Rhythm in the blood: The influence of rhythm skills on literacy development in third graders

Margaux Lê, Pauline Quémart, Anna Potocki, Manuel Gimenes, David Chesnet, Eric Lambert

Please cite this paper as: Lê, M., Quémart, P., Potocki, A., Gimenes, M., Chesnet, D., and Lambert, E. (2020). Rhythm in the blood: The influence of rhythm skills on literacy development in third graders. *Journal of Experimental Child Psychology*, 198. https://doi.org/10.1016/j.jecp.2020.104880

Rhythm in the blood: The influence of rhythm skills on literacy development in third graders

Margaux Lê[1], Pauline Quémart[1], Anna Potocki[1], Manuel Gimenes[1], David Chesnet[2], and Eric Lambert[1]

[1]Université de Poitiers, CNRS, Centre de Recherches sur la Cognition et l'Apprentissage, Poitiers

[2]CNRS, Université de Poitiers, MSHS, Poitiers

Abstract

Several studies have shown the influence of rhythm skills in the processing of written language, especially at the beginning of literacy development. The first objective of this study was to determine the persistence of this link at an advanced grade level. The second objective was to better understand the factors underlying this relationship and, more specifically, to examine the hypothesis of mediation by phonological and/or motor skills. In total, 278 third graders performed literacy tasks (word/pseudoword decoding and spelling), a rhythm production task, two phonological tasks (phonological awareness and rapid automatized naming), and motor tasks. Significant correlations were observed between literacy and each of rhythm skills, phonological skills, and motor skills. However, structural equation models showed that the influence of rhythm skills on literacy was mediated neither by phonological skills nor by motor abilities. These results suggest that rhythm skills continue to play a role in the acquisition of written language in third graders and that this contribution seems to be independent of phonological and motor skills.

Keywords: Rhythm, Reading, Spelling, Motor skills, Phonological skills, Structural Equation Modeling

Rhythm in the blood: The influence of rhythm skills on literacy development in third graders

Over the past three decades, an impressive number of studies have been conducted to better understand linguistic predictors of literacy acquisition across several writing systems (e.g., Goff, Pratt, & Ong, 2005; Hulme & Snowling, 2013; Kirby, Parrila, & Pfeiffer, 2003; Muter, Hulme, Snowling, & Stevenson, 2004). A substantial number of these studies have focused on the factors involved in learning to read (written word recognition, e.g., Gough, Ehri & Treiman, 1992) and spell (e.g., Treiman & Kessler, 2014). These studies showed that phonological awareness (Goswami & Bryant, 2016), short-term verbal memory (Peng et al., 2018), and rapid automatized naming (RAN) (Kirby et al., 2003) play a central role in successful written language acquisition. Beyond such linguistic factors, a growing number of studies have examined the links between nonlinguistic abilities and literacy development (e.g., Cameron et al., 2012). Among these abilities, rhythm skills have been shown to have a significant influence on reading and writing acquisition (David, Wade-Woolley, Kirby, & Smithrim, 2007; Lundetrae & Thomson, 2018; Ozernov-Palchik, Wolf, & Patel, 2018b). However, these studies have mainly focused on the early stages of literacy development, and little is known about the link between rhythm skills and literacy development after a few years of learning. In addition, most research has explained this link in terms of the mediation of phonological skills (Goswami, 2011; Ozernov-Palchik & Patel, 2018a). Nevertheless, according to Nithart et al. (2011), in higher grades, other processes could also underlie this link because the implication of explicit phonological skill is reduced when the child begins to master reading and writing. The objective of this study is both to validate the link between rhythm skills and literacy development with grade 3 students and to better understand the factors underlying this relationship.

Rhythmic abilities correspond to the ability to perceive and produce an organized pattern of stimuli in time (Fujii & Schlauf, 2013). These skills are usually separated into two categories: *speech rhythm* skills (i.e., prosodic sensitivity during speech) and *non-speech rhythm* skills (i.e., the processing of nonlinguistic rhythms such as during synchronization to a metronome) (Holliman, Wood & Sheehy, 2014). In this study, we focused on non-speech rhythm skills to examine the influence of rhythm skills on literacy development independently of language skills. For the sake of clarity, we will use the term "rhythm skills" throughout the manuscript; here, this term refers to non-speech rhythm

skills. Several studies have reported an effect of rhythm perception and production skills on literacy development. This conclusion is partly based on studies in typical development (David et al., 2007; Ozernov-Palchik, Wolf, & Patel, 2018b; Zhang, Meng, Wu, & Zhou, 2017), but the majority of these studies focused on children with learning disabilities (Corriveau & Goswami, 2009; Huss, Verney, Fosker, Mead, & Goswami, 2011; Lundetrae & Thomson, 2018; Thomson, & Goswami, 2008; Thomson, Fryer, Maltby, & Goswami, 2006; Wolff, 2002), which included results from musical and/or rhythmic training studies (Cogo-Moreira, de Avila, Ploubidis, & De Jesus Mari, 2013; Flaugnacco et al., 2015; Habib et al., 2016; Overy, 2000). Moreover, studies have found that children and adults with developmental dyslexia have deficits in timing perception, beat perception, and beat synchronization (Huss et al., 2011; Thomson et al., 2006; Thomson & Goswami, 2008; Wolff, 2002). For example, Lundetrae and Thomson (2018) showed that rhythmic abilities, added to other measures known to be predictors of literacy, improve the accuracy of a classification model to identify children with literacy difficulties. Similarly, children with specific language impairment (SLI) are less able to accurately synchronize their movements to an auditory stimulus (Corriveau & Goswami, 2009), and their rhythmic abilities are related to phonological skills (phonological awareness and RAN), word reading, and spelling after controlling for age, IQ, and motor skills. These results support the relationship between rhythmic and literacy impairments.

Rhythm Skills and Literacy: A Mediation by Phonological Skills?

The relationship between rhythmic abilities and literacy development may be mediated by phonological skills. This hypothesis is based on results from studies conducted in atypical development. According to the temporal sampling framework (Goswami, 2011), language impairment observed in dyslexia and SLI could be caused by a deficit in temporal auditory processing. This deficit would affect both rhythmic abilities and explicit phonological skills, such as phonological awareness. It would also indirectly impact literacy development. According to this hypothesis, training in rhythmic abilities would improve phonological skills and, consequently, reading level. Thus, several interventional studies have evaluated the efficacy of music training in children with dyslexia (Flaugnacco al., 2015; Habib et al., 2016; Overy, 2000) or poor readers (Cogo-Moreira et al., 2013),

and their results support this hypothesis. The authors reported positive effects of such interventions not only on reading skills but also on phonological abilities. Similarly, two studies compared the benefits of rhythmic training and phonemic intervention in particular (Bhide, Power & Goswami, 2013; Thomson, Leong & Goswami, 2013). In the two studies, specific effects of both rhythmic and phonemic training were observed on phonological skills, spelling skills, and word reading. All these results indicated an effect of rhythmic training on phonological awareness, suggesting that the efficacy of musical and rhythmic intervention on literacy is subtended by an improvement of explicit phonological abilities. However, in most of these studies, the interventions involved both non-speech rhythm tasks (e.g., playing a musical instrument, hand clapping) and speech rhythm tasks (e.g., segmenting a word into syllables by hand clapping), thus calling into question the specific role of non-speech rhythm skills on literacy development in children with learning disabilities.

The hypothesis of mediation by phonological skills also relies on the results from studies in children with typical development. Only a few studies have investigated this hypothesis in this population. Among them, a longitudinal study on 53 first graders showed that performance on rhythmic production tasks (e.g., tapping on the lap to the beat using alternating hands) predicts the level of pseudoword decoding and word reading in higher grades (grades 2 to 5) (David et al., 2007). In another study (Ozernov-Palchik et al., 2018b), the ability to discriminate between two rhythms was found to predict rapid automatized naming, phonological awareness, and letter-sound knowledge in 76 kindergarteners. In this study, structural equation modeling (SEM) was used to test the hypothesis of mediation by phonological awareness of the relationship between rhythm discrimination and early literacy skills (assessed using a letter-sound knowledge task). The results showed that both the direct and indirect paths by phonological awareness were significant, suggesting only partial mediation by phonological awareness.

The two studies described above indicated that perception and production of rhythm are important skills for literacy acquisition even in typical development. Furthermore, as for children with learning disabilities, the effect of rhythm skills would be mediated by phonological skills at the beginning of learning. In previous studies, phonological skills were assessed in kindergarten and first grade. However, in older children, the influence of phonological awareness decreases with the

consolidation of reading and writing skills (Kirby et al., 2003; Mann & Singson, 2003; Nithart et al., 2011). Therefore, mediation by phonological skills would imply that the influence of rhythm would also decrease over time. This decrease does not show up, since the relationship between rhythm and literacy persists in higher grades (Zhang et al., 2017). This persistence of the link between literacy and rhythm throughout literacy development needs to be further examined. One hypothesis is that the relationship between literacy and rhythm is mediated by a skill other than phonology.

Rhythm Skills and Literacy: A Mediation by Motor Skills?

Recent research has suggested that motor skills may be one such mediating factor. Motor skills are linked to literacy development. Fine motor skills measured in kindergarteners predict subsequent word-decoding and spelling levels (Cameron et al., 2012; Doyen, Lambert, Dumas, & Carlier, 2017; Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010). However, this link has rarely been investigated among older students. Only one study reported that fine motor coordination predicts academic achievement in 10- and 12-year-old children (Schmidt et al., 2017). In addition, learning disorder studies have shown that deficits in motor skills and deficits in reading or spelling acquisition are frequently associated. For example, motor difficulties have been reported in children with dyslexia or who are at risk of dyslexia (Brookman, McDonald, McDonald, & Bishop, 2013; Gooch, Hulme, Nash, & Snowling, 2013; Jover et al., 2013). Conversely, O'Hare and Khalid (2002) showed that reading difficulties were more frequent in children with developmental coordination disorder (DCD) (70%) than in children with typical development (14%).

Moreover, the results from correlational, behavioral, and neuroimaging studies suggest a relationship between motor skills and rhythmic abilities (Grahn & Brett, 2007; Monier & Droit-Volet, 2019; Whitall et al., 2008). For instance, Monier and Droit-Volet (2019) assessed 57 5- to 8-year-old children using sensorimotor synchronization and continuation tasks. For the two tasks, the stability of beat production and the ability to produce a new tempo (different from the preferred tempo) were correlated with fine motor skills. Moreover, the study of DCD suggests that deficits in motor and timing abilities are often associated and that children with DCD frequently present with impairments in sensorimotor synchronization (Roche, Viswanathan, Clark & Whitall, 2016; Whitall et al., 2008).

De Castelnau, Albaret, Chaix, and Zanone (2007) showed that children with DCD are less able to synchronize with a square flashing on a screen at regular intervals than children with typical development. In another study, Rosenblum and Regev (2013) compared children with and without DCD using an interactive metronome and showed that children with DCD were less able to synchronize their movements to the stimulus. Non-speech rhythmic abilities are also altered in other motor disorders, such as Parkinson's disease or stroke (Bienkiewicz & Craig, 2015). Interestingly, in these populations, rhythmic intervention was found to improve gait and motor abilities, suggesting an effect of rhythmic abilities on motor skills (Dalla Bella et al., 2017; Janzen, Haase, & Thaut, 2019; Schaefer, 2014). Furthermore, the results from neuroimaging studies suggest that there is a strong relationship between motor skills and rhythmic abilities because motor skills and rhythmic information processing share the same cerebral network. Both rhythm production (e.g., synchronizing to a beat) or rhythm perception (e.g., listening to a beat without any movement) recruit motor regions of the brain, such as the premotor cortex, supplementary motor area, cerebellum, and basal ganglia (Chen, Penhume & Zatorre, 2008; Granh & Brett, 2007).

The abovementioned studies suggest a – potentially causal – link between motor skills and literacy. They also showed the influence of rhythm on fine motor skills. Taken together, these two effects support a link between rhythm skills and literacy development mediated by motor skills.

The Present Study

Many studies have supported the existence of a relationship between rhythmic abilities and written language acquisition in children with learning disorders and those in early literacy development (kindergarten and grade 1). According to several authors (Goswami, 2011; Ozernov-Palchik & Patel, 2018a), this relationship is the result of mediation by phonological skills, known to be a strong predictor of literacy acquisition. Indeed, rhythmic and phonological abilities would both depend on more global temporal auditory processing (Goswami, 2011). Because the link between phonological skills and literacy decreases with age (Nithart et al., 2011), mediation by phonology would imply that the relationship between rhythm and literacy would also decrease with age. However, even if the evolution of this link in older children has been poorly investigated, some results suggest that this link persists in third grade and beyond (David et al., 2006; Zhang et al., 2017).

Therefore, we assume that other skills could mediate the link between literacy and rhythm and that phonological mediation should at least be less effective in students already learning to read.

In this study, we tested the possibility that mediation by motor skills could explain the effect of rhythmic abilities on reading and writing in advanced students. This new hypothesis has been supported by results showing that motor skills are linked to both rhythmic abilities and literacy development (Cameron et al., 2012; Monier & Droit-Volet, 2019).

To test these hypotheses (mediation by phonology and mediation by motor skills), we assessed literacy level, non-speech rhythmic abilities, phonological skills, and motor skills in a large sample of third graders without learning disabilities. Given that literacy refers to both reading and writing, both of these components were evaluated using reading and spelling tasks. Furthermore, we chose a sensorimotor synchronization task to ensure that linguistic abilities were not implicated in the rhythmic task. SEM was used to characterize the relationship between rhythmic ability and literacy.

First, we expected that the effect of rhythmic abilities on reading and spelling acquisition persists in grade 3. Second, we predicted that the relationship between rhythm and literacy would be at least *partially* mediated by phonology. Finally, given the persistence of the relationship between motor skills and literacy development, we also made the assumption that this effect would be mediated by motor skills.

Method

Participants

In total, 278 third graders (mean age = 8.4 years old; *SD* = 0.3 years; 154 girls and 124 boys) in 25 classes from 16 schools of the XXX region in France were recruited. Twelve children were excluded because of a nonverbal IQ score of less than 75, following the recommendation of the *Diagnostic and Statistical Manual of Mental Disorders (DSM–5)* of the American Psychiatric Association (2013). Ten children were excluded because of deficits in fine motor skills assessed by a scaled score less than 1.5 *SD* on the “Manual Dexterity” item (M-ABC, Henderson & Sudgen, 1992). Fourteen children were excluded because of reading deficits associated with a deficit in phonological awareness or in rapid automatic naming assessed by a scaled score lower than 1.5 *SD* on the BALE

reading test (Jacquier-Roux, Lequette, Pouget, Valdois, & Zorman, 2010). Therefore, the analyses were processed on 242 children (mean age = 8.4 years old; *SD* = 0.3 years; 137 girls and 105 boys). All the participants provided parental consent before participation, and the study was approved by the Ethics Committee for Non-Interventional Studies of the University of XXX, in accordance with the Declaration of Helsinki.

Material

Nonverbal IQ.

To estimate an IQ score, the brief version of the Wechsler Nonverbal Scale of Ability (Wechsler & Naglieri, 2009) was administered. This version contains two subtests: the Matrices subtest and the Spatial Span subtest. In the Matrices subtest, the children had to choose a picture that completed a logical sequence. In the Spatial Span subtest, the participants had to recall the sequence of blocks touched by the experimenter in the same order or in the reverse order. The scores of these items allowed the calculation of the nonverbal IQ score.

Literacy.

Reading. The word and pseudoword decoding task from the BALE battery (Jacquier-Roux et al., 2010) was administered to assess pseudoword decoding and word identification. In this subtest, three lists were presented to the child: one list of 20 regular words, one list of 20 irregular words and one list of 20 pseudowords. During the task, the child was asked to read each list as accurately and as quickly as possible. The number of misread words for each list was used for the analyses.

Spelling. The spelling task from the BALE battery (Jacquier-Roux et al., 2010) was administered to assess spelling skills. The child had to write, during a dictation task, three lists of 10 words composed of regular words, irregular words, and pseudowords. The dependent variable was the number of misspelled words from the three lists.

Rhythmic abilities.

A rhythmic production task inspired by that of Wolff (2002) was assigned to the participants. The task included two phases. First, in a paced condition, the participant had to tap in synchrony with a regular auditory beat. Second, in an unpaced condition, the stimulus disappeared, and the child had

to continue to produce the beat without the stimulus. Two beats were used: one beat at a rate of 1.5 Hz and the other beat at a rate of 2.5 Hz. Each beat was presented for 20 s (paced condition) and was followed by silencing for 20 s (unpaced condition). An accuracy score for the synchronization was prorated for each condition (paced and unpaced) and each frequency (1.5 Hz and 2.5 Hz) by calculating the difference between the mean inter-tap intervals (ITIs) and the interstimulus intervals (ISIs). The mean ITI was calculated on the 15 ITIs in the middle of each block. To assess the synchronization variability, the *SD*s of the 15 ITIs in the middle of each block was calculated. Finally, the accuracy scores and the variability scores were averaged to obtain two variables.

Phonological skills.

Phonological awareness. To assess phonological skills, a phoneme suppression task from the BALE battery (Jacquier-Roux et al., 2010) was administered. In this task, the child had to listen to a word and remove the first phoneme (N=10) or the final phoneme (N=10) to produce a new word. For example, if the experimenter said the word "pari" (*bet*) /pari/, the child had to remove the final sound "i" /i/ and say "par" (*by*) /par/. The number of errors was reported.

RAN. The RAN task from the BALE battery (Jacquier-Roux et al., 2010) was administered. In this task, the child had to name 30 simple objects as quickly and as accurately as possible. The time taken to name all the objects was used as a variable.

Fine motor skills.

The Manual Dexterity subtest from the M-ABC (Henderson & Sudgen, 1992) was administered. The three sections of the subtest evaluate three different components of fine motor skills: unimanual dexterity (Placing Pegs), bimanual coordination (Threading Lace), and visuomotor control (Flower Trail). In the Placing Pegs section, the child had to place 12 pegs on a board as quickly as possible, first with his or her dominant hand and then with his or her nondominant hand. For the Threading Lace section, the child had to thread a shoelace in a plank as quickly as possible. The Flower Trail section is a graphomotor task in which the child had to draw a line between two lines as quickly and as accurately as possible. The scaled scores of the three sections were calculated and averaged to identify children with a deficiency in fine motor skills. The time recorded for the dominant

hand dexterity (Placing Pegs), nondominant hand dexterity (Placing Pegs), and bimanual coordination (Threading Lace) tasks and the number of errors in the visuomotor control task (Flower Trail) were used as variables for the statistical analyses.

Procedure

The assessment of nonverbal IQ, literacy (i.e., decoding and spelling), rhythmic abilities, phonological skills (i.e., RAN and phonological awareness) and motor skills were administered individually by trained researchers. All the tests were divided into two 30-minute sessions. In the first session, the child performed the Placing Pegs unimanual dexterity task, the word reading task, and the rhythmic task. In the second session, the child performed the Threading Lace bimanual coordination task, the final/initial phoneme suppression task, the Matrices subtest, the Flower Trails visuomotor control task, the RAN task, and the Spatial Span subtest. The order of the tests in each session was fixed, but the order of the two individual sessions was counterbalanced. The spelling task was administered collectively in groups of 5 to 20 students.

Statistical Analyses

First, outliers – defined as data points below or above three *SDs* from the mean – were suppressed. Histograms and QQ-plots were examined to assess normality (Gel, Miao, & Gastwirth, 2005). When the normality assumption was not met, transformations were used to normalize the data. Synchronization accuracy, synchronization variability, bimanual coordination, and RAN were corrected using log transformations. Because of the presence of 0 values, regular word reading, word spelling, pseudoword decoding, pseudoword spelling, and visuomotor control were corrected using square-root transformations.

First, correlations between literacy and other skills (rhythmic abilities, phonological skills, and motor skills) were conducted. All the variables were expressed as the number of errors, the recorded times, the variability or deviation from the stimuli (i.e., the accuracy). Hence, for all the variables, a high value indicates a low performance, and vice versa. Therefore, positive correlations were expected between the different variables. A Benjamini and Hochberg correction was applied to account for increased Type I error from the multiple analyses (Benjamini & Hochberg, 2000). Then, to investigate

the relationships among our variables, we conducted confirmatory factor analysis (CFA) and SEM using the lavaan R package version 3.4.4 (R Development Core Team, 2005). To assess how well the model fit the data, different indices were examined: chi-square, comparative fit index (CFI), root mean square error of approximation (RMSEA), and standardized root mean square residual (SRMR). Because the chi-square is sensitive to the sample size and model size (Hu & Bentler, 1998), we decided to accept the model even if the statistic was below the cut-off ($p > .05$). A CFI value larger than .90, an SRMR value less than .09, and an RMSEA value less than .06 indicate a good fit (Hooper, Coughlan, & Mullen, 2008).

Results

The descriptive statistics for the different variables are reported in Table 1. The analysis of the standardized tests shows that the participants achieved scores in accordance with their age.

Table 1

Descriptive statistics for all the observed measures.

Measure	Mean	*SD*	Min	Max
Literacy skills (number of errors)				
Regular word reading (max 20)	2.6	2.3	0	10
Irregular word reading (max 20)	10	4.3	0	19
Pseudoword decoding (max 20)	4.7	2.7	0	13
Regular word spelling (max 10)	3.1	2.4	0	10
Irregular word spelling (max 10)	6.4	2.2	0	10
Pseudoword spelling (max 10)	2.8	2.0	0	9
Rhythm skills				
Synchronization accuracy (ITI differences in ms)	40	25	03	144
Synchronization variability (SD of the ITI differences)	72	33	30	201

Phonological skills				
Phonological awareness (phoneme suppression) (number of errors, max 20)	6.5	4.2	0	17
RAN (time in s)	24.36	5.49	15	43
Fine motor skills				
Dexterity (dominant hand) (time in s)	22.53	3.26	16	31
Dexterity (nondominant hand) (time in s)	25.76	3.67	18	36
Bimanual coordination (time in s)	29.42	8.62	16	60
Visuomotor control (number of errors)	2.05	1.77	0	7

Correlation Analysis

The correlations among measures are reported in Table 2.

Table 2

Correlations between literacy development (i.e., reading and spelling skills) and each of rhythm skills, phonological skills, and fine motor skills.

	Rhythm skills		Phonological skills		Fine motor skills			
	Accuracy	Variability	PA	RAN	MD DH	MD NDH	Bim. C	VMC
Reading skills								
Regular words	.18*	.19*	.23**	.11	.14	.16*	.11	.04
Irregular words	.10	.17*	.24**	.26**	.14	.12	.15*	16*
Pseudowords	.15*	.07	.24**	.10	.15*	.14	.06	.08
Spelling skills								
Regular words	.15	.10	.17*	.21**	.15*	.19*	.08	.08
Irregular words	.17*	.11	.17*	.12	.11	.10	.12	.08
Pseudowords	.20*	.17*	.19*	.14	.06	.04	.12	.10

Note. PA, phonological awareness; RAN, rapid automatized naming; MD, manual dexterity; DH, dominant hand; NDH, nondominant hand; Bim. C, bimanual coordination; VMC, visuomotor control. * $p < .05$; ** $p < .01$; *** $p < .001$ after Benjamini and Hochberg correction.

The literacy scores were significantly correlated with some measures of each of the main predictors (ranges: .17–.23 with rhythm skills, .14–.25 with phonological skills, and .14–.19 with motor skills). Phonological awareness was the most significant variable and was correlated with each literacy outcome (.17–.24), whereas bimanual coordination and visuo-motor coordination were the least significant variables and were correlated with irregular word reading only (correlations of .15 and .16 respectively). It should also be noted that all the literacy variables were significantly correlated with one of the two variables that measure rhythm skills.

Confirmatory Factor Analyses

To test the link between rhythm skills and literacy development, we conducted CFA to verify that the latent variables were adequately represented by the observed measures. A first CFA was conducted that included four latent variables: literacy skills (regular word reading, irregular word reading, pseudoword decoding, regular word spelling, irregular word spelling, and pseudoword spelling), rhythmic abilities (accuracy and variability), phonological skills (phonological awareness and RAN), and motor skills (dexterity of the dominant hand, dexterity of the nondominant hand, bimanual coordination, and visuomotor control). However, because the model did not converge when we constructed a latent variable for phonological skills, we dissociated phonological awareness and RAN. The second CFA included five latent variables: literacy skills (regular word reading, irregular word reading, pseudoword decoding, regular word spelling, irregular word spelling, and pseudoword spelling), rhythmic abilities (accuracy and variability), phonological awareness, RAN and motor skills (dexterity of the dominant hand, dexterity of the nondominant hand, bimanual coordination and visuomotor control). This CFA presented a good fit of the data ($\chi^2(69) = 80.749$, $p = .158$, CFI = .979, RMSEA = .029, SRMR = .042). Except for the visuomotor control variable, the observed variables

significantly represented their corresponding latent variable ($p < .05$). However, because of the good fit indicators, the visuomotor control variable was not excluded from the model.

Mediation Analysis

A model was conducted using SEM to test the mediation effects of phonological awareness, RAN, and motor skills and the direct effect of rhythmic abilities on literacy (see Figure 1). The model fit was good ($\chi^2(72) = 88.723$, $p = .088$, CFI = .971, RMSEA = .034, SRMR = .048). The direct effect of rhythm skills on literacy was significant despite the addition of phonological and motor predictors ($\beta = .36$, $p = .03$). Concerning mediation by phonological skills, the two phonological knowledge variables were strongly related to literacy development (γs = .26 and .20, respectively, both ps < .01). However, the results showed that the effect of rhythmic abilities on literacy skills was not mediated by phonological skills: neither the indirect path by phonological awareness ($\beta = .001$, $p = .94$) nor the indirect path by RAN ($\beta = .03$, $p = .15$) was significant. Similarly, the mediation by motor skills was not significant ($\beta = .005$, $p = .93$), although the relationship between rhythm skills and motor skills was significant ($\beta = 47$, $p = .006$).

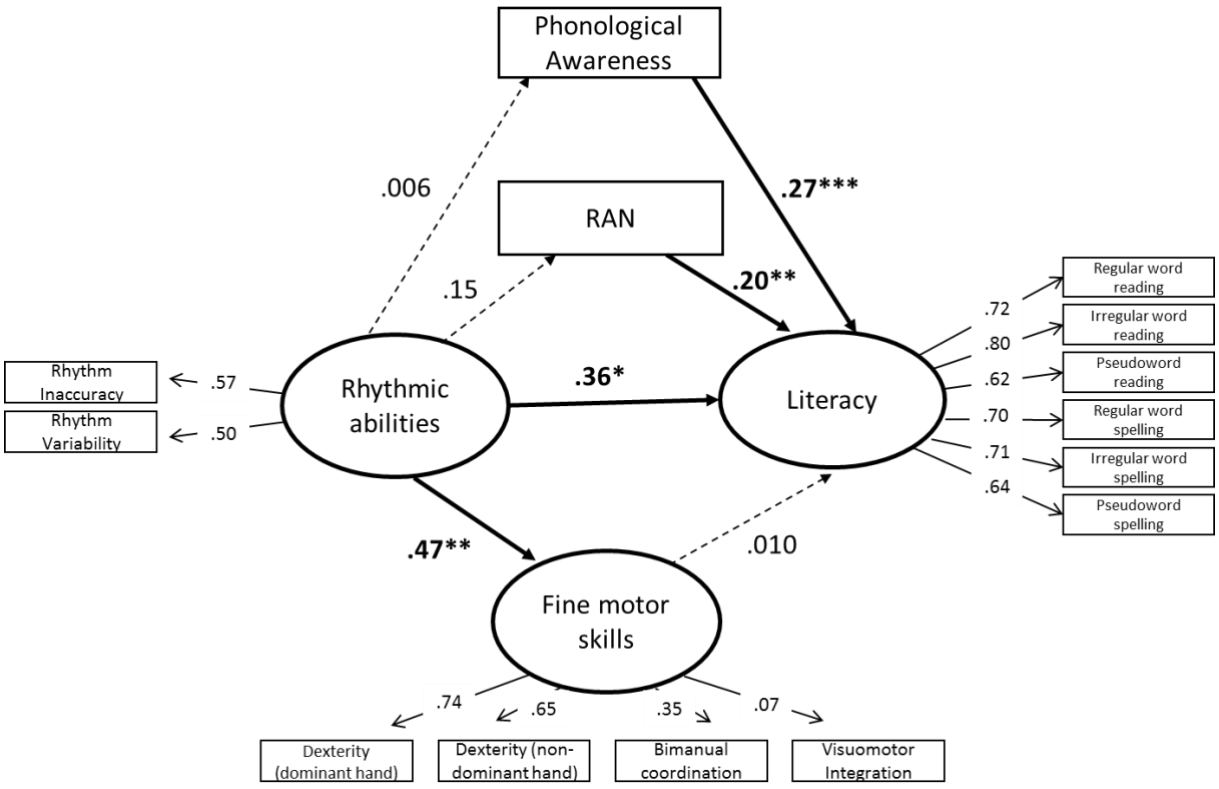

Fig. 1. Mediation model with rhythmic abilities as the predictor, fine motor skills, phonological awareness and RAN as mediator and literacy skills as outcome variables. RAN, rapid automatized naming.

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

Discussion

This study was designed to examine the relationship between rhythmic abilities and literacy development in third graders. This relationship has been repeatedly observed in children with learning disabilities (Corriveau & Goswami, 2009; Huss et al., 2011; Lundetrae & Thomson, 2018; Thomson et al., 2006; Thomson & Goswami, 2008; Wolff, 2002). However, only a handful of studies have been conducted in typically developing children, for which it is also crucial to understand the factors underlying literacy development (David et al., 2007; Ozernov-Palchik et al., 2018b; Zhang et al., 2017). Moreover, this issue has mainly been discussed in young students, and too few studies have been carried out among older students.

The first aim of this study was to determine the *persistence of the relationship* between rhythm skills and literacy development (i.e., reading and spelling) in third graders. Significant correlations were observed between literacy and the two measures of rhythm skills. First, rhythm synchronization was significantly correlated with several measures of reading. This finding is consistent with that observed by David et al. (2007) and Zhang et al. (2017), who found a relationship between rhythm (production and perception) and reading in English-speaking third graders and Chinese-English bilingual third graders. Nonlinguistic measures of rhythm: musical meter perception (Zhang et al., 2017) and tapping in synchrony with a beat (David et al., 2007 and the present study) are positively correlated with reading skills. Since the rhythmic tasks mentioned above did not involve a language component, the relationship between rhythm skills and literacy goes beyond the linguistics aspects. We confirm this result in a large population of French-speaking third graders. Second, our results also suggest that rhythm skills are related to several spelling skills. This result is not surprising, since reading and spelling involve, in part, similar mechanisms (e.g., Ehri, 1997). This result nonetheless extends the data in the current literature, which is, to the best of our knowledge, limited to reading

tasks. In summary, the results here indicate that the relationship between rhythm skills and literacy persists among third graders.

The second objective was to better understand the *factors underlying the relationship* between rhythm skills and literacy. Two hypotheses were contrasted: the hypothesis of mediation by phonological skills and the hypothesis of mediation by motor skills. The SEM analysis allows us to simultaneously examine the joint influence of these two predictors as well as the influence of rhythm skills on literacy development.

The link between rhythm skills and literacy could be mediated first by phonological skills. This hypothesis is the one most often explored in the literature (Goswami, 2011; Ozernov-Palchik & Patel, 2018a) but is almost exclusively explored in children with learning disorders or in younger children. In the present study, we tested this hypothesis in third graders with typical development. Our results do not support the hypothesis that the link between rhythm skills and literacy is mediated through phonological skills. Understanding this lack of mediation requires an examination of the relationship between rhythmic and phonological skills on the one hand and the relationship between phonological skills and literacy on the other hand. The SEM analysis reports that both phonological awareness and RAN significantly influence literacy development in third graders. This result is in line with the data in the literature (Kirby et al., 2003; Roman, Kirby, Parrila, Wade-Woolley, & Deacon, 2009) and confirms that explicit phonological skills play a role in literacy development in third graders.

However, contrary to previous studies (e.g., Huss et al., 2001; Ozernov et al., 2018b), the influence of rhythm skills on phonological skills was not significant. The difference observed in previous studies could therefore be explained by a specific influence of rhythm on phonological skills in students with a low level of phonological awareness (at the beginning of literacy development or in children with learning disorders). Rhythm skills could help children breakdown language chains into sublexical units, such as rhymes or syllables, thus facilitating awareness of the phonological units of language (Goswami, 2011; Moritz, Yampolsky, Papadelis, Thomson, & Wolf, 2013). However, once phonological awareness is initiated, rhythm skills no longer play a decisive role. This explanation appears to disagree with two studies that investigated phonological mediation in third graders. David

et al. (2007) observed an influence of rhythm on phonological awareness in third graders, but this study employed a longitudinal design with measurements of rhythm skills only recorded in first graders. This influence was also reported in third graders by Zhang et al. (2017), but this was among bilingual students whose level of phonological awareness may be lower than expected for grade 3. Our study is therefore the only one to test mediation by phonological skills in monolingual third graders. Another explanation for the non-significant influence of rhythmic skills on phonological skills could result from differences in tasks choices: for example, while we used a rhythm production task, Zhang et al. (2017) used a rhythm perception task that could be more related to phonological skills. In summary, despite the influence of phonological skills (phonological awareness and RAN) on literacy development in third graders, these skills do not mediate the link between rhythm skills and literacy.

The second hypothesis explaining the link between rhythm skills and literacy is that of mediation by motor skills. This hypothesis is based on several studies, which have shown a persistent link between motor and rhythm skills on the one hand (Monier & Droit-Volet, 2019) and motor skills and literacy on the other hand (Doyen et al., 2017; Schmidt et al., 2017). Despite significant correlations, the SEM analysis failed to show that motor skills mediate the link between rhythm skills and literacy in third graders. We decompose below the mediation by motor skills in the same way as we did for the mediation by phonological skills. Rhythm skills significantly influence motor skills. This result is in line with interventional studies of children undergoing music training: a specific form of rhythmic entrainment. Music training indeed enhances children's fine motor skills, suggesting an impact of rhythmic abilities on motor development. For example, five- to seven-year-old children achieved better performance in fine motor skills after one year of learning to play a musical instrument (Schlaug, Norton, Overy, & Winner, 2005), and six-year-olds showed greater relative voxel size in motor areas of the brain after one year of piano instruction (Hyde et al., 2009; for a review, see Miendlarzewska & Trost, 2014). However, motor skills did not significantly influence literacy development in our model. Although it is difficult to interpret an absence of results, several interpretations can be put forward to try to understand this finding. The first explanation is related to the age of the participants. Most studies examining the relationship between motor skills and literacy development assessed students at an early stage of learning (except Schmidt et al., 2017). The

influence of motor skills on literacy development may therefore be more pronounced in younger children. In addition, the tasks used to evaluate motor skills vary from a study to another and this could explain these different results. For example, we include different measures of FMS while other authors have used only paper-pen tasks such as figure and letter copy (i.e. Cameron et al., 2012). Finally, most of the studies conducted to date have performed correlation and regression analyses. In the present study, the use of SEM, which allows the inclusion of different variables within the same model, may reduce the weight of the different variables in the model. These arguments may explain why fine motor skills did not significantly influence literacy development in our study and, therefore, why motor skill mediation was not significant.

Therefore, the relationship between rhythm skills and literacy development in third graders cannot be explained by the involvement of phonological skills or motor skills. These results are not in line with the two hypotheses formulated above but can be explained in two ways.

The first way is to interpret our results as arguments in favor of a direct influence of rhythm skills on learning to read and spell. However, to the best of our knowledge, this possible direct influence has never been discussed in the literature. In kindergarteners, Ozernov et al. (2018b) found a direct influence of rhythm skills on literacy development independent of phonological mediation. However, this link is not interpreted as a direct influence: The authors propose that the link between rhythm skills and literacy may be explained by an intermediate variable that was not measured in their study (i.e., sensitivity to stimulus regularities). This possibility is discussed below.

The second way of interpreting this result is to say that the model does not take into account another variable that could potentially mediate the link between rhythm skills and literacy development. First, this direct effect of non-speech rhythm on literacy could be explained by the involvement of speech rhythm (i.e., prosody). Indeed, to avoid confusion between linguistic and nonlinguistic influences, only non-speech rhythm was evaluated in our study. However, numerous studies have reported an effect of speech rhythm on reading development (Calet, Gutiérrez-Palma, Simpson, González-Trujillo & Defior, 2012; Holliman, Wood & Sheehy, 2010a; 2010b). According to Wood, Wade-Wooley and Holliman (2009), speech rhythm skills influence reading and spelling development through different pathways, such as via vocabulary acquisition, phonological awareness

or morphological awareness. Since non-speech rhythm and speech rhythm are related and could imply common processes (Holliman et al., 2010b), it can be assumed that the influence of rhythm as highlighted in our study actually reflects the influence of speech rhythm. Therefore, the issue of the relationship between speech and non-speech rhythm as well as their distinct effect on literacy development requires further investigation. Second, another mediator could be statistical learning. According to Ozernov and Patel (2018a), the link between rhythm skills and literacy development may be because children who have the best skills to extract regularities in rhythmic patterns would also have better skills to detect statistical regularities in their environment (see also Elleman, Steacy & Compton, 2019). Statistical learning ability is very important for written language development because writing systems consist of regular structures from which patterns must be extracted from noise. Being able to implicitly extract the statistical regularities present in orthography is an important skill for literacy development (Gingras & Senechal, 2018; Perruchet & Pacton, 2006). Both rhythm synchronization and literacy development may require similar learning of statistical sequences. It is therefore conceivable that the link between rhythm and literacy is mediated by statistical learning. However, this assumption has not yet been directly tested. Finally, another potential mediating factor could be executive functions. Some studies reported an influence of executive functions on decoding and spelling (Altemeier, Abbott, & Berninger, 2006; Best, Miller, & Naglieri, 2011; Christopher et al., 2012). Executive functions are also related to rhythm skills (Bailey & Penhume, 2010; Monier & Droit-Volet, 2019; Tierney & Kraus, 2013). For example, Tierney & Kraus (2013) report that sustained attention is correlated to both synchronization and reading ability in teenagers, and they suggested that executive function and attention could explain, in part, the relationship between rhythm skills and reading. Taken together, these results suggest that several alternative factors are related to both literacy development and rhythm skills and could be possible mediators between the two skills.

The results presented in this study provide arguments for a better understanding of the contribution of linguistic and nonlinguistic skills to literacy development. Linguistic skills, and more specifically, phonological skills, explain French-speaking third graders' literacy development (reading and spelling). Beyond this linguistic contribution, nonlinguistic factors also appear to play a key role at this grade level. More specifically, we show that (non-speech) rhythm skills influence literacy

independently of phonological or motor skills. Further studies are needed to continue to explore and model the relationship between rhythm skills and the acquisition of written language to understand its underpinnings. Analyzing the reciprocal influences of rhythm on reading and spelling acquisition with possible mediators - i.e., speech rhythm, statistical learning or executive functions - in the same model could therefore be relevant. Moreover, future studies need to examine the evolution of the relationship between rhythm and literacy development. Cross-sectional studies would provide a better understanding of the role of rhythm in written language acquisition. Given the heterogeneity of the tasks that have been used in the studies conducted so far, a greater consensus in their choice would also be really beneficial to investigate how rhythm skills, motor skills and literacy are related.

Finally, our study may have direct application to literacy development support. Previous studies reported that music and speech rhythm-based interventions improve reading skills in children with dyslexia (e.g., Flaugnacco al., 2015; Thomson et al., 2013). Our results suggest that this benefit could be generalized to typically developing children and, more importantly, that non-speech rhythm training could also be an appropriate training method. Hence, it seems crucial to confirm the efficacy of rhythmic training on reading and writing in children with typical development by using interventional studies.

References

Altemeier, L., Jones, J., Abbott, R. D., & Berninger, V. W. (2006). Executive functions in becoming writing readers and reading writers: Note taking and report writing in third and fifth graders. *Developmental Neuropsychology*, *29*(1), 161–173.

American Psychiatric Association. (2013). *DSM–5 Diagnostic and statistical manual of mental disorders* (5th ed.). Washington, DC: Author.

Bailey, J. A., & Penhune, V. B. (2010). Rhythm synchronization performance and auditory working memory in early- and late-trained musicians. *Experimental Brain Research*, *204*(1), 91–101. Retrieved from https://doi.org/10.1007/s00221-010-2299-y

Best, J. R., Miller, P. H., & Naglieri, J. A. (2011). Relations between executive function and academic achievement from ages 5 to 17 in a large, representative national sample. *Learning and Individual Differences*, *21*(4), 327–336. Retrieved from https://doi.org/10.1016/j.lindif.2011.01.007

Benjamini, Y., & Hochberg, Y. (2000). On the adaptive control of the false discovery rate in multiple testing with independent statistics. *Journal of educational and Behavioral Statistics*, *25*(1), 60-83.

Bhide, A., Power, A., & Goswami, U. (2013). A rhythmic musical intervention for poor readers: A comparison of efficacy with a letter-based intervention. *Mind, Brain, and Education*, *7*(2), 113–123. Retrieved from https://doi.org/10.1111/mbe.12016

Bienkiewicz, M., & Craig, C. M. (2015). Parkinson's is time on your side? Evidence for difficulties with sensorimotor synchronization. *Frontiers in Neurology*, *6*, 249.

Brookman, A., McDonald, S., McDonald, D., & Bishop, D. V. M. (2013). Fine motor deficits in reading disability and language impairment: Same or different? *PeerJ*, *1*, e217. Retrieved from https://doi.org/10.7717/peerj.217

Calet, N., Gutiérrez-Palma, N., Simpson, I. C., González-Trujillo, M. C., & Defior, S. (2015). Suprasegmental phonology development and reading acquisition: A longitudinal study. *Scientific Studies of Reading*, *19*(1), 51-71.

Cameron, C. E., Brock, L. L., Murrah, W. M., Bell, L. H., Worzalla, S. L., Grissmer, D., & Morrison, F. J. (2012). Fine motor skills and executive function both contribute to kindergarten achievement. *Child Development*, *83*(4), 1229–1244. Retrieved from https://doi.org/10.1111/j.1467-8624.2012.01768.x

Cassar, M., & Treiman, R. (1997). The beginnings of orthographic knowledge: Children's knowledge of double letters in words. *Journal of Educational Psychology*, *89*(4), 631–644. Retrieved from https://doi.org/10.1037/0022-0663.89.4.631

Chen, J. L., Penhune, V. B., & Zatorre, R. J. (2008). Listening to musical rhythms recruits motor regions of the brain. *Cerebral Cortex*, *18*(12), 2844–2954.

Christopher, M. E., Miyake, A., Keenan, J. M., Pennington, B., DeFries, J. C., Wadsworth, S. J., . . Olson, R. K. (2012). Predicting word reading and comprehension with executive function and speed measures across development: A latent variable analysis. *Journal of Experimental Psychology: General*, *141*(3), 470–488. Retrieved from https://doi.org/10.1037/a0027375

Cogo-Moreira, H., de Ávila, C. R. B., Ploubidis, G. B., & Mari, J. de J. (2013). Effectiveness of music education for the improvement of reading skills and academic achievement in young poor readers: A pragmatic cluster-randomized, controlled clinical trial. *PLOS ONE*, *8*(3), e59984. Retrieved from https://doi.org/10.1371/journal.pone.0059984

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. Retrieved from https://doi.org/10.1016/j.cortex.2007.09.008

Dalla Bella, S. D., Benoit, C.-E., Farrugia, N., Keller, P. E., Obrig, H., Mainka, S., & Kotz, S. A. (2017). Gait improvement via rhythmic stimulation in Parkinson's disease is linked to rhythmic skills. *Scientific Reports*, *7*, 42005. Retrieved from https://doi.org/10.1038/srep42005

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. Retrieved from https://doi.org/10.1111/j.1467-9817.2006.00323.x

De Castelnau, P., Albaret, J.-M., Chaix, Y., & Zanone, P.-G. (2007). Developmental coordination disorder pertains to a deficit in perceptuo-motor synchronization independent of attentional capacities. *Human Movement Science*, *26*(3), 477–490. Retrieved from https://doi.org/10.1016/j.humov.2007.03.001

Doyen, A.-L., Lambert, E., Dumas, F., & Carlier, M. (2017). Manual performance as predictor of literacy acquisition: A study from kindergarten to Grade 1. *Cognitive Development*, *43*, 80–90. Retrieved from https://doi.org/10.1016/j.cogdev.2017.02.011

Ehri, L. C. (1997). Learning to read and learning to spell are one and the same, almost. In C.A. Perfetti, L. Rieben, M. Fayol (Eds), *Learning to Spell: Research, Theory, and Practice Across Languages* (pp. 237–268).

Elleman, A. M., Steacy, L. M., & Compton, D. L. (2019). The role of statistical learning in word reading and spelling development: More questions than answers. *Scientific studies of reading: the official journal of the Society for the Scientific Study of Reading*, 23(1), 1-7.

Flaugnacco, E., Lopez, L., Terribili, C., Montico, M., Zoia, S., & Schön, D. (2015). Music training increases phonological awareness and reading skills in developmental dyslexia: A randomized control trial. *PLOS ONE*, *10*(9), e0138715.

Fujii, S., & Schlaug, G. (2013). The Harvard Beat Assessment Test (H-BAT): A battery for assessing beat perception and production and their dissociation. *Frontiers in Human Neuroscience*, *7*. Retrieved from https://doi.org/10.3389/fnhum.2013.00771

Gel, Y., Miao, W., & Gastwirth, J. L. (2005). The importance of checking the assumptions underlying statistical analysis: Graphical methods for assessing normality. *Jurimetrics*, *46*, 3.

Gingras, M., & Sénéchal, M. (2019). Evidence of statistical learning of orthographic representations in grades 1–5: The case of silent letters and double consonants in French. *Scientific Studies of Reading*, *23*(1), 37–48. Retrieved from https://doi.org/10.1080/10888438.2018.1482303

Goff, D. A., Pratt, C., & Ong, B. (2005). The relations between children's reading comprehension, working memory, language skills and components of reading decoding in a normal sample. *Reading and Writing*, *18*(7), 583–616. Retrieved from https://doi.org/10.1007/s11145-004-7109-0

Gooch, D., Hulme, C., Nash, H. M., & Snowling, M. J. (2014). Comorbidities in preschool children at family risk of dyslexia. *Journal of Child Psychology and Psychiatry*, *55*(3), 237–246. Retrieved from https://doi.org/10.1111/jcpp.12139

Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Sciences*, *15*(1), 3–10. Retrieved from https://doi.org/10.1016/j.tics.2010.10.001

Goswami, U., & Bryant, P. (2016). *Phonological skills and learning to read*. Hillsdale, NJ: Erlbaum.

Gough, P. B., Ehri, L. C., & Treiman, R. (1992). Reading Acquisition. Hillsdale, NJ: Erlbaum.

Grahn, J. A., & Brett, M. (2007). Rhythm and beat perception in motor areas of the brain. *Journal of Cognitive Neuroscience*, *19*(5), 893–906. Retrieved from https://doi.org/10.1162/jocn.2007.19.5.893

Grissmer, D., Grimm, K. J., Aiyer, S. M., Murrah, W. M., & Steele, J. S. (2010). Fine motor skills and early comprehension of the world: Two new school readiness indicators. *Developmental Psychology*, *46*(5), 1008.

Habib, M., Lardy, C., Desiles, T., Commeiras, C., Chobert, J., & Besson, M. (2016). Music and dyslexia: A new musical training method to improve reading and related disorders. *Frontiers in Psychology*, *7*. Retrieved from https://doi.org/10.3389/fpsyg.2016.00026

Henderson, S., & Sugden, D. (1992). *Movement ABC (Assessment Battery for Children*). London: The Psychological Coop Ltd.

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.

Holliman, A. J., Wood, C., & Sheehy, K. (2010). Does speech rhythm sensitivity predict children's reading ability 1 year later?. *Journal of Educational Psychology*, *102*(2), 356.

Hooper, D., Coughlan, J., & Mullen, M. (2008). Structural equation modelling: Guidelines for determining model fit. *Articles*, *2*.

Hooper, S. R., Swartz, C. W., Wakely, M. B., de Kruif, R. E. L., & Montgomery, J. W. (2002). Executive functions in elementary school children with and without problems in written expression. *Journal of Learning Disabilities*, *35*(1), 57–68.

Hu, L., & Bentler, P. M. (1998). Fit indices in covariance structure modeling: Sensitivity to underparameterized model misspecification. *Psychological Methods*, *3*(4), 424–452. Retrieved from https://doi.org/10.1037/1082-989X.3.4.424

Hulme, C., & Snowling, M. J. (2013). Learning to read: what we know and what we need to understand better. *Child Development Perspectives*, *7*(1), 1–5. Retrieved from https://doi.org/10.1111/cdep.12005

Huss, M., Verney, J. P., Fosker, T., Mead, N., & Goswami, U. (2011). Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology. *Cortex*, *47*(6), 674–689. Retrieved from https://doi.org/10.1016/j.cortex.2010.07.010

Hyde, K., Lerch, J., Norton, A., Forgeard, M., Winner, E., Evans, A., & Schlaug, G. (2009). The effects of musical training on structural brain development. *Annals of the New York Academy of Sciences*, *1169*(1), 182–186.

Jacquier-Roux, M., Lequette, C., Pouget, G., Valdois, S., & Zorman, M. (2010). *BALE: Batterie analytique du langage écrit*. Grenoble: Cogni-Sciences, Laboratoire de Psychologie et NeuroCognition.

Janzen, T. B., Haase, M., & Thaut, M. H. (2019). Rhythmic priming across effector systems: A randomized controlled trial with Parkinson's disease patients. *Human Movement Science*, *64*, 355–365.

Jover, M., Ducrot, S., Huau, A., Bellocchi, S., Brun-Henin, F., & Mancini, J. (2013). Motor disorders in dyslexic children: A review and perspectives. *Enfance*, *4*(4), 323–347.

Kirby, J. R., Parrila, R. K., & Pfeiffer, S. L. (2003). Naming speed and phonological awareness as predictors of reading development. *Journal of Educational Psychology*, 95(3), 453–464. Retrieved from https://doi.org/10.1037/0022-0663.95.3.453

Lundetræ, K., & Thomson, J. M. (2018). Rhythm production at school entry as a predictor of poor reading and spelling at the end of first grade. *Reading and Writing*, *31*(1), 215–237. Retrieved from https://doi.org/10.1007/s11145-017-9782-9

Mann, V., & Singson, M. (2003). Linking morphological knowledge to English decoding ability: Large effects of little suffixes. In E. M. H. Assink, & D. Sandra (Eds.), *Reading complex words: Cross-language studies* (pp. 1–25). Retrieved from https://doi.org/10.1007/978-1-4757-3720-2_1

Miendlarzewska, E. A., & Trost, W. J. (2014). How musical training affects cognitive development: Rhythm, reward and other modulating variables. *Frontiers in Neuroscience, 7*. Retrieved from https://doi.org/10.3389/fnins.2013.00279

Monier, F., & Droit-Volet, S. (2019). Development of sensorimotor synchronization abilities: Motor and cognitive components. *Child Neuropsychology*, *25*(8), 1043–1062. Retrieved from https://doi.org/10.1080/09297049.2019.1569607

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. Retrieved from https://doi.org/10.1007/s11145-012-9389-0

Muter, V., Hulme, C., Snowling, M. J., & Stevenson, J. (2004). Phonemes, rimes, vocabulary, and grammatical skills as foundations of early reading development: Evidence from a longitudinal study. *Developmental Psychology*, *40*(5),665–681. Retrieved from https://doi.org/10.1037/0012-1649.40.5.665

Nithart, C., Demont, E., Metz-Lutz, M.-N., Majerus, S., Poncelet, M., & Leybaert, J. (2011). Early contribution of phonological awareness and later influence of phonological memory throughout reading acquisition. *Journal of Research in Reading*, *34*(3), 346–363. Retrieved from https://doi.org/10.1111/j.1467-9817.2009.01427.x

O'Hare, A., & Khalid, S. (2002). The association of abnormal cerebellar function in children with developmental coordination disorder and reading difficulties. *Dyslexia*, *8*(4), 234–248. Retrieved from https://doi.org/10.1002/dys.230

Overy, K. (2000). Dyslexia, temporal processing and music: The potential of music as an early learning aid for dyslexic children. *Psychology of Music*, *28*(2), 218–229. Retrieved from https://doi.org/10.1177/0305735600282010

Ozernov-Palchik, O., & Patel, A. D. (2018a). Musical rhythm and reading development: Does beat processing matter?: Rhythm and reading development. *Annals of the New York Academy of Sciences*, *1423*(1), 166–175. Retrieved from https://doi.org/10.1111/nyas.13853

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

Pacton, S., Perruchet, P., Fayol, M., & Cleeremans, A. (2001). Implicit learning out of the lab: The case of orthographic regularities. *Journal of Experimental Psychology*: *General*, *130*(3), 401–426. Retrieved from https://doi.org/10.1037/0096-3445.130.3.401

Peng, P., Barnes, M., Wang, C., Wang, W., Li, S., Swanson, H. L., . . . & Tao, S. (2018). A meta-analysis on the relation between reading and working memory. *Psychological Bulletin*, *144*(1), 48.

Perruchet, P., & Pacton, S. (2006). Implicit learning and statistical learning: One phenomenon, two approaches. *Trends in Cognitive Sciences*, *10*(5), 233–238.

Roche, R., Viswanathan, P., Clark, J. E., & Whitall, J. (2016). Children with developmental coordination disorder (DCD) can adapt to perceptible and subliminal rhythm changes but are more variable. *Human Movement Science*, *50*, 19–29. Retrieved from https://doi.org/10.1016/j.humov.2016.09.003

Roman, A. A., Kirby, J. R., Parrila, R. K., Wade-Woolley, L., & Deacon, S. H. (2009). Toward a comprehensive view of the skills involved in word reading in Grades 4, 6, and 8. *Journal of Experimental Child Psychology*, *102*(1), 96–113. Retrieved from https://doi.org/10.1016/j.jecp.2008.01.004

Rosenblum, S., & Regev, N. (2013). Timing abilities among children with developmental coordination disorders (DCD) in comparison to children with typical development. *Research in Developmental Disabilities*, *34*(1), 218–227. Retrieved from https://doi.org/10.1016/j.ridd.2012.07.011

Schaefer, R. S. (2014). Auditory rhythmic cueing in movement rehabilitation: Findings and possible mechanisms. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1658), 20130402. Retrieved from https://doi.org/10.1098/rstb.2013.0402

Schlaug, G., Norton, A., Overy, K., & Winner, E. (2005). Effects of music training on the child's brain and cognitive development. *Annals of the New York Academy of Sciences*, *1060*, 219. Retrieved from https://doi.org/10.1196/annals.1360.015

Schmidt, M., Egger, F., Benzing, V., Jäger, K., Conzelmann, A., Roebers, C. M., & Pesce, C. (2017). Disentangling the relationship between children's motor ability, executive function and academic achievement. *PLOS ONE*, *12*(8), e0182845.

Thomson, J. M., Fryer, B., Maltby, J., & Goswami, U. (2006). Auditory and motor rhythm awareness in adults with dyslexia. *Journal of Research in Reading*, *29*(3), 334–348. Retrieved from https://doi.org/10.1111/j.1467-9817.2006.00312.x

Thomson, J. M., & Goswami, U. (2008). Rhythmic processing in children with developmental dyslexia: Auditory and motor rhythms link to reading and spelling. *Journal of Physiology-Paris*, *102*(1), 120–129. Retrieved from https://doi.org/10.1016/j.jphysparis.2008.03.007

Thomson, J. M., Leong, V., & Goswami, U. (2013). Auditory processing interventions and developmental dyslexia: A comparison of phonemic and rhythmic approaches. *Reading and Writing*, *26*(2), 139–161. Retrieved from https://doi.org/10.1007/s11145-012-9359-6

Tierney, A. T., & Kraus, N. (2013). The ability to tap to a beat relates to cognitive, linguistic, and perceptual skills. *Brain and language*, *124*(3), 225-231.

Treiman, R., & Kessler, B. (2014). *How children learn to write words*. Oxford: Oxford University Press.

Vasuki, P. R. M., Sharma, M., Ibrahim, R., & Arciuli, J. (2017). Statistical learning and auditory processing in children with music training: An ERP study. *Clinical Neurophysiology*, *128*(7), 1270–1281.

Wechsler, D., & Naglieri, J. A. (2009). *WNV: Échelle non verbale d'intelligence: Manuel*. Montreuil, France: EPCA, les Éd. du Centre de psychologie appliquée.

Whitall, J., Chang, T.-Y., Horn, C. L., Jung-Potter, J., McMenamin, S., Wilms-Floet, A., & Clark, J. E. (2008). Auditory-motor coupling of bilateral finger tapping in children with and without DCD compared to adults. *Human Movement Science*, *27*(6), 914–931.

Wolff, P. H. (2002). Timing precision and rhythm in developmental dyslexia. *Reading and Writing*, *15*(1), 179–206. Retrieved from https://doi.org/10.1023/A:1013880723925

Wood, C., Wade-Woolley, L., & Holliman, A. J. (2009). Phonological awareness: Beyond phonemes. In Wood, C., & Connelly, V. (Eds.), *Contemporary perspectives on reading and spelling* (pp. 19-35). London : Routledge.

Zhang, J., Meng, Y., Wu, C., & Zhou, D. Q. (2017). Writing system modulates the association between sensitivity to acoustic cues in music and reading ability: Evidence from Chinese–English bilingual children. *Frontiers in Psychology*, *8*. Retrieved from https://doi.org/10.3389/fpsyg.2017.01965