

# Journal of Learning Disabilities

## **Sequence Processing in Music predicts Reading Skills in Young Brazilian Readers: A Longitudinal Study**

Journal:	<i>Journal of Learning Disabilities</i>
Manuscript ID	JLD-08-22-129.R3
Manuscript Type:	Article
Keywords:	reading < disability, language, assessment < reading

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Manuscripts

## Abstract

Musical abilities, both in the pitch and temporal dimension, have been shown to be positively associated with phonological awareness and reading abilities in both children and adults. There is increasing evidence that the relationship between music and language relies primarily on the temporal dimension, including both meter and rhythm. It remains unclear to what extent skill level in these temporal aspects of music may uniquely contribute to the prediction of reading outcomes. A longitudinal design was used to test a group-administered musical sequence transcription task (MSTT). This task was designed to preferentially engage sequence processing skills while controlling for fine-grained pitch discrimination and rhythm in terms of temporal grouping. Forty-five children, native speakers of Portuguese ( $M_{age} = 7.4$  years), completed the MSTT and a cognitive-linguistic protocol that included visual and auditory working memory tasks, as well as phonological awareness and reading tasks in second grade. Participants then completed reading assessments in third and fifth grade. Longitudinal regression models showed that MSTT and phonological awareness had comparable power to predict reading. MSTT showed an overall classification accuracy for identifying low-achievement readers in grades 2, 3 and 5 that was analogous to a comprehensive model including core predictors of reading disability. In addition, MSTT was the variable with the highest loading and the most discriminatory indicator of a phonological factor. These findings carry implications for the role of temporal sequence processing in contributing to the relationship between music and language and the potential use of MSTT as a language-independent, time- and cost-effective tool for the early identification of children at-risk for reading disability.

*Key words:* music, reading, reading disability, screening

## Sequence Processing in Music Predicts Reading Skills in Young Readers: A Longitudinal Study

Across most cultures, learning to read is essential for long-term educational, vocational, and economic potential (Riddick et al., 1999; Irwin et al., 2007). Children who experience difficulty learning to read are susceptible to feelings of frustration, low self-esteem, and helplessness. Individuals with learning disabilities are more likely to develop internalizing or externalizing behaviors and are more likely to receive a diagnosis of depression or anxiety (Lawrence, 2006; Riddick, 2009). Yet, an alarming rate of adolescents and adults worldwide have not acquired proficient reading skills according to the UNESCO report (Huebler, & Lu, 2013). Literacy levels are especially low in developing countries where schools have limited resources and/or when families come from a background of low socioeconomic status (SES; Ball et al., 2014). Brazil has one of the lowest levels of reading internationally (OECD, 2015). Approximately 54.73% of students are below grade level in reading proficiency by third grade, according to the National Literacy Assessment (INEP, 2018). Critical factors for low literacy attainment in Brazil include reduced access to literacy at home and very limited resources at schools (Enricone & Salles, 2011). Furthermore, standardized assessments for assessing the various components of reading, as well as screening protocols for early precursors of reading disability, are rare. Therefore, receiving a formal diagnosis of a reading disability or intervention/remediation for reading difficulties is improbable in Brazil (Andrade et al., 2015; Navas, 2013).

Longitudinal studies have shown that children classified as poor readers at the end of first grade rarely reach grade-level reading ability by the end of elementary school without intensive intervention (Francis et al., 1996; Juel, 1988; Torgesen & Burgess, 1998). This can lead to a downward cascading spiral, in which persistent difficulty with reading results in reduced reading exposure and engagement among poor readers, thereby hindering vocabulary growth in missing the opportunity to learn new words and content from text (Stanovich et al., 1986). By contrast, research has shown that when children are identified as at-risk for reading disability at the start of formal reading instruction and provided timely, targeted

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3 intervention, the majority of these children achieve grade-level reading-related skills by the beginning of  
4 first grade (Catts et al., 2015; Wanzek, & Vaughn, 2007; Wanzek et al., 2013).  
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7 Emerging research has demonstrated substantial progress in the ability to screen children at risk for  
8 subsequently developing reading disabilities as early as preschool (e.g., Catts, 2017). Early screening at the  
9 onset of formal reading instruction can help determine which children are at-risk to subsequently struggle  
10 and can further inform instruction and early intervention, which significantly improves outcomes (e.g.,  
11 Catts et al., 2001; Gaab & Petscher, 2022). It is important to note that screening for dyslexia differs from a  
12 diagnostic evaluation intended to formally identify or diagnose a child with developmental dyslexia. Risk  
13 factors assessed in a screening instrument do not determine whether a child will subsequently develop  
14 dyslexia. Rather, they assess the *probability* that a child will develop dyslexia (Catts & Petscher, 2022).  
15 Unfortunately, studies to date have primarily focused their efforts within high-resource countries, resulting  
16 in proposed screening methods that do not necessarily effectively apply to children in countries with fewer  
17 or very limited resources.  
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### 31 **The Need for Global Screening Tools for the Identification of Children At-Risk for Learning** 32 **Disabilities** 33 34 35

36 A global screening tool with the potential to reach communities with limited resources needs to  
37 fulfill a number of important criteria: cultural-appropriateness, easy access, promotion of equity in the  
38 screening process, and developmentally appropriate. Furthermore, it needs to be easy to administer in  
39 settings with limited resources, require minimal training, and exhibit high levels of both specificity and  
40 sensitivity to minimize the rate of false negatives (at-risk children who were not identified) and false  
41 positives (children inaccurately identified as at-risk, e.g., Catts, 2017; Petscher et al., 2019). Other essential  
42 criteria include appropriate reliability, validity, sample representativeness, and classification accuracy  
43 (Gaab & Petscher, 2022). However, fulfilling these criteria has proven to be difficult. Longitudinal,  
44 multifactorial screening designs assessing key pre-literacy skills starting in preschool and utilizing  
45 computer-adaptive testing to shorten administration time and increase engagement and effort are considered  
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3 an optimal solution (Catts & Petscher, 2018; McBride et al., 2010). However, this poses several issues for  
4 schools and/or families in low-resource countries that may not have access to the monetary and personnel  
5 resources (including ‘data-literacy’) necessary for implementing, updating, and interpreting this form of  
6 assessment (Mitchell et al., 2015). While effective advances in screening tools rapidly progress in high-  
7 resource countries, the requirement for one-on-one administration and length of administration (associated  
8 with high costs), as well as language-specific content, pose persistent problems for universal screening  
9 batteries (Compton et al., 2010; Adlof et al., 2017). This makes large-scale screening in educational settings  
10 difficult. An effective global screener calls for minimal training necessary for implementation and  
11 interpretation and should allow for administration in classroom settings across different languages and  
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### 24 **The Relationship Between Auditory Processing Skills, Speech Sound Perception, and Phonological** 25 **Awareness and its Importance for Reading Development** 26 27

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29 One key pre-literacy skill that has repeatedly been shown to be a reliable predictor of subsequent  
30 reading outcomes is phonological/phonemic awareness. This term describes the ability to manipulate  
31 speech sounds comprising words at the level of syllables, onset-rhymes and phonemes (e.g., Georgiou et  
32 al., 2008; Scarborough, 1998; Schatschneider et al., 2004, Ziegler & Goswami, 2005). The foundational  
33 skills that give rise to phonological awareness have yet to be fully understood, but it has been hypothesized  
34 that broad auditory processing deficits could play a causal role in developing poor phonological processing  
35 skills. Weaknesses in basic auditory processing have been reported in individuals with dyslexia, including  
36 discrimination of pitch and frequency modulation in quiet and in noise (Ahissar et al., 2000; Amitay et al.,  
37 2002; Lorusso et al., 2014; Wright & Conlon, 2009; Ziegler et al., 2009) and in slow (Goswami et al., 2002)  
38 as well as fast temporal transitions (e.g., Tallal & Piercy, 1973). However, numerous other studies failed to  
39 replicate these findings (for a review, see Goswami, 2015a and Hämäläinen et al., 2013). Furthermore,  
40 differences in the discrimination of speech sounds and/or categorical perception of speech sounds have  
41 been reported, but it is unclear whether this may play a causal role in the development of  
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3 phonological/phonemic processing deficits (Hämäläinen et al., 2013). However, when focusing on the first  
4 few years of development, the ability to perceive differences between speech sounds at seven months of  
5 age has been positively associated with subsequent phonological awareness in preschool (Cardillo, 2010).  
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7 Additionally, event-related potential (ERP) studies have demonstrated that neural responses to speech in  
8 newborns are associated with their later reading outcomes (Molfese, 2000; Molfese et al., 2002). To date,  
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10 it remains unclear whether basic auditory processing may serve as a reliable early indicator of risk for  
11 subsequent reading difficulty.  
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### 17 18 **The Relationships Between Music, Speech, and Language Skills** 19

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21 Interestingly, music encompasses acoustic properties that overlap with those inherent in speech,  
22 which suggests that music is one domain involving basic auditory discrimination skills that has in-turn been  
23 linked with phonological awareness, albeit inconsistently (Patel, 2012, 2014). Specifically, music and  
24 speech inherently share overlapping spectral (frequency/pitch) and temporal (timing/rhythm) properties,  
25 which suggest that the basic auditory processing necessary for music perception may also be associated  
26 with speech perception abilities (Chandrasekaran & Kraus, 2010; Chobert et al., 2012; Parbery-Clark et al.,  
27 2009; Patel, 2012). Moreover, music and language can arguably share some cognitive mechanisms that go  
28 beyond basic auditory processing. Both domains are based on patterned sound sequences hierarchically  
29 structured generating inherent structural relations (Koelsch, 2011; Patel, 2012) whose analysis may depend  
30 at first on the domain-general, mid-level cognitive mechanism of auditory sequence processing (e.g.,  
31 Fedorenko et al., 2009; Janata & Grafton, 2003; Osterhout et al., 2012; Shain et al., 2020).  
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44 Advanced musical skills, acquired through engagement in musical training, have been associated  
45 with advantages in perceiving pitch inflections within spoken language (Schön et al., 2004; Micheyl et al.,  
46 2006; Spiegel & Watson, 1984; Koelsch et al., 1999). In the temporal domain, perception of differences in  
47 rhythm/meter and sequencing in music and/or musical experience have been positively associated with  
48 speech-specific syllable discrimination and detection of segmental structure (François et al., 2013; Magne  
49 et al., 2016; Marie et al., 2011; Moreno et al., 2009; Zuk et al., 2013b). These associations between music  
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3 and speech may carry significance for phonological awareness since the ability to manipulate individual  
4 speech sounds within words draws upon spectral and temporal acoustic, such as distinguishing between  
5 certain phonemes and word boundaries through syllable duration patterns (Greenberg, 2005; Cutler, 2012;  
6 Ozernov-Palchik et al., 2018).  
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11 Musicality, defined as the potential for music perception and production independent of formal  
12 training (Gingras et al., 2015) has been positively associated with phonological awareness in preschool  
13 children (Anvari et al., 2002; Degé et al., 2020; Dege & Schwarzer, 2011; Douglas & Willatts, 1994;  
14 Forgeard et al., 2008; Lamb & Gregory, 1993; Moritz et al., 2013; Overy et al., 2003; Peynircioglu et al.,  
15 2002). Moreover, studies have shown that musicality differs between typical readers and individuals with  
16 reading deficits in adults (Thomson et al., 2006) and children (Bhide et al., 2013; Corriveau & Goswami,  
17 2009; Huss et al., 2011; Overy, 2000; Overy et al., 2003; Foregard et al., 2008). Furthermore, musical  
18 training, as well as music-based interventions from the preschool age onwards have been linked with  
19 improvements in phonological skills (e.g., Bolduc, 2009; Degé & Schwarzer, 2011; Moritz et al., 2013;  
20 Patscheke et al., 2019), as well as attention and working memory (Barbaroux et al., 2019), and long-term  
21 memory effects for learning novel words (Dittinger et al., 2021). These findings bring forth consideration  
22 of the extent to which putative relationships between musicality and phonological awareness may carry  
23 implications for reading development and what aspects of musicality could be underlying this relationship.  
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39 Few studies to date have investigated the relationship between auditory processing/music skills and  
40 early literacy skills in low-resource countries. One previous study identified positive links between a short,  
41 music-based assessment and emerging literacy skills among second-grade children in Brazil (Zuk et al.,  
42 2013a). Zuk and colleagues (2013a) targeted the overlap between linguistic and musical sequence  
43 processing through the design of a custom musical sequence transcription task (MSTT). This MSTT  
44 consists of isochronous 4-chord sequences, which include combinations of only two different 2-note chords,  
45 one in the low register and the other in the high register of the same A chord on the guitar. The low 2-note  
46 chord and the high two 2-note chord are separated by large intervals of one or more octaves. Children are  
47 asked to recall the sequence by writing it down on an answer sheet using two symbols (one for each chord;  
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3 see task and procedure details in the Method section). This task was designed to preferentially engage  
4 perceptual and cognitive mechanisms important for ‘auditory pattern sequencing,’ one of several  
5 mechanisms that may be shared between music and language (e.g., Grube et al., 2012; Fedorenko et al.,  
6 2009; Koelsch, 2011; Osterhout et al., 2012; Shain et al., 2020).

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11 Additionally, converging evidence supports the hypothesis that both deficits associated with  
12 dyslexia may be partially explained by difficulties in sequence processing, which may stem from more  
13 basic temporal processing deficits (Archer et al., 2020; Goswami, 2015b, 2018; Stein, 2018, 2019;  
14 Vidyasagar, 2019). Interestingly, Grube et al. (2012) reported that sound-sequence analysis appears more  
15 relevant to the relation between auditory processing and phonological skills than the analysis of single  
16 sounds. Discrimination between short sequences, e.g., indicating whether two four-tone sequences were  
17 “the same or different” in terms of pitch detection (global or local pitch changes) or temporal changes  
18 (deviation from isochronicity), but not between tone pairs, were significantly correlated to phonological  
19 skills (Grube et al., 2012). Moreover, MSTT allows for a fast, ecologically valid way to assess this temporal  
20 auditory processing skill in a classroom setting that is not contingent on a specific language, which has the  
21 potential to facilitate comparative studies and global use. However, it remains unclear whether MSTT  
22 performance is prospectively associated with subsequent reading skills. Using a cross-sectional design, Zuk  
23 et al. (2013a) reported significant positive associations between the MSTT and several linguistic tasks  
24 (reading speed, accuracy, completion, and word spelling) in primary school children. Another positive  
25 aspect of the MSTT is that it is culture/language independent and can be administered regardless of  
26 language background and literacy skills. Moreover, as a musical activity, MSTT is inherently engaging and  
27 motivating to children (Goswami, 2012; Hallam, 2010).

### 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 **The Current Study**

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50 The Zuk et al. (2013a) study identified an expedient, classroom-based, and ecologically feasible  
51 music-based assessment appropriate for implementation in developing countries and linked with key pre-  
52 literacy skills. However, it remains unclear to what extent the MSTT may predict long-term literacy  
53 skills.



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3 outcomes. To address this gap in our understanding, the present study builds on these previous findings by  
4 carrying out a longitudinal follow-up of these participants to examine how the MSTT predicts longitudinal  
5 reading outcomes. The present study aims to expand on the findings from Zuk and colleagues (2013a) by  
6 determining whether the MSTT is prospectively associated with subsequent reading outcomes over a three-  
7 year period. Specifically, we hypothesize that MSTT, assessed in the second grade, will significantly predict  
8 subsequent word reading in fifth grade. This work offers the first attempt to assess the potential for MSTT  
9 to serve as an early indication of risk for reading disability. If so, it may serve as a quick, classroom-based,  
10 ecologically feasible task that could assist with identifying children at-risk for reading difficulties in  
11 conjunction with traditional early screening tools. This would be especially effective in settings where  
12 standardized tests are not available in the language of instruction or where resources for the development  
13 and purchase of standardized assessments are lacking.  
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26 Finally, an exploratory factor analysis with the behavioral measures as assessed in grade 2 and the  
27 MSTT was performed to examine the underlying mechanism and related construct of the MSTT. MSTT  
28 requires a motor component during the output/production phase and involves executive functioning skills  
29 including inhibition and working memory. Examining the cognitive underpinnings of the MSTT can guide  
30 the development of future screening instruments and can give insights into the development of atypical  
31 reading skills in Brazilian Portuguese.  
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## 40 Method

### 41 Participants

42 The current study is a longitudinal follow-up of Zuk et al. (2013a). Forty-five children (29 males;  
43 16 females; 4 with left handedness) initially participated from 'Colégio Criativo,' Marília, an elementary  
44 school in São Paulo, Brazil. Legal guardians provided informed written consent prior to second-grade  
45 testing. All testing occurred on school premises during school hours with permission from the school  
46 administration, principal, and teachers. Students initially enrolled in the study were in the second grade of  
47 primary school, as per grade distinctions in the Brazilian education system. The study protocol was  
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3 approved by the “Ethics Committee from the Faculty of Science and Philosophy of São Paulo State  
4 University “Júlio de Mesquita Filho” – Faculdade de Filosofia e Ciências/Universidade Estadual Paulista,  
5 Marília, São Paulo, Brazil.  
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9 Age was calculated at the onset of testing, at which time children ranged in age from six to eight  
10 years ( $M_{age}$ : 7 years and 4 months,  $SD$ : 4 months). Forty out of 45 children were right-handed (based on  
11 reports from parents, classroom teachers, and physical education teachers). All participants had normal  
12 hearing. This was assessed via school screening and parent interviews. Furthermore, no speech deficits  
13 were reported, which was assessed by a pedagogical coordinator who carefully monitored the speech and  
14 language development of all children starting in preschool. Also, these children had no formal musical  
15 training outside of general primary school curricula. Starting in second grade, this group of children  
16 participated in group music classes, which involved singing, listening to music, and music perception  
17 games, but did not involve learning to read music or learning a musical instrument. Pedagogical approaches  
18 to teaching music adopted by the music teacher were based on group lessons, including attentive listening  
19 to different dimensions of musical materials (e.g., melody, harmony, rhythm, and emotions) through several  
20 activities (such as drawing and painting the images brought by instrumental music) and musical games  
21 involving singing, reproduction, comparison and predictions of musical elements as well as further  
22 discussion of these musical dimensions. Therefore, the music lessons reflected the view that a central aim  
23 of the music curriculum should involve the construction of musical meaning and mental representations of  
24 fundamental organizing structures of music through attentive listening and singing, which should be a basis  
25 for subsequent music learning in more formal settings (Bamberger, 2006; Barret, 2007; Gordon, 2011;  
26 Wiggins, 2007) and even precede it (Gordon, 2011). It is worthy of note that it is very unlikely that the  
27 music lessons played a relevant role in the children’s MSTT performance since all tests, including MSTT,  
28 were administered during the four first weeks after the start of the second-grade school year (see procedure  
29 section).  
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53 All participants were native speakers of Brazilian Portuguese, the language in which all testing  
54 occurred. Furthermore, all students came from upper-middle class families, and most had at least one parent  
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3 who was a working professional. Forty-one of the 45 original children (25 males; 16 females) assessed in  
4 the second grade were reassessed in the third (mean age: 8 years and 11 months, *SD*: 4 months) and fifth  
5 grade as well (mean age: 10 years and 11 months, *SD*: 4 months).  
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## 9 **Behavioral Measures**

### 10 *Cognitive and Linguistic Measures*

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15 Cognitive and linguistic abilities (including reading) were assessed by administering tasks from the  
16 Cognitive-Linguistic Protocol (CLP, Capellini & Smythe, 2008), which are described briefly here (for a  
17 detailed description of all measures, see Zuk et al., 2013a). The CLP was designed in Brazilian Portuguese.  
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19 The alphabet task was a test of letter knowledge in which participants were required to write the 26 letters  
20 of the alphabet from memory. Reading abilities were measured by assessing reading rate (number of  
21 correctly pronounced words per minute), reading word accuracy, and pseudoword reading accuracy tasks.  
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23 The phonological awareness tasks consisted of alliteration detection, rhyme detection, and syllable  
24 segmentation. In the alliteration and rhyme detection tasks, participants had to correctly identify, from three  
25 words spoken by the examiner, the two words with the same initial sound and the two words with the same  
26 final sound, respectively. The syllable segmentation task consisted of students repeating words spoken by  
27 the examiner while tapping each syllable. Participants also completed two tasks measuring the time (in  
28 seconds) to rapid naming of objects and digits, and three tasks measuring verbal working memory,  
29 namely, word sequence, nonword repetition, and verbal backward digit span. Additionally, participants  
30 engaged in a word discrimination task (i.e., identifying whether two words spoken by the examiner were  
31 the same or different), and also completed a rhythm production task. In this task, they had to reproduce  
32 rhythmic items demonstrated by the examiner by tapping out the rhythm on their desk. Participants also  
33 engaged in visual short-term memory tasks.  
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### 50 *Musical Sequence Transcription Task*

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53 In second grade, participants completed the Musical Sequence Transcription Task (MSTT). The  
54 task was designed to preferentially engage perceptual and cognitive mechanisms important for 'auditory  
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3 pattern sequencing,' including auditory working memory. However, MSTT also contains a sound-to-  
4 symbol mapping component and requires both a motor output during the output/production phase and may  
5 engage attention and executive functions, particularly inhibition (since children have to wait for four beats  
6 until the examiner allows them to start recalling the sequence). The musical task involved a sequence of  
7 four two-note chords played isochronally on the guitar in a predetermined arrangement. All four-chord  
8 sequences consisted of only two different 2-note chords, one in the low register and the other one in the  
9 high register of the same A chord on the guitar (see Figure 1A). In each sequence, the 2-note chords were  
10 combined in order to originate a four-element sequence. As can be seen in the piano of Figure 1B, the two  
11 notes of the low 2-note chord, i.e., A (110 Hz) and E (165 Hz), form a perfect fifth interval (7 semitones),  
12 and the two notes of the high 2-note chord, i.e., E (330 Hz) and A (440 Hz) form a perfect fourth interval  
13 (5 semitones). Both 2-note chords included the same pitches, A and E, but spanned one octave between the  
14 low E of the "thick sound" and the high E of the "thin sound" and two octaves between the low A of the  
15 "thick sound" and the high A of the "thin sound." Children were then taught to code the two chords with  
16 two respective symbols. The thin sound (higher pitched fourth) was marked with a vertical line 'l' and the  
17 thick sound (lower pitched fifth) was marked with a circle 'O' (See Figure 2 and description below).

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The design of the MSTT deliberately does not require the perception of fine pitch variations. This ensured that low performance on MSTT could not be explained by a possible low-level deficit in perception of fine-grained pitch. Moreover, because the sequences consisted of the same 2-note intervals in two different registers and were presented isochronally, the MSTT was designed to be devoid of both harmonic variation (e.g., musical syntax) and rhythm (in terms of temporal grouping). ----INSERT FIGURE 1 HERE

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8           The MSTT was administered collectively to the 45 children at the first time point (in second grade).  
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10       Children were introduced to the MSTT as the “Smart Ear Game”. All students were given the same amount  
11 of instruction time, training trials (sequences), and exposure to the two chords. Initially, in a learning phase,  
12 children were presented with either the low or the high 2-note chords and were asked which of the two  
13 symbols, a vertical line “I” or a circle “O”, best represented these chords. Most of them agreed that the  
14 vertical line was a better fit to represent the “thin sound” (high 2-note chord) and the circle to represent the  
15 “thick sound” (low 2-note chord). In both training and task phases, the sequences of the MSTT were  
16 presented to participants in a slow, isochronous manner, consistent in tempo throughout the entire task  
17 (approximately 88 beats per minute). After a short pause equal to the length of the sequence, students  
18 received a signal from the examiner allowing them to take the pencil and start recalling the chords in the  
19 order that they were presented using the symbols for the “thin” and “thick” sounds/chords. Although all  
20 experimental trials comprised of four-element sequences, training also included simple five-element  
21 sequences. However, children were never explicitly informed about the number of chords in each sequence  
22 throughout the experiment and the inclusion of five-element sequences in the training trials was intended  
23 to prevent the a-priori conclusion that all sequences would consist of just four elements. Students were not  
24 permitted to write anything before they received a signal from the administrator. The entire task comprised  
25 20 trials consisting of nine unique sequences, each presented twice with an additional two repetitions of the  
26 first sequence presented at equally spaced intervals across the series of trials. A correct recall of all four  
27 chords in the right order of the individual sequence was considered a correct response, leading to a  
28 maximum score of 20 on the task. If students recalled more or less than four chords, the trial was scored as  
29 incorrect. The duration of each sequence is 11 seconds including the four preparation beats, the four 2-note  
30 chords, and the last four beats. The overall duration of the collective administration of the task, including  
31 instruction and training examples, was around 35 min.  
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## Procedure

During the first four weeks of the second-grade school year, participants were assessed on the MSTT and all behavioral subtests of the Cognitive-Linguistic Protocol by Capellini and Smythe (C&S). The MSTT was administered to all participants concurrently in the music classroom, followed by individual and group administration of the linguistic and cognitive tests over six weeks. The following assessments were administered individually: reading speed, reading accuracy, reading completion, reading pseudowords, alliteration, rhyme, syllable segmentation, auditory word discrimination, rhythm production, word sequence, nonword repetition, verbal number sequence backwards, rapid object naming, rapid number naming, figure order, and figure rotation error. In contrast, the following subtests were administered in the classroom: the alphabet task, writing words and writing pseudowords. Since all assessments took place during school hours, whole-classroom administration was implemented for time efficiency on assessments that did not require one-on-one administration. Testing began at the beginning of the academic calendar year and concluded within six weeks.

Due to time constraints, only a subset of measures was administered in third grade, which included reading rate/fluency, reading accuracy, reading pseudowords, phonological processing tasks, the rhythm production task, verbal working memory tasks, and rapid automatized naming (RAN) tasks. In fifth grade, all tasks from the third-grade assessment battery were re-administered, as well as the following measures: the alphabet task, the writing tasks (spelling of words and pseudowords), the visual short-term memory tasks, and the shapes copying task. The time elapsed between the initial MSTT testing at the second grade and third and fifth-grade tests was one and three years, respectively. Even though interventions were recommended and available to all struggling readers from 2<sup>nd</sup> to 5<sup>th</sup> grade, some children did not receive interventions because parents opted-out (see info in Andrade et al., 2015).

## Data Pre-processing

An initial inspection indicated that scores from the tasks assessing three aspects of reading ability (word accuracy, pseudoword reading accuracy, and reading rate) were significantly correlated (Pearson's

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3 *r*-values from .4 to .56, all *p*-values < .001), suggesting the aggregation of scores by factor analysis. All  
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5 three tasks showed high loadings (range of loadings: .63 - .88; range communalities: .39 - .78) on the single  
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7 factor of the minimum residual factor analysis model<sup>1</sup>. The factor model explained 52% of the variance of  
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9 the raw scores and the multiple *R*<sup>2</sup> between estimated factor scores and factors was .83. Subsequently,  
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11 students' scores were extracted by regression from the latent factor and termed *reading ability*, which was  
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13 thereby used as the dependent variable in subsequent analyses. Note that combining scores of reading  
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15 accuracy (words and/or pseudowords) and reading rate to obtain a composite score is commonly employed  
16  
17 in related literature (Babayigit & Stainthorp, 2011; Catts et al., 2002, 2015; Compton et al., 2010; Torgesen  
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19 et al., 2001; Vellutino et al., 2008; Wagner et al., 1994).

22 Similarly, scores from the three tasks measuring aspects of phonological awareness (alliteration,  
23  
24 rhyme, and syllable segmentation) showed significant correlations (Pearson's *r*-values from .35 to .6, all *p*-  
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26 values < .001) and were subjected to a minimum residual factor analysis which explained 49% of the  
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28 variance in the raw scores and the multiple *R*<sup>2</sup> between estimated factor scores and factors was .8. All three  
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30 tasks loaded highly (range loadings: .51 - .86; range communalities: .26 - .74) on a single factor. Latent  
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32 scores of this factor, labeled as *phonological awareness (PA)*, were extracted through regression and used  
33  
34 as a predictor in the subsequent analyses.

37 In addition, we computed a composite score from the two rapid automatized naming (RAN)  
38  
39 subtasks from a principal component analysis which scales the resulting component scores to have a mean  
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41 of 0 and unit variance. The scores from the two subtasks (rapid object naming and rapid digit naming) were  
42  
43 correlated very highly (*r* = .79, *p* < .001) which would lead to multi-collinearity issues when using both  
44  
45 scores simultaneously in a regression model.

47 Finally, a binary variable was created from the *reading ability* factor scores (see above) for  
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49 indicating children who were at risk for reading disability (at-risk status). In accordance with Andrade et  
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51 al. (2015) and Fuchs et al. (2012), we defined all children scoring at least one standard deviation or more  
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3 below the mean of their grade group as being at-risk. For grades 2 and 3 this resulted in six students being  
4 defined as being at-risk for reading disabilities, but seven students for grade 5. Accordingly, 39, 35 and 34  
5 were defined as not being at-risk for grades 2, 3, and 5 respectively. We computed the at-risk variable  
6 separately for each grade.  
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## 10 11 12 **Statistical Analysis** 13

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15 The statistical analyses of the data collected in second, third, and fifth grade were performed in  
16 three different steps, each targeting a different aspect of reading development and musical ability. All  
17 analyses were carried out using the statistical software environment R, version 3.4.1.  
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### 20 21 ***Longitudinal Mixed Effects Models of Reading Ability*** 22

23 In the first step we constructed longitudinal mixed effects models of reading ability. We followed  
24 the recommendations for the construction and evaluation of longitudinal models provided in Long (2012).  
25 The reference model included reading ability as a dependent variable, the timepoints of data collection as  
26 the only fixed effects predictor variable and participant-ID as a random intercept effect. This null model  
27 was compared to models that also included the PA and RAN aggregate scores as well as the MSTT scores  
28 from second grade as predictor variables. The choice of predictor variables was informed by previous  
29 literature (McBride-Chang & Kail, 2002; Torgesen et al., 2011; Wagner et al., 1994) indicating that  
30 phonological processing and rapid automatized naming are two main predictors of reading acquisition.  
31 Consistently with this literature, the principal component analysis presented in Zuk et al. (2013a) also  
32 showed that MSTT, rhyme, alliteration, and RAN measures as well as word sequence all loaded very highly  
33 on the same component, thus demonstrating their strong associations. Because of the robust empirical  
34 support for the predictive value of PA and RAN combined with our goal to test the predictive power of  
35 MSTT, we have chosen MSTT, RAN and PA as the predictor variables for reading abilities in the present  
36 study. Predictor variables were employed to predict the overall level of the *reading ability* (intercept model)  
37 or the overall level as well as the increase in *reading ability* over time (intercept and slope model). We  
38 employed a model selection strategy that started with the full model including main effects and interaction  
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3 effects with time of all three predictors (PA, RAN, MSTT). Non-significant terms were removed from the  
4 full model and the model fit of the resulting reduced model was compared to the full model and the null  
5 model. Model fit was assessed on the Bayesian Information Criterion (BIC) and on likelihood ratio tests.  
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### 8 9 ***Prediction of Low-Achievement Readers***

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11 In a second step we computed a series of logistic regression models for the prediction of low-  
12 achievement readers. The binary variables *at-risk for reading disability* for each grade (2, 3, 5) were used  
13 as dependent variables. With each of these three dependent variables we computed two variants, one variant  
14 used the MSTT as the only predictor and the other variant used MSTT, RAN and PA as predictor variables.  
15 Both variants were compared by assessing their accuracy (i.e., proportion of students correctly classified),  
16 sensitivity, specificity, and by computing the area under the receiver operating characteristic (ROC) curve  
17 (AUC). Generally, on all four measures higher values indicate a better prediction and discrimination of the  
18 model. The AUC method is a widely employed statistic to assess the discriminatory power of logistic  
19 regression models. The ROC curve is usually a convex curve generated by plotting sensitivity (percentage  
20 of true positives) in the y-axis against 1-specificity (percentage of false positives) in the x-axis across all  
21 possible cut-off points. The AUC provides a non-parametric estimate of how closely predicted probabilities  
22 are linked to the low-achievement group of readers and representing a discriminatory power of  
23 identification (Swets, 1988). By definition, AUC values range from .5 (chance level) to 1 (perfect  
24 association). If the AUC has a value of .5 it means that the ROC curve falls in the diagonal and that  
25 discrimination power of the prediction model is at the chance level, whereas AUC values over .5 indicate  
26 discriminatory capacity of the evaluated model. According to Hosmer and Lemeshow (2000) AUC values  
27 from .7 to .8 are considered acceptable, from .8 to .9 excellent and above .9 outstanding.  
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### 47 ***Locating the MSTT in the Factor Structure of the Assessment Measures Battery***

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49 In the third and final step we explored through an exploratory factor analysis the location of the  
50 MSTT in the factor structure of the assessment measures battery. MSTT has both a motor component during  
51 the output/production phase and requires executive functions and attention skills. Therefore, we also  
52 performed an exploratory factor analysis on the data from all cognitive-linguistic measures and MSTT taken  
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3 in grade 2 in order to examine the likely cognitive underpinnings of the MSTT task. Exploratory factor  
4 analysis allows us to explore how variables correlate to each other and thus cluster together to represent  
5 potential cognitive dimensions or factors. Investigating the specific and salient loadings of measures onto  
6 each factor (commonalities) will enable us to: (a) infer what these potential cognitive factors/dimensions  
7 are and name them, and (b) to infer the level of shared cognitive mechanisms between a given measure and  
8 a cognitive factor through its communality, which represents the total amount of variance this measure  
9 shares with other measures that form the factor.  
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## 17 **Results**

21 Investigation of the extent to which MSTT contributes to the prediction of subsequent reading  
22 outcomes, while accounting for additional contributing factors, is outlined via two approaches as follows:  
23 a) longitudinal mixed models with reading ability scores across years 2, 3 and 5 as the repeated measures  
24 outcome variable and scores from the MSTT, phonological awareness and rapid automatized naming  
25 (RAN) tasks (assessed in year 2) as predictors; b) logistic regression to examine the potential for MSTT to  
26 predict low-achievement reader status at each longitudinal timepoint.  
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33 ----INSERT TABLE 1 HERE----

### 34 **Longitudinal Mixed Effects Models of Reading Ability**

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36 In a first step, a full mixed effects model was fitted to the longitudinal data, including main effects  
37 of timepoint (grade of testing) and of all three predictors of interest (MSTT, Rapid Automated Naming,  
38 Phonological Awareness). The full model also included three interaction effects of timepoint with each of  
39 the three predictor variables. All main and interaction effects of the full model were significant at the  $p <$   
40  $.05$  level with the exception of the interaction effects time x phonological awareness and time x MSTT.  
41 Removing these two non-significant terms gave rise to a reduced model, which showed a better fit to the  
42 data than the full model, and a null model that only included time but none of the other predictor variables.  
43 Model fit indices (Bayesian Information Criterion, BIC,  $p$ -values from likelihood ratio tests) of the null  
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3 model, the full model, and the reduced model are given in Table 2. The reduced model for the development  
4 of reading abilities is summarized in Table 3.  
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9 The model in Table 3 shows a significant positive effect for grade of assessment ( $p = .044$ ) which  
10 simply indicates that children become better readers over time. The rapid automatized naming (RAN) task  
11 is a time-based measure (the faster the children name the objects the lower the score) which has previously  
12 been shown to be negatively correlated to reading ability (e.g., Denckla & Cutting, 1999; Wolf & Bower,  
13 1999). Here we observe that RAN shows the strongest main effect on reading ability ( $p < .001$ , decrease in  
14 marginal  $R^2 = .22$ ). Therefore, as hypothesized, shorter naming times on the RAN tasks assessed in grade  
15 2 were observed to significantly contribute to the prediction of fifth grade reading abilities.  
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18 The interaction between RAN and grade of testing is also significant ( $p < .001$ , decrease in  $R_m^2 =$   
19  $.08$ ), suggesting that the influence of the RAN speed assessed in grade 2 decreases over time. In addition,  
20 MSTT scores had a significant positive effect ( $p = .011$ , decrease in  $R_m^2 = .03$ ), meaning that children with  
21 higher MSTT scores in second grade tend to show better reading abilities. Similarly, phonological  
22 awareness (PA) was also positively related to reading abilities ( $p = .02$ , decrease in  $R_m^2 = .02$ ). Because  
23 interactions for time x PA and time x MSTT were non-significant (i.e., the importance of PA and MSTT  
24 remained consistent over time), they were not included in the model.  
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27 In sum, reading ability increases over time from grade 2 to 5 and MSTT, PA and RAN aggregate  
28 scores taken in grade 2 are all significant predictors of reading ability across the primary school years.  
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### 31 **Prediction of Low-Achievement Readers**

32 The longitudinal mixed effects models above have shown that performance scores from the MSTT  
33 as well as phonological awareness (PA) and rapid automatized naming (RAN) composite scores are  
34 associated with the overall level of reading outcomes in the full sample of children. In practice, it is  
35 furthermore important to effectively identify whether children present with an early risk for reading  
36 disability (low achievers at 2<sup>nd</sup> and 3<sup>rd</sup> grades) will subsequently develop reading disabilities (low achievers  
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3 at 5<sup>th</sup> grade). To address this, we used the binary variable, low-achievement reader status, for each grade  
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5 (grade 2: 6 children with low reading achievement status, i.e., 1 *SD* below the mean; grade 3: 6 children;  
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7 grade 5: 7 children) as the dependent variable in a series of logistic regression models. To assess the  
8  
9 contribution of MSTT to prediction of low-achievement reader status, we compared two models, one using  
10  
11 only the MSTT score and a model with all three predictor variables (MSTT, Phonological Awareness, Rapid  
12  
13 Automatized Naming) from grade 2 as predictors. For all models, overall classification accuracy (child low-  
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15 achievement readers/non-low-achievement readers) as well as sensitivity and specificity of the logistic  
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17 regression model were recorded. Results are summarised in Table 4 and show that the classification  
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19 accuracy of all models is in the range of 83% to 91%. This means that between 4 and 7 children (depending  
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21 on the sample) were misclassified. Absolute misclassification numbers were generally balanced with  
22  
23 respect to the low- and high-achieving groups. Because the low achievement group was substantially  
24  
25 smaller due to the definition criterion, this resulted in substantially lower sensitivity than specificity rates.  
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27 In contrast to Fuchs et al. (2012) and Andrade et al. (2015), this represents a conservative approach for  
28  
29 logistic regression modelling (i.e., producing almost no false positives but affording several misses).  
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33 For the prediction of low-achievement readers, assessed in grade 5, the model including MSTT, PA  
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35 and RAN assessed in grade 2 as predictors classifies 83% of all participants accurately. The model using  
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37 only the MSTT model achieves a comparable classification rate of 85%. Performances of typical and low-  
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39 achievement readers on MSTT and cognitive-linguistic tasks are provided in the Supplemental Table 1.  
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41 Table 4 also shows the association of the binary low-achievement/non-low-achievement variables  
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43 and the model predictions on the continuous probability scale by computing the area under the receiver  
44  
45 operating characteristic (ROC) curve (AUC).  
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49 Additionally, Table 4 shows that across all grades, the AUC values of the combined predictor  
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51 models are superior compared to the corresponding models that contain only the MSTT as a predictor. This  
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53 superiority is linked to a higher sensitivity of the combined predictor models. In contrast, the specificity of  
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55 all MSTT models is higher than that of the combined predictor models. Hence, using the MSTT as a single  
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3 predictor produces slightly fewer false positives but this comes at the price of a slightly lower overall  
4 accuracy.  
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7 In sum, identifying low-achievement readers solely on the basis of MSTT achieves an overall  
8 classification accuracy that is only slightly lower than models that also include PA and RAN scores. The  
9 relatively good performance of the model using only the MSTT as a predictor is particularly true for long-  
10 term predictions (i.e., reading abilities in grade 5 predicted by scores from grade 2).  
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### 15 16 **Locating the MSTT in the Factor Structure of Assessment Measures** 17

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19 In order to examine cognitive underpinnings of the MSTT task, we performed an exploratory factor  
20 analysis with a descriptive aim on the data from all 21 measures taken in grade 2. An initial parallel analysis  
21 based on randomly re-sampled correlation matrices suggested the presence of a strong first factor and the  
22 high value of MacDonalD's coefficient omega ( $\omega = 0.7$ ) indicated the presence of a general factor  
23 common to all items. Therefore, we subsequently performed a series of hierarchical factor analyses, always  
24 including a general factor and between three and seven secondary group factors (i.e., so-called Schmid-  
25 Leiman factor models). We used principal axis factoring with oblimin rotation and compared different  
26 solutions on the Bayes Information Criterion (BIC). The solution with three group factors achieved the  
27 smallest BIC value and was considered the most adequate solution for the data. Supplemental Table 2 shows  
28 the factor loadings of all items. The general factor has high loadings from almost all measures and can  
29 therefore be considered a factor of general cognitive ability or 'g' factor. The items measuring reading  
30 abilities load most strongly on the first group factor. The second group factor has high loadings from the  
31 auditory measures (auditory discrimination, rhythm production) as well as from the phonological measures  
32 (alliteration, rhyming, syllable segmentation, rapid automatized naming of objects and digits), working  
33 memory (word sequence, figure ordering) and the MSTT. In fact, the MSTT has the highest loading on this  
34 factor and can therefore be considered the most discriminating indicator of this phonological-working  
35 memory factor. The third group factor was characterized by highest loadings from figure rotation and  
36 nonword repetition. A potential interpretation of this factor structure with regards to the MSTT might  
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3 suggest that, for performing well on the MSTT, a combination of auditory discrimination, working memory  
4 or phonological abilities are required, which distinguishes this test from other tests loading on the same  
5 latent factor. However, the parameter estimates of the bifactor solution given in Table 5 of the Appendix  
6 should only be interpreted with care and from a descriptive perspective as they are unlikely to represent the  
7 true bifactor model parameters from the population (see Mansolf & Reise, 2016).  
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## 13 14 **Discussion**

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17 The present study investigated the extent to which MSTT, a musical task collectively administered  
18 in the classroom, predicts subsequent reading outcomes among children in Brazil. MSTT consists of  
19 isochronous 4-chord sequences made of different combinations of only two different 2-note chords, one in  
20 the low register and the other in the high register of the same A chord on the guitar. However, MSTT also  
21 contains a sound-to-symbol mapping component and requires both a motor output during the  
22 output/production phase and may engage executive functions, particularly inhibition (since children have  
23 to wait for four beats until the examiner allows them to start recalling the sequence) and working memory  
24 skills to recall the sequence. The present study carried out a longitudinal follow-up of Zuk et al. (2013a)  
25 participants to examine how the MSTT predicts longitudinal reading outcomes. We hypothesized that  
26 MSTT, assessed in second grade, would significantly predict subsequent word reading in fifth grade.  
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### 38 **Replicating Zuk et al. (2013a) Findings in a Longitudinal Study**

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41 As expected, reading ability increases over time (from grade 2 to grade 5) and multiple regression  
42 analysis reveals that MSTT, PA and RAN are all significant predictors of the outcome variable, reading  
43 ability (determined by a composite of reading fluency, reading accuracy and reading pseudowords). In a  
44 longitudinal regression model with the outcome variable of reading ability and the MSTT, phonological  
45 awareness, and rapid automatized naming as predictors, the rapid automatized naming tasks were found to  
46 be the strongest predictors, followed by phonological awareness and MSTT both showing comparable  
47 effects. Interestingly, the interaction between RAN and grade of testing was significant (which was not the  
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3 case for PA and MSTT), suggesting that the strength of the effect of RAN on reading ability decreases over  
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5 time.  
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7 These findings are consistent with evidence suggesting that both domains can share cognitive  
8 mechanisms at the mid-level of auditory sequence processing (Janata & Grafton, 2003; Osterhout et al.,  
9 2012; Shain et al., 2020). Secondly, these findings are in line with the growing body of evidence suggesting  
10 positive relationships of musicality with both phonological awareness and reading abilities in both typical  
11 (Anvari et al., 2002; Dege & Schwarzer, 2011; Douglas & Willatts, 1994; Forgeard et al., 2008; Lamb &  
12 Gregory, 1993; Moritz et al., 2013; Overy et al., 2003; Peynircioglu et al., 2002) and atypical readers  
13 (Thomson et al., 2006) and children (Bhide et al., 2013; Corriveau & Goswami, 2009; Huss et al., 2011;  
14 Overy, 2000; Overy et al., 2003; Foregard et al., 2008).  
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#### 24 **MSTT Identifying Low-Achievement Readers**

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27 A subsequent analysis recoded reading outcome scores for each grade (2, 3 and 5) into low versus  
28 high achievement to examine the degree to which the MSTT, Phonological Awareness, and Rapid Naming  
29 can contribute to classify children as low vs high achievement readers. Two prediction models were used  
30 to assess how much MSTT contributes toward prediction of poor reader status: the MSTT-only model and  
31 the whole model based on all three predictor variables (MSTT, Phonological Awareness factor score, Rapid  
32 Automatized Naming component score). For identifying low-achievement readers we decided to use an  
33 evaluation method known as the area under the receiver-operating characteristic (ROC) curve (AUC) which  
34 is a widely employed statistic to assess the discriminatory power of logistic regression models (Adlof et al.,  
35 2017; Fuchs et al., 2012; Hendricks et al., 2019; Petscher et al., 2019).  
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46 For identifying low-achievement readers on its own, MSTT achieved an overall accuracy for grades  
47 2 and 3 ( $AUC = 0.86$ ) that is lower than the identification accuracy of the whole model, i.e. MSTT, PA and  
48 RAN as predictors ( $AUC_{\text{year } 2} = 0.91$ ,  $AUC_{\text{year } 3} = 0.90$ ) and in grade 5 the performance of the model  
49 including only MSTT was comparable to the full model.  
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3 It is worth mentioning that, even though the MSTT performed worse than the full model across all  
4 grades according to the AUC criterion, it still has the best specificity across all years. Overall, the AUC  
5 values of all models fall within the range of excellent to outstanding according to the classification provided  
6 by Hosmer and Lemeshow (2000). It is also interesting that the models using the MSTT as the only  
7 predictor reached an identification accuracy similar to levels reported in earlier studies with much larger  
8 samples that investigated the effectiveness of either univariate (only one screener) or multivariate screening  
9 (multiple screeners) models where AUC values range from .85 to .86 (see Petscher et al., 2019). Adding  
10 multiple indicators to the screening measures (e.g., progress monitoring or teacher ratings) has been shown  
11 to improve identification accuracy. Similar to the present findings, Compton et al. (2012) report an increase  
12 in AUC from .88 (single indicator model) to .92 (multiple indicator model). A recent study found that  
13 adding a group-administered word reading task to a group-administered listening comprehension task  
14 increased AUC value in the prediction of risk of language impairment from .699 to .792 (Adlof et al., 2017).  
15 However, the word reading task alone in the dyslexia screener reached an AUC of .85 and did not improve  
16 by including the listening comprehension task (Adlof et al., 2017). Taken together these results point to a  
17 promising perspective for the use of the MSTT as a complementary screening tool in multivariate screening  
18 models, especially for group-administered tasks.  
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### 36 37 **Potential Cognitive Mechanisms Underlying Performance in the MSTT Task.** 38 39

40 While the MSTT is a music-based tool assessing auditory sequence processing, it is important to  
41 consider additional cognitive constructs that may underlie this task. One consideration pertains to the extent  
42 to which children may be engaging verbal working memory resources to recode and memorize the chord  
43 sequences verbally, such as using “low” or “thick” vs. “high” or “thin.” Secondly, it could be asked whether  
44 MSTT might be measuring the visual processing involved in sound-symbol correspondence or, thirdly,  
45 whether children could be memorizing the chord sequences verbally. To address this question an  
46 exploratory factor analysis was performed on all 21 measures taken in grade 2 (including MSTT) to gain  
47 some insight into related constructs and potential underlying cognitive mechanisms of the MSTT task. The  
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3 most adequate solution for the data yielded three group factors. The items measuring reading abilities  
4 loaded most strongly on the first group factor whereas MSTT loaded most strongly on the second factor,  
5 labeled as phonological factor because its highest loadings were from the phonological and auditory  
6 memory measures. By having the highest loading on this second factor, MSTT can be considered the most  
7 discriminating indicator of this phonological factor. The third group factor, labeled as short-term working  
8 memory factor, was characterized by highest loadings from figure rotation and nonword repetition.  
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16 The results from the PCA indicate that the subtests word sequence repetition and nonword  
17 repetition loaded differentially on the phonological and working-memory factors. This result is intriguing  
18 because both tasks can be regarded as indexing verbal short-term memory. This suggests that the MSTT is  
19 highly related to auditory and phonological processing abilities. MSTT was designed to preferentially  
20 engage auditory sequence processing but does not require fine-grained pitch perception (2-note chords are  
21 separated by large intervals: one octave or more) and being devoid of both harmonic syntax (no chord  
22 changes) and rhythm in terms of temporal grouping as well (isochronous sequences). It therefore seems to  
23 be a measure of sequencing skills of larger auditory chunks similar to sequences of syllables or a measure  
24 of verbal working memory of larger auditory “objects” such as syllables, onsets, rhymes, or whole words.  
25 Therefore, it seems to be measuring different skills than those underlying nonword repetition wherein the  
26 emphasis is primarily on the accurate repetition of phonemes and their sequence from phonological working  
27 memory. Future studies that systematically vary specific components of the MTSS are needed to further  
28 investigate which aspects of the task are most predictive of subsequent reading outcomes and to further  
29 investigate the underlying perceptual and cognitive mechanisms of the MSTT.  
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### 46 **Limitations and Future Directions**

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48 The present findings are to be interpreted in the context of some notable limitations. First, the  
49 modest sample size drawn from only one school imposes strong restrictions regarding the generalization to  
50 the larger population of primary school children in Brazil, let alone in other countries. Therefore, it is  
51 necessary to replicate this work with a larger and more heterogeneous sample of primary school children.  
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3 Secondly, the present study was conducted with a sample of children from upper-middle class  
4 families, suggesting that the observed reading and writing difficulties are not primarily the result of lower  
5 family socioeconomic status (SES), a relevant variable in Brazil (Enricone, & Salles, 2011). Hence, there  
6 is a need to address the role of SES for the development of reading abilities more explicitly in future studies.  
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11 In order to understand the association between MSTT scores taken at an early age and the  
12 subsequent development of reading and writing abilities, more longitudinal observations are needed, e.g.  
13 assessing reading and writing abilities at six months intervals ranging from first to fifth grade. Another  
14 future direction concerns the implementation of the MSTT in countries other than Brazil to test its cross-  
15 linguistic and cross-cultural applicability. MSTT is non-verbal in nature and uses very basic rhythmic  
16 structures that are not biased towards any particular musical culture (at least within the broad spectrum of  
17 Western musical cultures). These characteristics make it very much plausible that the MSTT should work  
18 equally well in European countries with more transparent (e.g., German, Finish, Italian, Spanish) or even  
19 less transparent orthographies such as English when compared to Portuguese (see Ziegler & Goswami,  
20 2005). Therefore, future research is necessary to evaluate the feasibility of implementing MSTT in other  
21 languages and cultures.  
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### 34 35 **Conclusion** 36

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38 The preliminary findings of this study carry implications for the role of temporal sequence  
39 processing in contributing to the relation between music and language while suggesting that the MSTT may  
40 be helpful as an expedient, ecologically valid approach to assess auditory sequence processing skills in a  
41 classroom setting without the need for a costly or language-specific measure. Moreover, these preliminary  
42 findings also indicate the potential use of MSTT as a language-independent, time- and cost-effective tool  
43 for the early identification of children at-risk for reading disability. Finally, MSTT carries the potential for  
44 its use in comparative studies across different language regions. However, the present results are not  
45 intended as a form of proof that the MSTT is a valid screening tool given the small sample size and the lack  
46 of a well-designed psychometric validation study. Instead, these results should be interpreted as preliminary  
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3 evidence that a group-administered musical activity designed to engage auditory sequence processing has  
4 the potential to predict subsequent reading abilities one to three years after its administration. Although the  
5 MSTT does not require fine-grained pitch perception, syntax, or rhythm processing (in terms of temporal  
6 grouping) it is still a musical task. The musical nature of the MSTT makes it very pleasurable and  
7 motivating for children (Goswami, 2012; Hallam, 2010). Because the MSTT can be run with groups of  
8 children and requires only minimal training for its implementation and interpretation, it is suitable for the  
9 administration in classroom settings. Hence, this study contributes to the scarce evidence on the accuracy  
10 as well as time and cost effectiveness of collectively administered screening procedure for children (Adlof  
11 et al., 2017; Andrade et al., 2015; Hendricks et al., 2019; Petscher et al., 2019). Because of the nonverbal  
12 nature of the MSTT and its very basic rhythmic structures which are not biased towards any particular  
13 Western musical culture it has the potential of providing a relatively time- and cost-effective mean of early  
14 identification of children at-risk for reading disability in different languages.  
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3 [Endnote](#)  
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5 —<sup>1</sup>Minimum residual factor analysis was chosen as analytic method because it commonly  
6 produces solutions very similar to maximum likelihood factor analysis (ML FA) but is generally  
7 more robust and can be computed in situations where ML FA cannot be employed (e.g., matrices  
8 are not invertible; Harmann & Jones, 1966).  
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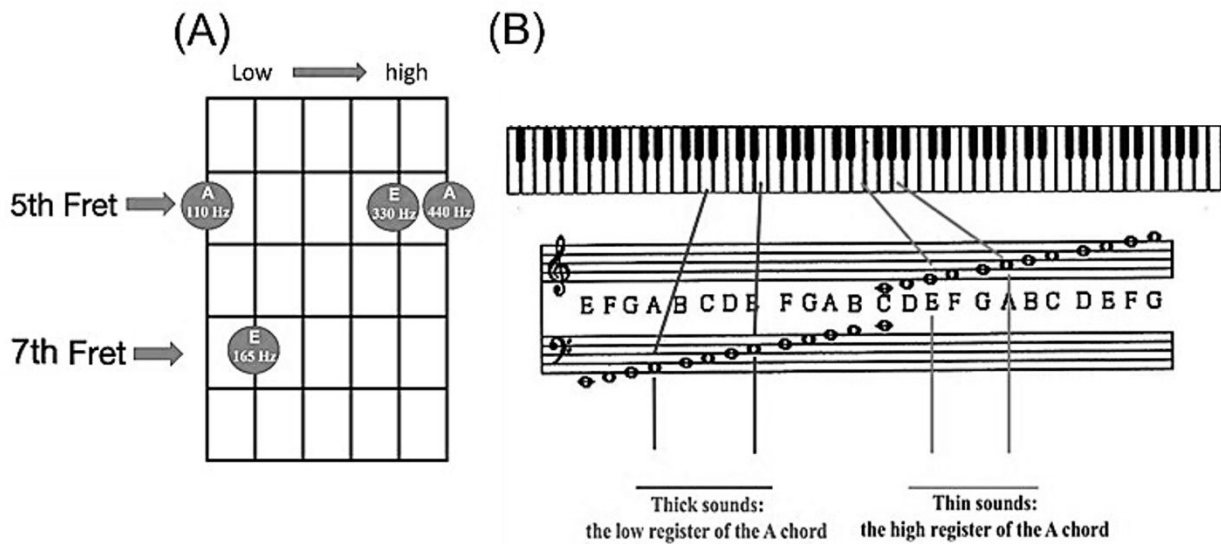


Figure 1.

MSTT 2-note Chords Based on the A Chord on both Guitar (A) and Piano (B).

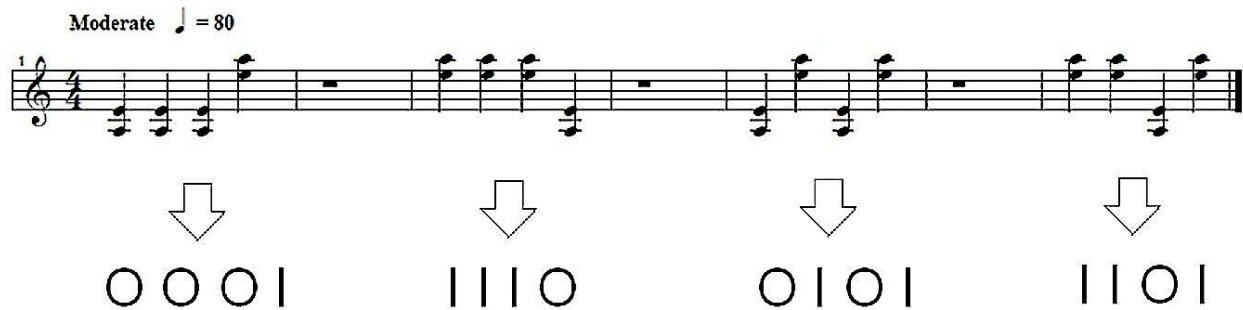


Figure 2. Examples of MSTT Sequences and How Students Recalled them Using a Circle "O" for the Low Chords and a Vertical Line "I" for the High Chords (Delmolin et al., 2017).

**Table 1.***Means and Standard Deviations for the Administered Measures*

Measures	Grade 2			Grade 3			Grade 5		
	<i>N</i>	<i>M</i>	<i>SD</i>	<i>N</i>	<i>M</i>	<i>SD</i>	<i>N</i>	<i>M</i>	<i>SD</i>
Age (years)	45	7.34	.32	41	8.33	.337	41	10.32	.329
MSTT	45	11.87	5.26						
Alphabet	45	24.47	2.73						
Reading Rate	45	32.29	15.28	41	50.05	20.64	41	64.34	15.42
Reading Accuracy	45	61.84	14.16	42	66.29	4.192	41	67.39	2.93
Reading Pseudowords	45	9.31	1.31	41	9.44	1.026	41	9.71	0.72
Reading Ability Factor Score	45	-0.40	1.31	41	0.09	0.54	41	0.34	0.35
Alliteration	45	8.18	1.77						
Rhyme	45	16.53	2.91						
Syllable Segmentation	45	11.53	0.84						
PA Factor Score	45	-0.28	0.91						
Auditory Word Discrimination	45	18.62	0.98						
Rhythm	45	5.04	2.01						
Word Sequence	45	3.76	1.15						
Nonword repetition	45	20.76	2.10						
Individual Digit Memory	45	4.49	1.53						
Shapes Copying	45	4.84	2.13						
Figure Ordering	45	5.62	1.13						
Figure Rotation Error	45	2.4	3.13						
RAN Objects	45	38.64	8.39						
RAN Digits	45	45.04	10.35						
RAN Component Score	45	0	1						

*Note.* Factor Score = factor analysis score, Component Score = principal component analysis score, PA Factor Score = Phonological Awareness factor analysis score, RAN Component Score = Rapid Automatized Naming principal component score.

**Table 2.***Evaluation of Longitudinal Models of Reading Development*

Model	<i>df</i>	BIC	$\chi^2$ diff	<i>p</i>
Null	4	317.62	-	-
Reduced	8	263.98	73.02	< .001
Full	10	268.82	4.84	.089

*Note.* The null model includes only timepoint (i.e., grade of testing) as the predictor. The full model includes time and scores of MSTT, phonological awareness, and RAN measured in grade 2 as predictors as well as interaction effects between time and the three score variables. The reduced model is similar to the full model but has two non-significant interaction terms removed. Dependent variable: reading ability factor scores. Lower values on the Bayesian Information Criterion indicate a better model fit. Chi square differences and corresponding *p*-values refer to the likelihood ratio comparing the null model to the reduced and reduced to full model.

**Table 3.**

*Longitudinal Regression Model for Reading Abilities including MSTT, Phonological Awareness, and RAN As Predictors*

Variable	<i>B</i>	<i>SE B</i>	<i>df</i>	<i>t</i>	<i>P</i>	<i>Decrease in <math>R_m^2</math></i>
Intercept	-0.48	0.23	98.82	-2.04	.044*	
Grade	0.11	0.05	84.56	2.5	.014**	
PA	0.19	.008	45.71	2.42	.02*	.02
RAN	-1.04	0.14	119.81	-7.38	<.001***	.21
MSTT	0.03	0.01	42.5	2.67	.011*	.03
Grade x RAN	0.21	0.04	84.06	5.45	<.001***	.08
<i>R</i> <sup>2</sup> marginal		0.57				
<i>R</i> <sup>2</sup> conditional		0.65				

*Note.* MSTT = Muscial Sequence Transcription Task, PA = Phonological Awareness factor score, RAN = Rapid Automatized Naming principal component score. Note that for RAN higher scores indicate a worse performance. Also note that for mixed effect models there are two types of the *R*<sup>2</sup> coefficient, i.e., conditional *R*<sup>2</sup> which includes random effects and marginal *R*<sup>2</sup> including only fixed effects (Nakagawa & Schielzeth, 2013). Decrease in *R*<sub>*m*</sub><sup>2</sup> is a measure of effect size for the individual predictors and denotes the decrease in marginal *R*<sup>2</sup> when the predictor is removed from the model. \* *p* ≤ .05, \*\**p* ≤ .01, \*\*\* *p* ≤ .001.

**Table 4.**

*Classification Accuracy Indices for Predicting Reading Low-achievement Reader Status at the Beginning of Second and Third Grades, and At the End of Fifth Grade*

Grade	Predictors	Accuracy	Sensitivity	Specificity	AUC
2	MSTT, PA, RAN	0.91	0.67	0.95	0.92
2	MSTT	0.86	0.17	0.97	0.83
3	MSTT, PA, RAN	0.90	0.67	0.94	0.94
3	MSTT	0.86	0.17	0.97	0.80
5	MSTT, PA, RAN	0.83	0.29	0.94	0.91
5	MSTT	0.85	0.29	0.97	0.83

*Note.* Dependent variable: low-achievement reader status (binary). PA = Phonological Awareness factor score, RAN = Rapid Automatized Naming principal component score.

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5 **Table S1.**

6 Means (M) and standard deviations (SD) on the cognitive-linguistic measures administered to participants  
7 (N) of typical (T) and low-achieving/atypical readers (A) groups at grades 2, 3, and 5.  
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10 Readers: A Longitudinal Study  
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Measures		Grade 2			Grade 3			Grade 5		
		N	M	SD	N	M	SD	N	M	SD
Age (years)	T	39	6.87	0.34	35	7.85	.35	34	9.88	0.33
	A	6	7.33	0.52	6	8.33	0.52	7	10.14	0.69
MSTT	T		12.72	4.72						
	A		6.33	5.64						
Reading (correct words + words per minute)	T		112	16.1				147	13.62	
	A		48	26.0				116	10.3	
Reading Pseudowords	T		9.72	0.51		9.63	0.81		9.85	0.36
	A		6.66	1.86		8.33	1.50		9.00	1.41
<b>Reading Factor Score</b>	T		0.05	0.41		0.26	0.40		0.48	0.41
	A		-3.37	0		-0.89	0		-0.31	0
Alliteration	T		8.49	1.54		8.68	1.64		9.47	0.99
	A		6.16	2.04		6.66	2.34		9.28	0.95
Rhyme	T		16.9	2.50		17.7	2.93		18.6	1.81
	A		13.8	4.12		14.8	2.99		15.2	1.70
Syllable Segmentation	T		11.5	0.88		11.7	0.71		11.9	0.24
	A		11.3	0.52		10.8	1.94		11.8	0.38
<b>PA Factor Score</b>	T		-0.11	0.79		0.04	0.88		0.48	0.48
	A		-1.33	0.98		-1.13	1.40		0.08	0.43
Auditory word discrimination	T		18.7	0.41					18.9	0.79
	A		17.5	2.34					19	0
Rhythm	T		5.28	1.92		5.62	1.83		8	1.49
	A		3.50	2.07		4.50	1.64		6.43	1.27
Word Sequence	T		3.92	1.11		4.48	1.07		5.20	0.94
	A		2.66	0.81		3.66	1.36		4.57	1.13
Nonword repetition	T		20.95	2.16		20.51	1.77		22.82	0.46

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	A	19.50	1.05	20.00	2.12	22.57	0.79
Indirect Digit Memory	T	4.61	1.53			5.63	1.39
	A	3.66	1.37			4.86	1.46
Shapes Copying	T	5.02	2.00			5.73	1.58
	A	3.66	2.73			5.85	1.46
Figure Ordering	T	5.77	1.13			5.67	1.36
	A	4.66	.52			5.14	1.46
Figure Rotation Error	T	2.41	3.21			1.03	1.73
	A	2.33	2.73			1.00	1.29
Rapid Naming (Object)	T	37.54	7.21	33.35	6.17	29.03	4.95
	A	45.83	12.40	39.16	5.27	32.14	4.67
Rapid Naming (digits)	T	43.00	7.18	37.11	6.51	29.67	6.32
	A	58.33	17.52	49.17	11.94	34.43	5.50
<b>RAN Component Score</b>	T	0.46	0.75	-0.13	0.70	-0.80	0.61
	A	1.80	1.69	0.88	0.83	-0.34	0.54

*Note.* Factor Score = factor analysis score, Component Score = principal component analysis score, PA Factor Score = Phonological Awareness factor analysis score, RAN Component Score = Rapid Automatized Naming principal component score.

**JOURNAL OF LEARNING DISABILITIES SUPPLEMENTAL FILE****Table S2.**

Factor loadings of hierarchical factor model of all measures taken in year 2.

**ARTICLE TITLE:** Sequence Processing in Music predicts Reading Skills in Young Brazilian Readers: A Longitudinal Study

<i>Item</i>	<i>g</i>	Schmid Leiman Factor loadings < 0.2			<i>h</i> <sup>2</sup>
		Literacy	Phonological	Working Memory	
MSTT	0.45		0.59		0.55
Alphabet	0.46				0.26
Readmin	0.77	0.25	0.20		0.71
TotalWord	0.86	0.33			0.88
TotalTime-	0.88	0.37			0.92
PswRead	0.60	0.20	0.23	-0.21	0.50
WordWrit	0.83	0.26	0.25		0.83
PswWrit	0.78	0.29			0.74
Aliter	0.41		0.41	0.23	0.39
Rhyme	0.55		0.32		0.45
SyllabSeg	0.21		0.29	0.25	0.18
AudDisc	0.25		0.44		0.25
RhytProd	0.34		0.44		0.32
WordSeq	0.47		0.42		0.41
NonwordRep	0.27			0.40	0.24
IndDigMem	0.27		0.27		0.16
CopForm	0.24		0.34		0.20
FigOrd	0.23		0.37		0.19
RotError-				0.77	0.63
FigNam-	0.70	0.27		0.28	0.65
DigNam-	0.71	0.32	-0.20	0.26	0.72