Gordon, R. L., Fehd, H. M., & McCandliss, B. D. (2015). Does music training enhance literacy skills? A meta-analysis. *Frontiers in Psychology*, *6:1777*. https://doi.org/10.3389/fpsyg.2015.01777

Gordon, R. L., Shivers, C. M., Wieland, E. A., Kotz, S. A., Yoder, P. J., & Devin Mcauley, J. (2015). Musical rhythm discrimination explains individual differences in grammar skills in children. *Developmental Science*, *18*(4), 635–644. https://doi.org/10.1111/desc.12230

Goswami, U. (2002). Phonology, Reading Development, and Dyslexia: A Cross-Linguistic Perspective. *Annals of Dyslexia*, *52*, 141–162. https://doi.org/10.1007/s11881-002-0010-0

Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in*

*Cognitive Sciences*, *15*(1), 3–10. https://doi.org/10.1016/j.tics.2010.10.001

Herrera, L., Lorenzo, O., Defior, S., Fernandez-Smith, G., & Costa-Giomi, E. (2011). Effects of phonological and musical training on the reading readiness of native- and foreign-Spanish-speaking children. *Psychology of Music*, *39*(1), 68–81. https://doi.org/10.1177/0305735610361995

Holliman, A. J., Wood, C., & Sheehy, K. (2010). The contribution of sensitivity to speech rhythm and non-speech rhythm to early reading development. *Educational Psychology*, *30*(3), 247–267. https://doi.org/10.1080/01443410903560922

JASP Team. (2018). *JASP (Version 0.9.2.0)*.

Kaviani, H., Mirbaha, H., Pournaseh, M., & Sagan, O. (2014). Can music lessons increase the performance of preschool children in IQ tests? *Cognitive Processing*, *15*(1), 77–84. https://doi.org/10.1007/s10339-013-0574-0

Kenney, S. H. (1997). Music in the developmentally appropriate integrated curriculum. In C. H. Hart, D. C. Burts, & R. Charlesworth (Eds.), *Integrated curriculum and developmentally appropriate practice: Birth to age eight* (pp. 103–144). State University of New York Press.

Kim, S. (2015). *ppcor: Partial and Semi-Partial (Part) Correlation. R package version 1.1*. 1–9. https://cran.r-project.org/web/packages/ppcor/index.html

Kraus, N., & Chandrasekaran, B. (2010). Music training for the development of auditory skills. *Nature Reviews. Neuroscience*, *11*(8), 599–605. https://doi.org/10.1038/nrn2882

Kuhn, M. R., Schwanenflugel, P. J., Meisinger, E. B., Levy, B. A., & Rasinski, T. V. (2010). Aligning Theory and Assessment of Reading Fluency: Automaticity, Prosody, and Definitions of Fluency. *Reading Research Quarterly*, *45*(2), 230–251. https://doi.org/10.1598/rrq.45.2.4

Lamb, S. J., & Gregory, A. H. (1993). The Relationship between Music and Reading in Beginning

Readers. *Educational Psychology*, *13*(1), 19–27. https://doi.org/10.1080/0144341930130103

Lee, H., & Noppeney, U. (2014). Music expertise shapes audiovisual temporal integration windows for speech, sinewave speech, and music. *Frontiers in Psychology, 5:868*. https://doi.org/10.3389/fpsyg.2014.00868

Lee, Y. S., Ahn, S., Holt, R. F., & Schellenberg, E. G. (2020). Rhythm and syntax processing in school-age children. *Developmental Psychology*, *56*(9), 1632–1641. https://doi.org/10.1037/dev0000969

Linnavalli, T., Putkinen, V., Lipsanen, J., Huotilainen, M., & Tervaniemi, M. (2018). Music playschool enhances children's linguistic skills. *Scientific Reports*, *8*(1), 1–10. https://doi.org/10.1038/s41598-018-27126-5

Lukács, B., Deszpot, G., Szirányi, B., Honbolygó, F., & Nemes, L. N. (2018). Új modellek az ének-zene tanításban: aktív zenetanulási módszerek és oktatás-idegtudományi hatásvizsgálatuk [New models in music education: Active Music Learning methods and the investigation of their training effects from educational neuroscience perspec. *Magyar Tudomány*, *179*(6), 831–836. https://doi.org/10.1556/2065.179.2018.6.9

Lukács, B., & Honbolygó, F. (2019). Task-Dependent Mechanisms in the Perception of Music and Speech: Domain-Specific Transfer Effects of Elementary School Music Education. *Journal of Research in Music Education*, *67*(2), 153–170. https://doi.org/10.1177/0022429419836422

Mann, V. A., & Liberman, I. Y. (1984). Phonological awareness and verbal short-term memory. *Journal of Learning Disabilities*, *17*(10), 592–599. https://doi.org/10.1177/002221948401701005

Maróti, E., Barabás, E., Deszpot, G., Farnadi, T., Nemes, L. N., Szirányi, B., & Honbolygó, F. (2019). Does moving to the music make you smarter? The relation of sensorimotor entrainment to cognitive, linguistic, musical, and social skills. *Psychology of Music*, *47*(5), 663–679. https://doi.org/10.1177/0305735618778765

Maróti, E., Honbolygó, F., & Weiss, B. (2019). Neural entrainment to the beat in multiple frequency bands in 6–7-year-old children. *International Journal of Psychophysiology*, *141*(2019), 45–55. https://doi.org/10.1016/j.ijpsycho.2019.05.005

Matute, E., Rosselli, M., Ardila, A., & Morales, G. (2004). Verbal and Nonverbal Fluency in Spanish-Speaking Children. *Developmental Neuropsychology*, *26*(2), 647–660. https://doi.org/10.1207/s15326942dn2602

McMullen, E., & Saffran, J. R. (2004). Music and Language: A Developmental Comparison. *Music Perception*, *21*(3), 289–311. https://doi.org/10.1525/mp.2004.21.3.289

Melby-Lervåg, M., Lyster, S. A. H., & Hulme, C. (2012). Phonological skills and their role in learning to read: A meta-analytic review. *Psychological Bulletin*, *138*(2), 322–352. https://doi.org/10.1037/a0026744

Mészáros, A., Kónya, A., & Kas, B. (2011). A verbális fluenciatesztek felvételének és értékelésének módszertana [Methods in the administration and evaluation of verbal fluency tests (Hungarian)]. *Alkalmazott Pszichológia*, *2*, 53–76. http://ap.elte.hu/wp-content/uploads/2012/09/APA_2011-2.pdf

Miller, J., & Schwanenflugel, P. J. (2008). A Longitudinal Study of the Development of Reading Prosody as a Dimension of Oral Reading Fluency in Early Elementary School Children. *Reading Research Quarterly*, *43*(4), 336–354. https://doi.org/10.1598/rrq.43.4.2

Miyamoto, K. A. (2007). Musical Characteristics of Preschool-Age Students: A Review of Literature. *Update: Applications of Research in Music Education*, *26*(1), 26–40. https://doi.org/10.1177/87551233070260010104

Moll, K., Ramus, F., Bartling, J., Bruder, J., Kunze, S., Neuhoff, N., Streiftau, S., Lyytinen, H., Leppänen, P. H. T., Lohvansuu, K., Tóth, D., Honbolygó, F., Csépe, V., Bogliotti, C., Iannuzzi, S., Démonet, J. F., Longeras, E., Valdois, S., George, F., … Landerl, K. (2014). Cognitive mechanisms underlying reading and spelling development in five European orthographies. *Learning and Instruction*, *29*, 65–77. https://doi.org/10.1016/j.learninstruc.2013.09.003

Moreno, S., & Bidelman, G. M. (2014). Examining neural plasticity and cognitive benefit through the unique lens of musical training. *Hearing Research*, *308*, 84–97. https://doi.org/10.1016/j.heares.2013.09.012

Moritz, C., Yampolsky, S., Papadelis, G., Thomson, J., & Wolf, M. (2013). Links between early rhythm skills, musical training, and phonological awareness. *Reading and Writing*, *26*(5), 739–769. https://doi.org/10.1017/CBO9781107415324.004

Nagyné Réz, I., Lányiné Engelmayer, Á., Kuncz, E., Mészáros, A., & Mlinkó, R. (2008). *Wechsler Intelligence Scale for Children – fourth edition. Magyar adaptáció [Hungarian adaptation]*. OS-Hungary Ltd.

Nichols, E. S., & Grahn, J. A. (2016). Neural correlates of audiovisual integration in music reading. *Neuropsychologia*, *91*, 199–210. https://doi.org/10.1016/j.neuropsychologia.2016.08.011

Ozernov-Palchik, O., Wolf, M., & Patel, A. D. (2018). Relationships between early literacy and nonlinguistic rhythmic processes in kindergarteners. *Journal of Experimental Child Psychology*, *167*, 354–368. https://doi.org/10.1016/j.jecp.2017.11.009

Paraskevopoulos, E., Kuchenbuch, A., Herholz, S. C., & Pantev, C. (2012). Musical expertise induces audiovisual integration of abstract congruency rules. *Journal of Neuroscience*, *32*(50), 18196–18203. https://doi.org/10.1523/JNEUROSCI.1947-12.2012

Patel, A. D. (2003). Language, music, syntax and the brain. *Nature Neuroscience*, *6*(7), 674–681. https://doi.org/10.1038/nn1082

Patel, A. D. (2008). *Music, language, and the brain*. University Press.

Patscheke, H., Degé, F., & Schwarzer, G. (2019). The effects of training in rhythm and pitch on phonological awareness in four- to six-year-old children. *Psychology of Music*, *47*(3), 376–391. https://doi.org/10.1177/0305735618756763

Peretz, I., & Coltheart, M. (2003). Modularity of music processing. *Nature Neuroscience*, *6*(7), 688–691. https://doi.org/10.1038/nn1083

R Core Team. (2019). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.r-project.org/

Schwanenflugel, P. J., Hamilton, A. M., Wisenbaker, J. M., Kuhn, M. R., & Stahl, S. A. (2004). Becoming a fluent reader: reading skill and prosodic features in the oral reading of young readers. *Journal of Educational Psychology*, *96*(1), 119–129. https://doi.org/10.1037/0022-0663.96.1.119.Becoming

Steinbrink, C., Knigge, J., Mannhaupt, G., Sallat, S., & Werkle, A. (2019). Are temporal and tonal musical skills related to phonological awareness and literacy skills? - Evidence from two cross-sectional studies with children from different age groups. *Frontiers in Psychology*, *10:805*. https://doi.org/10.3389/fpsyg.2019.00805

Swaminathan, S., & Schellenberg, E. G. (2020). Musical Ability, Music Training, and Language Ability in Childhood. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *46*(12), 2340–2348. https://doi.org/10.1037/xlm0000798

Swaminathan, S., Schellenberg, E. G., & Venkatesan, K. (2018). Explaining the Association Between Music Training and Reading in Adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *44*(6), 992–999. https://doi.org/10.1037/xlm0000493.supp

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1994). Longitudinal studies of phonological processing and reading. *Journal of Learning Disabilities*, *27*(5), 276–286. https://doi.org/10.1177/002221949402700503

Tóth, D., Csépe, V., Vaessen, A., & Blomert, L. (2014). *A diszlexia differenciáldiagnózisa. Az olvasás és helyesírás kognitív elemzése. Technikai kézikönyv. [3DM-H: Dyslexia Differential Diagnosis. Cognitive analysis of reading and spelling (Hungarian)]*. Kogentum.

Wagner, R. K., & Torgesen, J. K. (1987). The Nature of Phonological Processing and Its Causal Role in the Acquisition of Reading Skills. *Psychological Bulletin*, *101*(2), 192–212. https://doi.org/10.1037/0033-2909.101.2.192

Wechsler, D. (2003). *Wechsler Intelligence Scale for Children, fourth edition (WISC-IV)*. The Psychological Corporation.

Wimmer, H., Landerl, K., Linortner, R., & Hummer, P. (1991). The relationship of phonemic awareness to reading acquisition: More consequence than precondition but still important. *Cognition*, *40*(3), 219–249. https://doi.org/10.1016/0010-0277(91)90026-Z

Wolf, M., & Bowers, P. G. (1999). The double-deficit hypothesis for the developmental dyslexias. *Journal of Educational Psychology*, *91*(3), 415–438. https://doi.org/10.1037/0022-0663.91.3.415

Wolters, A. P., Kim, Y. S. G., & Szura, J. W. (2020). Is Reading Prosody Related to Reading Comprehension? A Meta-analysis. *Scientific Studies of Reading*. https://doi.org/10.1080/10888438.2020.1850733

Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: a psycholinguistic grain size theory. *Psychological Bulletin*, *131*(1), 3–29. https://doi.org/10.1037/0033-2909.131.1.3

Ziegler, J. C., Pech-Georgel, C., George, F., & Foxton, J. M. (2012). Global and local pitch perception in children with developmental dyslexia. *Brain and Language*, *120*(3), 265–270.

https://doi.org/10.1016/j.bandl.2011.12.002

# Longitudinal associations between melodic auditory-visual integration and reading precursor skills in beginning readers

## Supplementary Material

**Supplementary Table 1**

*Pretraining Spearman correlations between possible confounding variables, precursors of reading, and musical abilities*

| Measures | Age | Gender | SES | Musical background | Nonverbal IQ | Verbal IQ |
|---|---|---|---|---|---|---|
| PA Accuracy | -0.05 | -0.30* | 0.19 | -0.16 | 0.30* | -0.04 |
| PA Speed | 0.13 | -0.16 | 0.19 | -0.01 | 0.29* | 0.15 |
| RAN Digits | 0.29** | -0.15 | -0.14 | 0.05 | 0.21 | 0.17 |
| RAN Pictures | 0.15 | -0.07 | -0.24* | 0.04 | 0.13 | 0.10 |
| Phonemic Fluency | 0.11 | -0.03 | -0.10 | 0.04 | 0.20 | **0.45*** ** |
| Verbal STM | 0.17 | -0.04 | 0.00 | -0.14 | 0.28** | 0.12 |
| Melody Discrimination | 0.16 | -0.03 | -0.08 | -0.01 | 0.23* | 0.02 |
| Pitch Discrimination | 0.02 | 0.04 | -0.01 | 0.00 | 0.03 | 0.03 |
| Rhythm Discrimination | 0.24* | 0.16 | -0.04 | 0.13 | 0.13 | 0.08 |
| Harmony Discrimination | -0.18 | 0.09 | 0.24* | 0.08 | 0.06 | -0.14 |
| Tempo Discrimination | 0.08 | -0.01 | 0.05 | -0.13 | 0.18 | -0.22* |
| Melody Connection | 0.20 | -0.07 | 0.17 | -0.04 | 0.20 | 0.07 |
| Rhythm Connection | 0.01 | 0.15 | -0.02 | -0.11 | 0.16 | -0.03 |

*Note*. SES = socioeconomic status (parents' highest education); PA = phonemic awareness (3DM-H Phoneme Deletion); RAN = rapid automatized naming (3DM-H subtests); STM = short-term memory (WISC-IV Digit Span). Correlations that remained significant after the Benjamini-Hochberg correction are written in bold.

*$p$ < .05, **$p$ < .01, ***$p$ < .001.

**Supplementary Table 2**

*Posttraining Spearman correlations between possible confounding variables, precursors of reading, and musical abilities*

| Measures | Age | Gender | SES | Musical background | Nonverbal IQ | Verbal IQ |
|---|---|---|---|---|---|---|
| PA Accuracy | 0.28* | -0.12 | -0.12 | 0.16 | 0.15 | 0.25 |
| PA Speed | 0.31* | -0.13 | -0.02 | 0.12 | 0.14 | 0.23 |
| RAN Digits | 0.17 | -0.13 | -0.19 | 0.02 | 0.10 | 0.27* |
| RAN Pictures | 0.06 | 0.06 | -0.21 | -0.05 | 0.17 | 0.29** |
| Phonemic Fluency | 0.05 | 0.06 | -0.25* | 0.09 | 0.16 | **0.45*** ** |
| Verbal STM | 0.15 | -0.02 | -0.10 | -0.09 | 0.22* | 0.21 |
| Melody Discrimination | 0.09 | -0.11 | 0.14 | 0.00 | 0.23* | 0.02 |
| Pitch Discrimination | 0.00 | -0.02 | 0.06 | 0.00 | 0.15 | -0.05 |
| Rhythm Discrimination | -0.10 | 0.15 | 0.14 | -0.13 | 0.23* | -0.10 |
| Harmony Discrimination | -0.09 | -0.17 | 0.12 | **-0.28*** | **0.28*** | 0.02 |
| Tempo Discrimination | -0.02 | -0.07 | 0.04 | -0.08 | 0.21 | -0.10 |
| Melody Connection | 0.24* | 0.01 | 0.07 | -0.10 | **0.39*** ** | 0.03 |
| Rhythm Connection | -0.05 | -0.08 | 0.07 | -0.20 | **0.37*** ** | -0.01 |

*Note*. SES = socioeconomic status (parents' highest education); PA = phonemic awareness (3DM-H Phoneme Deletion); RAN = rapid automatized naming (3DM-H subtests); STM = short-term memory (WISC-IV Digit Span). Correlations that remained significant after the Benjamini-Hochberg correction are written in bold.

*$p$ < .05, **$p$ < .01, ***$p$ < .001.

**Supplementary Table 3**

*Pretraining partial Spearman correlations between the precursors of reading and musical abilities after controlling for IQ measures*

| | Musical abilities | | | | | | |
|---|---|---|---|---|---|---|---|
| | Discrimination | | | | | Auditory-Visual Connection | |
| Measures | Melody | Pitch | Rhythm | Harmony | Tempo | Melody | Rhythm |
| PA Accuracy | 0.03 | -0.20 | -0.24 | -0.07 | -0.21 | -0.11 | 0.03 |
| PA Speed | 0.01 | -0.05 | 0.03 | -0.08 | -0.08 | 0.11 | 0.00 |
| RAN Digits | 0.16 | 0.11 | 0.19 | -0.04 | 0.17 | 0.06 | 0.30** |
| RAN Pictures | -0.03 | -0.04 | 0.06 | -0.11 | 0.09 | -0.03 | 0.19 |
| Phonemic Fluency | 0.06 | 0.11 | -0.02 | -0.04 | 0.04 | -0.05 | 0.11 |
| Verbal STM | 0.15 | 0.00 | 0.16 | -0.06 | 0.03 | 0.04 | 0.28** |

*Note*. PA = phonemic awareness (3DM-H Phoneme Deletion); RAN = rapid automatized naming (3DM-H subtests); STM = short-term memory (WISC-IV Digit Span). None of the partial correlations marked with asterisks remained significant after the correction for multiple comparisons.

*$p$ < .05, **$p$ < .01, ***$p$ < .001.

**Supplementary Table 4**

*Posttraining partial Spearman correlations between the precursors of reading and musical abilities after controlling for IQ measures*

| | Musical abilities | | | | | | |
|---|---|---|---|---|---|---|---|
| | Discrimination | | | | | Auditory-Visual Connection | |
| Measures | Melody | Pitch | Rhythm | Harmony | Tempo | Melody | Rhythm |
| PA Accuracy | 0.17 | -0.09 | 0.14 | -0.02 | -0.07 | 0.13 | 0.31* |
| PA Speed | 0.11 | -0.14 | 0.13 | -0.05 | -0.25 | 0.08 | 0.16 |
| RAN Digits | 0.05 | -0.14 | 0.02 | 0.03 | 0.09 | 0.12 | 0.01 |
| RAN Pictures | 0.09 | -0.13 | 0.08 | 0.02 | 0.04 | 0.01 | 0.06 |
| Phonemic Fluency | -0.06 | 0.03 | 0.09 | 0.00 | 0.06 | -0.07 | 0.02 |
| Verbal STM | -0.04 | 0.03 | 0.20 | -0.07 | 0.12 | 0.09 | 0.02 |

*Note*. PA = phonemic awareness (3DM-H Phoneme Deletion); RAN = rapid automatized naming (3DM-H subtests); STM = short-term memory (WISC-IV Digit Span). None of the partial correlations marked with asterisks remained significant after the correction for multiple comparisons.

*$p < .05$, **$p < .01$, ***$p < .001$.