Rhythm as an independent determinant of developmental dyslexia

Article *in* Developmental Psychology · January 2022

DOI: 10.1037/dev0001293

6 authors, including:

Valentin Bégel
McGill University
31 PUBLICATIONS **382** CITATIONS
SEE PROFILE

Simone Dalla Bella
Université de Montréal
157 PUBLICATIONS **3,745** CITATIONS
SEE PROFILE

Quentin Devignes
McLean Hospital
9 PUBLICATIONS **15** CITATIONS
SEE PROFILE

Delphine Dellacherie
Université de Lille
34 PUBLICATIONS **411** CITATIONS
SEE PROFILE

Developmental Psychology

Rhythm as an Independent Determinant of Developmental Dyslexia

Valentin Bégel, Simone Dalla Bella, Quentin Devignes, Madeline Vandenbergue, Marie-Pierre Lemaître, and Delphine Dellacherie

Online First Publication, January 10, 2022. http://dx.doi.org/10.1037/dev0001293

CITATION

Bégel, V., Dalla Bella, S., Devignes, Q., Vandenbergue, M., Lemaître, M.-P., & Dellacherie, D. (2022, January 10). Rhythm as an Independent Determinant of Developmental Dyslexia. *Developmental Psychology*. Advance online publication. http://dx.doi.org/10.1037/dev0001293

Developmental Psychology

© 2021 American Psychological Association
ISSN: 0012-1649

https://doi.org/10.1037/dev0001293

Rhythm as an Independent Determinant of Developmental Dyslexia

Valentin Bégel[1], Simone Dalla Bella[2, 3, 4], Quentin Devignes[5], Madeline Vandenbergue[1], Marie-Pierre Lemaître[5], and Delphine Dellacherie[1, 6]

[1] ULR 4072–PSITEC–Psychologie: Interactions, Temps, Emotions, Cognition, Lille University
[2] International Laboratory for Brain, Music and Sound Research (BRAMS), Montreal, Quebec, Canada
[3] Department of Psychology, University of Montreal
[4] Department of Cognitive Psychology, University of Economics and Human Sciences in Warsaw
[5] Department of Pediatric Neurology, Centre de Référence Trouble des Apprentissages, University Hospital of Lille
[6] Department of Pediatric Neurology, Centre de Référence Maladies Rares, University Hospital of Lille

Temporal accounts of Developmental Dyslexia (DD) postulate that a timing impairment plays an important role in this learning disorder. However, DD has been associated with timing disorders as well as other motor and cognitive dysfunctions. It is still unclear whether nonverbal timing skills per se may be considered as independent determinants of DD. In this study, we investigated the independent contribution of predictive timing to DD above and beyond the motor and cognitive dysfunctions typically associated with this disorder. Twenty-one children with DD (aged 8–12, nine females) and 27 controls (14 females) were evaluated on perceptual timing, finger tapping, fine motor control, as well as attention and executive tasks. Participants were native French speakers from various socioeconomic backgrounds. The performance of children with DD was poorer than that of controls in most of the tasks. Predictors of DD, as identified by logistic regression modeling, were beat perception and precision in tapping to the beat, which are both predictive timing variables, children's tapping rate, and cognitive flexibility. These data support temporal accounts of DD in which predictive timing impairments partially explain the core phonological deficit, independent from general motor and cognitive functioning, making predictive timing a valuable tool for early diagnosis and remediation of DD.

Keywords: Developmental Dyslexia, rhythm, music, temporal processing

Developmental Dyslexia (DD) is a neurodevelopmental disorder that affects reading skills in 5% to 17% of school-age children (Habib & Giraud, 2013). It manifests as inaccurate fluent word recognition and spelling despite standard education and sociocultural opportunities, normal intelligence, and motivation (Démonet et al., 2004). The prevailing hypothesis is that reading difficulties in dyslexia arise from a core phonological deficit, characterized by a difficulty in accessing or manipulating sound-based, phonological word representations (Stanovich, 1988). However, deficits in DD extend also beyond phonology by encroaching into other motor and cognitive domains, indicating that DD is a multifactorial disorder (Menghini et al., 2010; Perry et al., 2019). Deficits are observed in sensorimotor functions (Ramus, 2003), manual dexterity (Chaix et al., 2007), attention (Stoet et al., 2007), working memory (Beneventi et al., 2010), executive functions (Lewandowska et al., 2014), and timing (Leong & Goswami, 2014). These capacities are variably affected in different DD individuals (Heim et al., 2008). The multifactorial view of DD postulates that this disorder likely results from multiple causes. Thus, probabilistic and multifactorial models of DD present a promising way to account for the multiple deficits characterizing DD, while allowing identification of the most relevant determinant factors of this condition (Pennington, 2006; van Bergen et al.,

---

Valentin Bégel https://orcid.org/0000-0003-4049-1126
Simone Dalla Bella https://orcid.org/0000-0001-9813-7408
Quentin Devignes https://orcid.org/0000-0002-7544-6328
Delphine Dellacherie https://orcid.org/0000-0002-3543-8606

This work was supported by grants from the Fondation Maladies Rares ("Temdance" Grant) to Delphine Dellacherie, Simone Dalla Bella, and Valentin Bégel; the ANRt CIFRE (Conventions Industrielles de Formation par la Recherche) to Valentin Bégel; and the Casavant Chair in Neuropsychology and Music Cognition, and NSERC (RGPIN-2019-05453) to Simone Dalla Bella. We thank all children and their families for their participation in the study, and the two speech therapists, Emilie Ayrolles and Loïc Gamot. We also thank Jessica Slater for her very insightful comments. Data can be transmitted upon request. The study was not preregistered.

The authors declare no competing interests.

Correspondence concerning this article should be addressed to Valentin Bégel, who is now at Department of Psychology, McGill University, 1205 Docteur Penfield Avenue, Montreal, QC H3A 1B1, Canada, or Simone Dalla Bella, Department of Psychology, University of Montreal, CP 6128 Succursale Centre-Ville, Montreal, QC H3C 3J7, Canada, or Delphine Dellacherie, Department of Pediatric Neurology, Centre de Référence Maladies Rares, University Hospital of Lille, 2 Avenue Oscar Lambret, 59037 Lille, France. Email: valentin.begel@mcgill.ca or simone.dalla.bella@umontreal.ca or delphine.dellacherie@univ-lille.fr

2014). Deficits in processing predictable event timing could play an important role in the poor development of reading and literacy skills in DD (Goswami, 2011), together with other difficulties (e.g., phonological and cognitive deficits). A critical question addressed in this study is to what extent deficits in predictive timing can be singled out as independent determinants of DD, above and beyond other motor and cognitive deficits.

Predictive timing refers to the capacity to build temporal expectancies about oncoming events based on previous information (Piras & Coull, 2011). It can be studied via tasks involving the timing of single events, such as predicting the time to contact when intercepting a ball (Lee et al., 1983), or repetitive and predictable rhythmic sequences. Language and music are typical examples of signals with a predictable structure in which the appropriate sequencing and timing of events is critical (Dalla Bella et al., 2013; Kotz & Schwartze, 2010; Ravignani et al., 2019). Their metrical structure comprises alternating patterns of "strong" and "weak" elements, such as accented tones in music and stressed syllables in speech. Prediction of the temporal location of stressed syllables facilitates the processing of syntax embedded in speech (Kotz & Schmidt-Kassow, 2015). In this study, we focus on predictive timing mechanisms involved in processing the highly regular structures of musical rhythm. This can be studied with perceptual or motor tasks using the regular pulse underlying a rhythmic simple or complex auditory sequence (e.g., a metronome or music; Dalla Bella et al., 2017; London, 2012; Repp & Su, 2013).

Evidence of impaired predictive timing in DD is robust. This deficit manifests as inaccurate rhythm perception (Goswami et al., 2013), or increased variability in motor tapping tasks (Leong & Goswami, 2014; Thomson et al., 2006). Recent theories of DD postulate that poor temporal sampling and coding of events affect the treatment of phonological information in DD (Goswami, 2011). From a Temporal Sampling Framework perspective (Goswami, 2011), timing disorders hamper temporal segmentation of the acoustic signal into syllables. This can account for the deficit in syllable stress perception observed in DD (Leong et al., 2011). In speech, stressed syllables occur approximately every 500 ms across languages (2 Hz; Arvaniti, 2009; Dauer, 1983). This frequency is within the range of comfortable music tempi (Ding et al., 2017), and around the preferred spontaneous production rate (McAuley et al., 2006). Therefore, reading and language deficits observed in DD may be explained by difficulties in processing rhythmic information at frequencies around 2 Hz. Consistent with these approaches to DD, measures of reading and language abilities (e.g., phonological awareness, literacy skills) correlate with measures of predictive timing in nonverbal tasks (e.g., when perceiving or producing a musical beat; Bekius et al., 2016; Gordon et al., 2015; Tierney & Kraus, 2013).

Predictive timing is sustained by a complex neuronal network including the dorsal premotor cortex (Chen et al., 2008; Grahn & Brett, 2007), the cerebellum, and the basal ganglia (Coull et al., 2011; Paquette et al., 2017). The cerebellum and the basal ganglia are subcortical structures playing an important role in the temporal processing of linguistic information (De Smet et al., 2013; Kotz & Schwartze, 2010). There is a partial overlap between these regions and the structural and functional brain anomalies linked to impaired phonological processing in individuals with DD (Eckert, 2004; Krishnan et al., 2016). Other cortical dysfunctions have also been consistently reported in DD, in regions such as the left occipito-parietal regions, the inferior frontal gyrus, the primary motor cortex and the anterior insula (for a meta-analysis, see Richlan et al., 2013). These cortical areas are not involved in timing per se, but they are highly connected to both the cerebellum and the basal ganglia (e.g., Daskalakis et al., 2004; Postuma & Dagher, 2006). The partial overlap between cortical and subcortical structures associated with DD and predictive timing networks strengthens the notion that timing may play a role as a determinant of DD.

To date, little effort has been made to single out the determinants of DD among measures of timing abilities (Flaugnacco et al., 2014; Huss et al., 2011). Flaugnacco et al. (2014) categorized children with DD into severe versus moderately impaired based on their phonological skills and used logistic regression to pinpoint the timing measures that differentiate the two groups. The probability of belonging to one of these two groups was predicted successfully by the performance in a rhythm perception and a rhythm reproduction task after controlling for general intelligence, working memory, and auditory attention. However, it is not possible to conclude whether the performance in rhythmic tasks is ultimately a determinant per se of DD, or rather only of its severity, due to the lack of a control group in this study. Other studies (Cancer & Antonietti, 2018; Huss et al., 2011) identified predictive timing tested in perceptual tasks as a determinant of phonological awareness in DD.

These studies did not include extensive testing of attention and executive functions, although these cognitive functions contribute significantly to the representation of duration during development (Droit-Volet, 2013). Executive functions rely on a set of general-purpose control mechanisms that regulate thoughts and behaviors (Miyake & Friedman, 2012). Central executive components include working memory, inhibition, and cognitive flexibility (Diamond, 2013). Attention-based theories of DD, such as the Sluggish Attentional Shifting (SAS) hypothesis, postulate that deficits in attention and executive functions may be causes of reading disorders (Lallier & Valdois, 2012), as DD is associated with difficulties in most attentional and executive functions (Lallier et al., 2010; Lallier & Valdois, 2012; Lewandowska et al., 2014; Stoet et al., 2007). Moura and collaborators (Moura et al., 2014) used a logistic regression approach and identified cognitive flexibility (shifting) as the sole determinant of DD among a variety of tasks testing executive functions (processing speed, planning, and verbal fluency). Cognitive flexibility is defined as the capacity to inhibit a dominant or automatic response and update the content of working memory; it is crucial for switching from one instruction to another in a task and inhibiting the learned responses when moving to the next instruction. This capacity for attentional shifting, especially when processing rapid and sequential stimulus sequences, is impaired in DD (Lallier et al., 2010; Stoet et al., 2007). Notably, executive processes such as cognitive flexibility and working memory are recruited when performing timing tasks, such as interval production and perception (Buhusi & Meck, 2009; Ogden et al., 2014). In addition, recent evidence suggests that cognitive flexibility is related to predictive timing skills in attention-deficit-hyperactivity disorder (ADHD; Puyjarinet et al., 2017).

In summary, it appears that both predictive timing skills and cognitive flexibility may be treated as determinants of DD. Yet, it is still unclear whether these capacities can be distinguished in their contribution to DD, above and beyond other functions. They have not previously been examined together in the same group of children with DD with the goal of pinpointing the independent and unique contribution of each capacity after controlling for other motor and cognitive skills. In addition, the links between (a) motor and cognitive impairments, (b) predictive timing deficits, and (c) impaired reading and language abilities characteristic of DD remain to be elucidated. In the present study, we tested predictive timing with an array of perception and production timing tasks from the Battery for the Assessment of Sensorimotor and Timing Abilities (BAASTA; Dalla Bella et al., 2017) to identify the specific predictive timing mechanisms malfunctioning in DD. These tasks provide a thorough assessment of timing and rhythmic skills and have proven sensitive to interindividual differences in both adults and children (e.g., Bégel et al., 2017; Falk et al., 2015; Puyjarinet et al., 2017). In addition, we tested children's fine motor and cognitive skills, with a focus on skills that are typically impaired in DD (attention, executive functions, working memory, and manual dexterity; Chaix et al., 2007; Lewandowska et al., 2014). We compared children with DD to age-matched typically developing children. To test whether predictive timing measures uniquely contribute to distinguishing children with DD from controls, we used logistic regression modeling. If a deficit in predictive timing is a mere consequence of a more general malfunctioning in other motor and cognitive functions, predictive timing will not appear as an independent determinant of DD. On the contrary, if predictive timing specifically contributes to DD, this factor will increase the probability that a child is classified as a dyslexic, independently from other functions. Finally, we used regression models to test whether there is a linear relationship between variables identified as good predictors in the logistic regression models and reading variables in children with DD.

Method

Participants

Twenty-one children with DD (nine females, four left-handed), aged between 9.3 and 11.8 years (*M* = 10.26, *SD* = .60), were recruited at the Centre Régional de Diagnostic des Troubles d'Apprentissage, at the University Hospital of Lille, France. All children with DD received a complete neurological, neuropsychological, and language assessment by an interdisciplinary team of neurologists, psychologists, and speech therapists. The diagnosis of DD was based on the Diagnostic and Statistical Manual of Mental Disorders-Fourth Edition (*DSM–IV*). Children with DD's reading age, measured with a standardized reading test (Alouette test; Lefavrais, 1965), was delayed by at least 18 months. In addition, they presented at least one deficit in reading or transcription strategies of regular, irregular, or pseudowords (z-score < -2) tested with the Batterie Analytique du Langage Écrit (BALE; Jacquier-Roux et al., 2010). Children general intelligence, tested with the WISC-IV intelligence scale (Wechsler, 2002), was within the normal range (Verbal Comprehension Index: *M* = 103.05, *SD* = 11.21; Perceptual Reasoning Index: *M* = 97.44, *SD* = 17.20; Processing Speed Index: *M* = 93.06, *SD* = 8.84; Working Memory Index: *M* = 88.71, *SD* = 12.97).

Twenty-seven control children (14 females, five right-handed) aged between 9 and 12.8 years (*M* = 10.51, *SD* = 1.01), were recruited at schools and recreation centers in the Lille Area. The two groups did not differ in general intelligence, tested with the Matrix reasoning subtest (control group, *M* = 10.67, *SD* = 2.72; DD group, *M* = 10.51, *SD* = 2.62; $t(39.82) = 1.83$, $p > .05$).

To ensure that our results would not be biased by the well-known heterogeneity of dyslexic profiles, only children with DD without comorbidities were selected for this study. Children with DD who displayed impairments in verbal and/or perceptual reasoning, with sensory deficits, neurological, psychiatric disorders, or who were diagnosed with developmental disorders (ADHD, DCD, or SLI) were not included in the study. Controls with neurological, psychiatric, or sensory antecedents and suspicion of learning or attention disabilities were excluded from the study. In addition, control children with a deficit in one of the five subtests (Matrix reasoning, Coding, Digit span, Letter-number sequencing, and Symbol search) from the WISC-IV intelligence scale (Wechsler, 2002) used to evaluate general cognitive abilities were not included in the study. Finally, children with suspected high intellectual potential (i.e., Matrix reasoning >15) were also excluded from the study.

Considerable efforts were made to select a homogenous group of children without comorbidities, following the procedure presented above. With these strict criteria, the number of participants we could include was limited (48 children in total), although it is a standard sample size for studies in this field. However, groups' homogeneity considerably increases statistical power and interpretability of the results, especially in studies with developmental populations (Jiang et al., 2010). We conducted a priori power analyses with G*Power3 (Faul et al., 2007) to make sure that this sample size was sufficient (see Appendix A).

All participants and their parents signed informed consent to participate in the study, in accordance with the Declaration of Helsinki. This study was conducted in 2015, before the "jardé" law was applied in France (2016). Consequently, as a noninterventional study, it was exempted from the French Ethics Committee (Comité de Protection des Personnes, CPP); the study title is "Rhythm as an independent determinant of Developmental Dyslexia" and the study was not preregistered. The data that support the findings of this study and the analyses codes are available from the corresponding authors upon reasonable request.

Predictive Timing Tasks: BAASTA

Predictive timing was assessed with two perceptual tests (Anisochrony detection and the Beat Alignment Test), and with two sensorimotor tests, namely finger tapping to the beat of a metronome or music (Paced tapping), and Adaptive tapping. Two other perceptual and motor tests were also added to control for children skills in perception of single durations (Duration discrimination) and spontaneous motor rate and variability (Unpaced tapping). Children were tested with a tablet version of BAASTA (Acer Iconia Tab 10 model; Bégel et al., 2018; Puyjarinet et al., 2017). Auditory stimuli were delivered via headphones (Sennheiser HD280). Stimuli were presented at a comfortable sound level (60 dB). In perceptual tasks (Duration discrimination, Anisochrony detection, and Beat Alignment Test [BAT]), responses were provided verbally by the children ("yes" or "no"), and entered by the Experimenter on the tablet interface. "Yes" indicated that the two durations were the same, the auditory sequence (metronome or music) was regular, and that a metronome was aligned with the musical beat. In sensorimotor tasks, children tapped with their index finger on the tablet. The order of perceptual and sensorimotor tasks was counterbalanced across participants.

Perception Tasks

Duration Discrimination. With this test, we assessed duration perception. Two tones were presented (frequency = 1 kHz, interval between tones = 600 ms) and children were asked whether the second tone (target, between 600 and 1,000 ms), was longer than the first (standard, 600 ms) or had the same duration. A perceptual threshold was calculated (Weber fraction, in percent of duration or Inter-Onset-Interval, IOI) based on a 2 down/1 up staircase procedure (for details, see Dalla Bella et al., 2017). The lower the perceptual threshold, the better the performance.

Anisochrony Detection Test With Tones and Music. This test served to assess children's ability to perceive a temporal irregularity (i.e., deviation from the beat). Children judged whether a rhythmic sequence (a metronome, or a musical excerpt) was "regular" or "irregular." Metronome sequences were composed of five tones (tone duration = 150 ms; frequency = 1,047 Hz). Musical sequences were two bars extracted from Bach's "Badinerie" (orchestral suite for flute BWV 1067), played with a piano timbre. In the regular version, isochronous tones or musical beats were played at a constant interval of 750 ms. In the irregular version, tones or musical beats were time shifted by up to 225 ms (30% of the previous intervals). A perceptual threshold was calculated using the same procedure as for Duration discrimination.

Beat Alignment Test (BAT). We tested beat perception by asking children to judge whether a metronome superimposed onto a musical excerpt was or was not aligned to the beat. Musical excerpts were taken from Bach's "Badinerie" and from Rossini's "William Tell Overture" (20 beats each) and were presented at three different tempi (Inter-Beat Interval [IBI], of 450, 600, and 750 ms). After seven beats, a metronome (isochronous tones with a triangle timbre) was superimposed onto the music, either aligned (24 stimuli) or not to the beat. When unaligned, tones occurred earlier or later than the beat by 33% of the quarter note duration (phase shift, 24 stimuli), or the interval between the tones was increased or decreased by 10% of the quarter note duration (period shift, 24 stimuli). Stimuli were presented in a pseudorandomized order. The sensitivity index (d') was calculated, corresponding to the standardized difference between the hits (i.e., when a misaligned metronome was correctly detected) and false alarms (i.e., when a misalignment was erroneously reported); d' was calculated separately for each tempo (450, 600, and 750 ms), and for all the trials.

Production Tasks

Spontaneous Tapping. Rate and motor variability were tested with the Unpaced tapping task. Children were instructed to produce finger taps with their dominant hand at a comfortable rate for 60 s. The task was performed twice, before and after the other production tasks. The first 10 taps were discarded. We computed tapping rate (mean Inter-Tap Interval, ITI), and motor variability as indicated by the coefficient of variation (CV) of the ITI (*SD* of the ITIs/mean ITI).

Paced Tapping. We tested children's capacity to track the beat of rhythmic sequences by asking them to tap to the tones of a metronome or to the musical beat. The sequences included 60 isochronous piano tones (tone frequency = 1319 Hz) or 64-beats musical excerpts taken from Bach's "Badinerie" and from Rossini's "William Tell Overture" (beat = quarter note). The IBI was 600 ms, which is within the range for optimal rhythm perception (Drake & Botte, 1993; London, 2012). Each condition (Metronome and Music) was repeated twice, preceded by a short practice trial. Children were instructed to start tapping after a few beats. The first 10 taps of each trial were discarded. Synchronization of taps to the beat was measured with circular statistics (e.g., for details, see Dalla Bella et al., 2017). Each finger tap is represented by an angle (unitary vector) on a 360° polar scale, in which the circle represents the IBI of the stimuli. The length of resultant vector R is referred to as the synchronization consistency and was considered as the main index for synchronization. Its value varies between 0 (no synchronization) and 1 (perfect synchronization).

Adaptive Tapping. We assessed children's adaptation to a changing pacing stimulus in tapping. Sequences of 10 tones were presented. The first six tones' IOIs were always 600 ms. The next four tones were either presented with the same IOI (no change, one-third of the trials), or at a faster or slower tempo. The changes were either of 30 ms (final IOI of 630 or 570 ms) or 75 ms (final IOI of 675 or 525 ms). Children were instructed to finger tap to the tones, adapt to the changes when they occurred, and continue tapping at the rate indicated by the last tones for a period corresponding to 10 IOIs in the absence of stimulation. Finally, they had to report whether they perceived an acceleration, a deceleration or no change in the sequence at the end of each trial. Ten blocks of six trials (four with tempo change, two without) were presented in random order. Only tapping sequences in which participants synchronized with the metronome and in which there were at least eight taps without outliers in the continuation phase were analyzed. Outlier taps were removed (for details, see Dalla Bella et al., 2017). An adaptation index was computed as a measure of adaptation of tapping to the tempo change (Dalla Bella et al., 2017). Perfect adaptation is indicated by an adaptation index of 1; values lower than 1 indicates undercorrection and values greater than 1 overcorrection. Adaptation indices were calculated separately for tempo increases (i.e., faster tempi with final sequence IOIs of 570 and 525 ms), and tempo decreases (slower tempi with final sequence IOIs of 630 and 675 ms). To measure the sensitivity to the tempo change, d' was also calculated. For all tasks, when there were two trials, the performances in the two trials were averaged.

Motor and Cognitive Assessment

Attention, working memory, and executive functions were assessed for all participants with standardized tests.

Manual Dexterity

We measured unimanual finger and hand dexterity with the Purdue Pegboard (Tiffin & Asher, 1948). Children had to place cylindrical metal pegs in holes (maximum = 25) with their preferred hand. There were three 30-s trials, preceded by a short practice trial. The mean of the number of holes filled in the three trials was the final score.

Attention and Executive Functions

Five tests from the test of Everyday Attention for Children (Manly et al., 2001), administered in the order presented below, were included to assess attentional and executive functions.

Selective Attention. The goal of this task was to find the pairs of identical spaceship drawings (20 target items and 108 pairs of distractors) distributed as quickly as possible. A performance score was calculated based on the number of good pairs of drawings circled and the time taken to do it.

Cognitive Flexibility. This task consisted in counting the number of "creatures" (i.e., little green monsters) visible all along their burrow. Arrows were interspersed among the creatures and pointed either upward or downward. The goal was to begin counting the creatures one by one and to change the direction of counting when the sense of the next arrow was downward, until the last creature was presented. A score based on the number of good responses was calculated, reflecting the capacity to accurately count the creatures despite changes (Cognitive flexibility control, maximum = 7). A composite score of speed processing corresponding to the time divided by the number of good answers was also computed (Cognitive flexibility speed, the lower the score of speed processing, the better).

Divided Attention. The Selective attention task and an auditory attention task consisting in counting the number of sounds (between five and 16 tones) are done at the same time. The number of good responses on the visual and the auditory tasks and the total time spent to complete the test are used to calculate the score. The children stopped the test when they thought they had found all visual stimuli.

Inhibition. This task was a Go/No go task consisting in pointing to a series of squares drawn on a sheet with a felt-tip pen while listening to short sequences of tones (from four to 16 tones). Children were instructed to stop pointing when a different timbre occurred. The rate of presentation of the tones increased progressively. The score is the number of good responses (maximum = 20). This task was not timed, but the stimuli occurred sequentially.

Sustained Attention. Children listened to a stream of spoken digits presented at a rate of one each 2 s. They were asked to detect a particular target sequence (two consecutive "5"), and to report the digit occurring immediately before the sequence. The task lasts 16 min, 40 targets were presented. The score is the number of good responses (maximum = 40).

Short-Term and Working Memory. The standardized score including forward and backward Digit span tasks from the WISC-IV (Wechsler, 2002) was used. Children must repeat numbers in the same order as presented aloud by the examiner (forward Digit span) or in the reverse order of the one presented by the examiner (backward Digit span). This task was not timed.

Statistical Analysis

Normality was tested for each variable (Shapiro-Wilk test) within each group separately. We used *t* tests (normal distribution) and Wilcoxon tests (nonnormal distribution) to compare the performance of controls and children with DD in timing, fine motor, and cognitive tasks.

In predictive timing tasks, an analysis of variance (ANOVA) was used to test the effect of group (Dyslexia vs. Control) as between-subjects factor and tempo (ITI = 450 ms, 600 ms, or 750 ms) as within-subjects factor on the BAT d'. This test addressed the question of whether beat perception was impaired in DD, and if the tempo influenced the performance in each group. In Paced tapping, we tested the effect of the type of stimuli (music or metronome) as within-subjects factor in an ANOVA. The two groups (Dyslexia vs. Control) were entered as between-subjects factor to identify if children with DD were impaired in tapping with simple and complex stimuli. In the adaptative task, ANOVA with direction of change (acceleration or deceleration) and amplitude of change (small or large) as two within-subject factors was carried out on d'(perception) and on the adaptation index (production).

Moreover, tapping to the beat involves both perceptual and motor components. To test whether group and stimulus differences persisted after partialing out the motor component in Paced tapping, analysis of covariance (ANCOVA) was run adding Unpaced motor rate (ITI), variability (CV), and the performance at the Purdue pegboard as covariates. We also used linear regression to further investigate the relation between the perceptual (BAT), motor (Unpaced tapping), and synchronization (Paced tapping) aspects of timing (all data were mean-centered). Analyses were restricted to these tasks, as it was previously shown that the perceptual and motor component of beat perception are highly correlated (Puyjarinet et al., 2017).

We computed Pearson (normal data) and Spearman (nonnormal data) correlations to test the relation between timing and rhythm skills measured with BAASTA and cognitive tasks (see Appendix C). Note that these correlation analyses are exploratory.

We used logistic regression modeling to assess whether timing and rhythm skills can predict DD independently of motor as well as IQ, attentional and executive behavioral measures. Children's group was entered as a binary dependent variable (0 = control, 1 = children with DD) into a logistic regression model. We first included independent variable from the timing and rhythm variables that showed significant differences between the two groups of participants separately for perception and production. Once the best fitting models were obtained with this procedure, other motor and cognitive measures were included one by one to assess the independence of timing and rhythm processes from more general motor and cognitive processes. The best fitting models, based on Akaike's information criterion (AIC; Akaike, 1974; Bozdogan, 1987), are reported. Predicted probabilities based on the model were computed for each variable after controlling for all other variables (i.e., when other variables are set to the mean of the sample). Finally, linear regression models were used to fit the variables identified as significant predictors in the logistic regression with the reading variables in children with DD (data were mean-centered before the analyses).

Note that the presence of extreme cases (i.e., outliers) may influence the analyses. Therefore, we identified extreme cases in all variables. Extreme cases are defined as participants who deviate by more than Q1 – 1.5*Interquartile range (IQR) or less than Q3 –1.5*IQR, where Q1 is the first quartile and Q3 is the third quartile of the whole group median value.

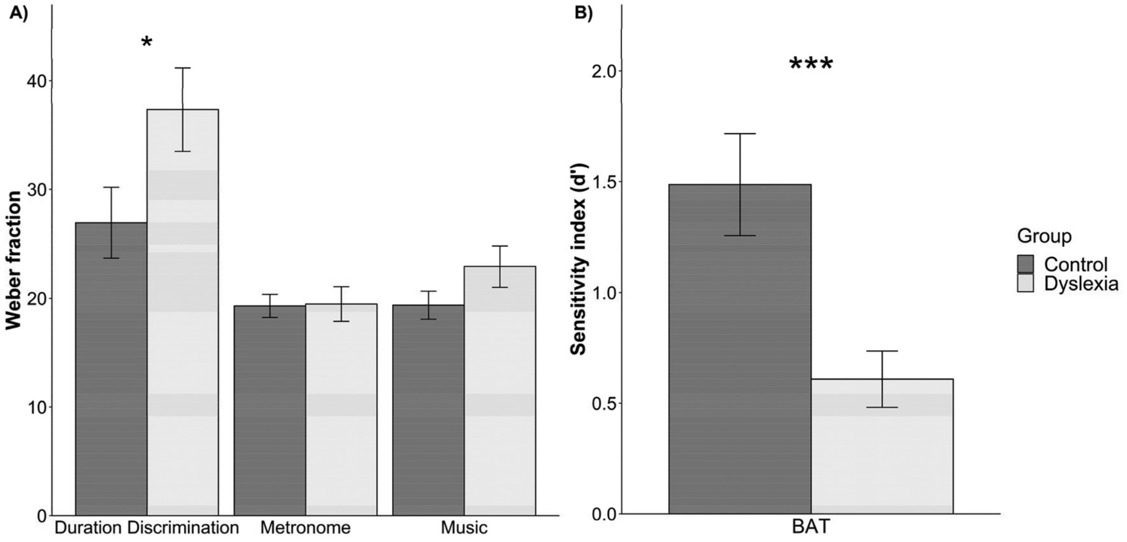
Results

Predictive Timing Skills: BAASTA

Results from the perceptual tasks for children with DD and controls are illustrated in Figure 1. Children with DD showed impaired discrimination of durations ($W = 97.5$, $p < .05$, $d = .54$),

Figure 1

Results Obtained by Controls and Children With DD on All Perceptual Tasks of BAASTA



Note. (A) Duration discrimination, Anisochrony detection with tones and music, (B) BAT. Error bars represent *SEM*. BAASTA = Battery for the Assessment of Sensorimotor and Timing Abilities; DD = Developmental Dyslexia; BAT = Beat Alignment Test. * $p < .05$. *** $p < .005$.

and difficulties in beat perception as revealed by the BAT ($W = 420$, $p < .005$, $d = .68$). For both groups, perception of the alignment of a metronome to the beat of music was worse when music was presented at a faster (i.e., ITI = 450 ms) than at slower tempi (i.e., ITI = 600 and 750 ms; d' fast tempo, $M = .78$, $SD = 1.01$; d' medium tempo, $M = 1.14$, $SD = .97$, d' slow tempo, $M = 1.18$, $SD = 1.16$; $F(1, 46) = 7.39$, $p < .005$, $\eta_p^2 = 2.28$). No interaction was found between group and tempo.

Children with DD tapped at a faster rate than controls (controls, $M = 636.99$ ms, $SD = 93.16$, children with DD, $M = 504.46$ ms, $SD = 89.57$, $t(43.91) = 4.99$, $p < .0001$, $d = 1.45$), as shown in the Unpaced tapping task. However, tapping variability (CV) did not differ significantly between the groups (controls, $M = .10$, $SD = .07$; children with DD, $M = .12$, $SD = .05$). Results from Paced tapping and Adaptive tapping tasks are shown in Figure 2. Children with DD exhibited poorer synchronization to the beat, as revealed by lower synchronization consistency with a metronome and music than controls ($F(1, 45) = 15.21$, $p < .0005$, $\eta_p^2 = .25$). Synchronization was more difficult when tapping to music than to a metronome, for both groups ($F(1, 45) = 19.50$, $p < .0001$, $\eta_p^2 = .30$). There was no interaction between group and stimulus type. Children with DD were still impaired when controlling for variability in Unpaced tapping ($F(1, 44) = 14.20$, $p < .001$, $\eta_p^2 = .24$), Unpaced tapping rate ($F(1, 44) = 10.39$, $p < .01$, $\eta_p^2 = .19$), and Manual dexterity ($F(1, 44) = 9.64$, $p < .005$, $\eta_p^2 = .18$). Moreover, all children tapped earlier than the beat, as revealed by their negative asynchrony (Metronome: controls, $M = -39.49$ ms, $SD = 25.13$, children with DD, $M = -49.75$ ms, $SD = 34.03$; Music: controls, $M = -27.68$ ms, $SD = 40.93$, children with DD, $M = -17.11$ ms, $SD = 58.76$). There was no interaction between group and stimulus type. In both groups, children's asynchrony is significantly different from zero in Paced tapping with a metronome ($t(41) = -9.74$, $p < .0001$, $d = 1.50$), and with music ($t(42) = -3.12$, $p < .005$, $d = .48$). In Adaptive tapping, children with DD adapted as well as controls to acceleration and deceleration ($F(1, 45) = .91$, *ns*). Despite spared motor performance, however, children with DD showed poorer perception of tempo changes than controls ($F(1, 45) = 4.21$, $p < .05$, $\eta_p^2 = .09$). Interaction between the group and the tempo changes was significant ($F(1, 45) = 6.09$, $p < .05$, $\eta_p^2 = .12$). Post hoc tests revealed that the difference between the two groups was visible only for large tempo changes (large tempo: $t(38.22) = 2.68$, $p < .05$, $d = .80$; small tempo: $t(41.32) = .73$, *ns*, Bonferroni corrected).

We computed correlations between Duration discrimination and predictive timing measures in children with DD to test the relation between the deficits in perception of duration and the deficits in predictive timing. None of them reached significance ($p > .05$, no correction for multiple comparisons).

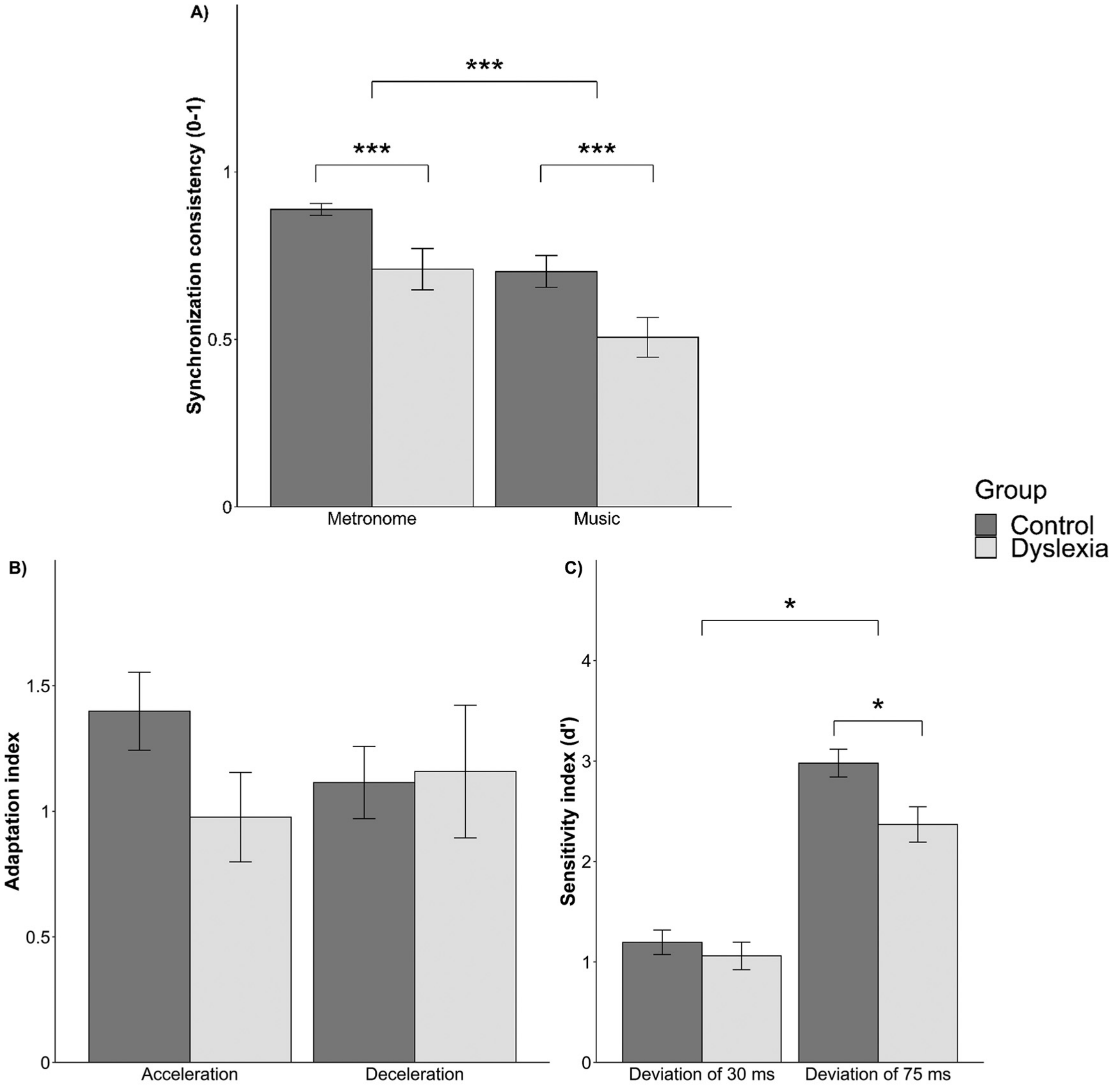
To test the relation between Paced tapping (averaged for metronome and music) and the BAT, we performed a regression analysis showing that the performance at the BAT accounted for synchronization consistency ($R^2 = .59$, $F(3, 43) = 20.33$, $p < .0001$; Main effect of the BAT, $t = 4.46$, $p < .001$, no interaction between the BAT and the group, Appendix B). Individual results in the BAT and synchronization consistency are presented in Figure 3. Results were confirmed after excluding the extreme case in synchronization consistency. The variability in Unpaced tapping did not account for synchronization consistency.

Fine Motor and Cognitive Skills

Differences between controls and children with DD on Manual dexterity and cognitive tasks are presented in Table 1. As can be seen, controls outperformed children with DD in most of the tasks. Note that the sustained attention test that we used involves a working memory component, because the task requires participants to

Figure 2

Results Obtained by Controls and Children With DD on Production Tasks of BAASTA



Note. (A) Paced tapping, (B) (C) Adaptive tapping. Error bars represent *SEM*. BAASTA = Battery for the Assessment of Sensorimotor and Timing Abilities; DD = Developmental Dyslexia.
* $p < .05$. *** $p < .005$.

remember the previous numbers heard. Therefore, difficulties in this task may also arise from working memory constraints.

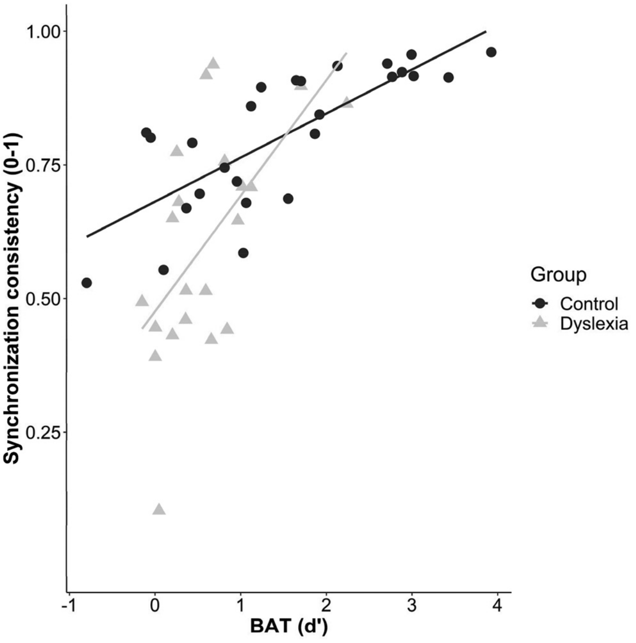
We computed regression analyses to explain the variability at the BAT and Synchronization consistency by Cognitive flexibility, while also taking group as a predictor in the model. The link between BAT, synchronization consistency and Cognitive flexibility has been previously reported (Puyjarinet et al., 2017). These variables were chosen because they have been identified as significant predictors of DD in previous studies (Cancer & Antonietti, 2018; Flaugnacco et al., 2014; Huss et al., 2011; Moura et al., 2014). These variables were also the ones that came out as significant predictors of DD in the logistic regression models (see below, Individual Differences as Determinants of DD). Only the performance on the BAT could be accounted for by Cognitive flexibility (speed; $R^2 = .28$, $F(3, 44) = 5.7$, $p < .01$; effect of Cognitive flexibility—speed—in the model, $t = -2.22$, $p < .05$, Appendix B). There was no interaction with the group. Individual measures at these tasks are presented in Figure 4. Due to the presence of extreme cases in the DD group, we repeated the analyses after discarding these participants (two children, based on their results for Cognitive flexibility, and one child, for Tapping with music). The results were replicated after removal of the outliers.

Individual Differences as Determinants of DD

We used logistic regression to assess whether timing and rhythm perceptual skills (first model) and production skills

Figure 3

Individual Performances in Synchronization Consistency (Averaged Across Stimuli) and the Beat Alignment Test (BAT)



(second model) can be used to determine group membership (control or DD), independently of motor and cognitive measures. Correlations between the predictors of models are presented in Appendix C.

First Model (Perception)

Measures of timing and rhythm perception obtained from BAASTA for dyslexic children and controls were first included as predictors in the model. The variables that did not significantly contribute to the model were identified using the AIC (Akaike, 1974; Bozdogan, 1987). Once the best fitting model based on these measures was identified, Manual dexterity, Divided attention, Sustained attention, Working memory, Inhibition, Cognitive flexibility, and the performance in Unpaced tapping (*M* and CV ITI) were added one by one to the model. The Matrix reasoning subtest from the WISC-IV intelligence scale was also added to control for general intelligence in the model. The variables that did not significantly contribute to the model were not included in the final model. The final model is shown in Table 2. The model fit is highly significant and can correctly identify whether a child belongs to the control or to the DD group in 87% of the cases. Lower performances on the BAT, faster spontaneous tapping rate in Unpaced tapping, and lower speed in Cognitive flexibility independently increase the probability that a child is dyslexic. A reduction of 1 *SD* ($d' = .04$) in the performance on the BAT increases the probability of being classified as dyslexic by 30%. An increased performance of 1 *SD* (40% relative to the group average) in Cognitive flexibility (speed) increases the probability of being classified as dyslexic of 46%. Finally, an increase in Unpaced tapping rate of 1 *SD* (i.e., ITI of 467 ms) increases the probability of being classified as dyslexic by 47%.

Second Model (Production)

The same procedure as above was applied but taking the performances on the production tasks of BAASTA as predictors. The final model is reported in Table 2. The model provides a highly significant fit and can correctly classify children to the DD or the control group in 87% of the cases. The probability that the participant is classified as dyslexic increases by 47% when the participant had faster Unpaced rate of 1 *SD* in comparison with the group mean. Among rhythm production tasks, synchronization consistency also came out as a significant predictor, even though the effect is marginal when adding Cognitive flexibility (control). A score of 1 *SD* below the mean of the group in synchronization consistency increases the chance that a child is classified as dyslexic by 10%, and by 44% for Cognitive flexibility (control).

It is important to note that the two models yielded similar results when excluding three children with DD that were considered as potential outliers based on their results in Cognitive flexibility (two children) and in Tapping with music (one child). The models without the outliers are presented in Appendix D. The fact that the significance of the independent variables are not influenced by the presence or absence of these participants shows the robustness of the models.

The models with other variables are presented in Appendix E. The perceptual model with the Cognitive flexibility control index has a lower AIC, but none of the variables were significant predictors ($p > .05$). In addition, classification with this model was correct in 100% of the cases, meaning that all participants were assigned to the correct group. Even if this model has strengths, it has to be interpreted cautiously. Sustained attention is also a significant factor when added to the Production model, and both *M* ITI and Tapping with music (Synchronization consistency) are

Table 1

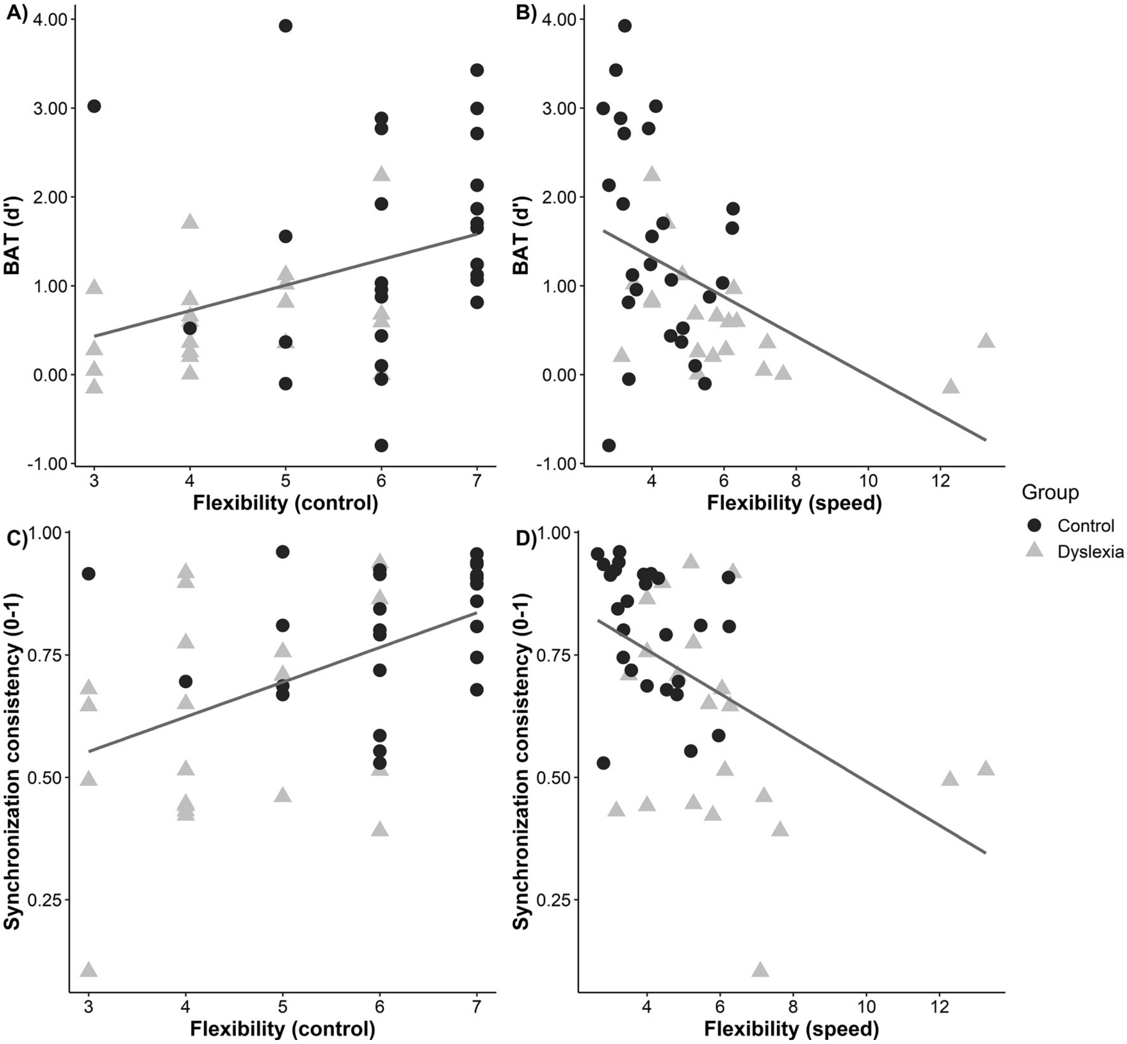
Results Obtained by Controls and Children With DD on the Motor and Cognitive Tasks

Task	Controls *M* (*SD*)	Children with DD *M* (*SD*)	Test value	*p*	*d*
Manual dexterity	14.4 (1.2)	13.3 (1.3)	$W = 414.5$	<.005	0.66
Selective attention	3.8 (1.3)	3.7 (1.1)	$t(45.7) = 0.4$	.36	0.10
Divided attention	1.8 (3.3)	4.7 (4.4)	$W = 152$	<.005	0.66
Sustained attention	36.3 (2.7)	31.6 (6.1)	$t(26.0) = 3.3$	<.01	1.05
Working memory	10.3 (2.5)	8.0 (3.5)	$t(28.1) = 2.3$	<.05	0.76
Inhibition	14.8 (2.5)	12.0 (2.6)	$t(42.0) = 3.8$	<.001	1.12
Cognitive flexibility					
Control	6.1 (1.0)	4.4 (1.0)	$W = 491.5$	<.001	1.02
Speed	4.1 (1.1)	6.1 (2.5)	$W = 118$	<.001	0.81

Note. DD = Developmental Dyslexia. Statistical comparisons of the two subgroups are reported.

Figure 4

Scatter Plots of the Relations Between Cognitive Flexibility and Predictive Timing



Note. Regressions line for the two groups taken together are presented.

significant. Nevertheless, the overall model fit is lower than the one with Cognitive flexibility (control).

We included the variables identified as determinants of DD in the logistic regression models (*M* ITI, BAT -d'-, Tapping Music -Synchronization consistency-, Cognitive flexibility -speed-, and Cognitive flexibility -control-) as independent variables in linear regression models with reading variables (regular, irregular, and nonwords reading and transcription) as dependent variables in the DD group. An effect of BAT on nonword reading (R^2 = .27, F(1, 15) = 5.50, $p < .05$, Appendix B) and irregular word transcription (R^2 = .27, F(1, 15) = 5.43, $p < .05$, Appendix B) were found. An effect of Cognitive flexibility -control- on regular word reading (R^2 = .55, F(1, 16) = 9.19, $p < .05$, Appendix B) and irregular word transcription (R^2 = .26, F(1, 16) = 2.31, $p < .05$, Appendix B) were also found. A marginally significant effect ($p < .1$) was found for tapping with music and irregular word transcription. No effects were found for Cognitive flexibility (speed).

Discussion

The present study aimed at examining the independent contribution of predictive timing disorders to DD after controlling for motor and cognitive skills in children with DD. The results revealed that poor performances of DD children in both perceptual and sensorimotor predictive timing tasks on the one hand and in a cognitive flexibility task on the other hand acted as independent determinants of DD among various nonphonological variables. To the best of our knowledge, this is the first time that the independent contributions of predictive timing and cognitive flexibility to DD have been highlighted.

Children with DD exhibit deficits in predictive timing, including the perception of the beat (Goswami et al., 2013), as well as synchronization with a metronome (Thomson & Goswami, 2008) and with music (Overy et al., 2003). Here we found that these deficits are still observed when controlling for Unpaced tapping rate and variability as well as fine motor control (i.e., manual dexterity). Children with DD had a faster spontaneous rate than controls, but

Table 2
Logistic Regressions

	Null −2LL = −11.98, final −2LL = −32.89, $\chi^2 = 41.83$, $p < .001$; Nagelkerke $R^2 = 0.78$; AIC = 31.96				
Statistics predictor	B	*SE* (β)	Exp (β)	Wald test	*p*
First model					
Intercept	16.08	6.29	NA	2.51	<.05
Mean ITI	−0.04	0.01	0.96	−2.92	<.005
BAT (*d*′)	−1.80	0.88	0.16	−2.05	<.05
Cognitive flexibility (speed)	1.28	0.62	3.60	2.07	<.05
	Null −2LL = −9.68, final −2LL = −32.39, $\chi^2 = 46.43$, $p < .001$; Nagelkerke $R^2 = 0.83$; AIC = 27.36				
Statistics predictor	B	*SE* (β)	Exp (β)	Wald test	*p*
Second model					
Intercept	34.80	12.34	NA	2.82	<.01
Mean ITI	−0.04	0.14	1.15	−2.62	<.01
Tapping music (synchronization consistency)	−0.69	0.39	1.48	−1.78	<.1
Cognitive flexibility (control)	−2.60	0.95	2.59	−2.74	<.01

Note. AIC = Akaike's information criterion; BAT = Beat Alignment Test; NA = not available.

their variability in self-paced tapping was similar. Children with DD's poor performance in predictive timing, tested with a perceptual task (BAT), shows that their difficulties in predictive timing are not merely due to poor motor performance. Indeed, these difficulties arise when tracking a beat even in the absence of a motor response. In addition, children with DD have displayed difficulties with the perception of single durations (Casini et al., 2018), a deficit we confirmed in the Duration discrimination task; yet, this deficit was not correlated with predictive timing measures, suggesting that poor coding of single durations is not the cause of predictive timing impairments. Partly independent mechanisms may be involved when performing a predictive timing task and a duration perception task (Puyjarinet et al., 2017).

Children with DD also showed deficits in fine motor skills (manual dexterity) and cognitive functioning (divided and sustained attention, working memory, inhibition, and cognitive flexibility), which is in keeping with previous studies (Chaix et al., 2007; Menghini et al., 2010). Nevertheless, among these multiple candidates which could be determinant in DD, the logistic regression allowed us to identify the best predictors of DD: beat perception and precision in tapping to the beat which are both predictive timing variables, children's tapping rate, and cognitive flexibility. Fine motor control did not appear as a significant independent variable above and beyond timing skills. Cognitive flexibility came out as a determinant of DD along with tapping rate and predictive timing measures. Sustained attention also came out as a significant factor when associated with rhythm production variables, even if the general fit of the model was better with cognitive flexibility. Interindividual differences at the BAT, a perceptual beat processing task, were crucial to identify whether children belonged to the DD group or the control group. This identification was better than that obtained with a production task (Paced tapping with music), and scores at the BAT were also better predictors of reading skills than Paced tapping in children with DD. Note that the BAT and Paced tapping with music are highly correlated, implying that overall, the capacity to track the beat in a musical sequence is an important determinant of DD. This suggests that mechanisms of predictive timing rely on a strong association between perception and action that is affected in DD. A faster Unpaced tapping rate was also a significant factor independently from other fine motor control or cognitive components.

The links between reading skills and the predictive timing skills identified as a predictor of DD have already been highlighted in other studies. Tierney and Kraus (2013) showed that correlations between synchronization with a metronome and reading exist in typically developing adolescents. This association was also demonstrated in kindergarteners (Ozernov-Palchik et al., 2018) and in school-age children (Bonacina et al., 2020). The authors found that rhythm and meter perception accounted for phonological awareness and letter-sound knowledge. In the current study, we found relatively limited correlations between predictive timing and phonological skills. The reading tests used may not be sensitive enough to highlight all the correlations between predictive timing skills and reading skills. However, it is important to note that reading variables were available only for participants in the DD group. Further studies will be needed to identify the links between rhythmic and cognitive skills, notably the ones identified as predictors of DD in this study, and reading proficiency as a continuous outcome variable in good and poor readers.

Generally, there are well known relations between music processing and reading abilities; it has been suggested that the ability to process music, and in particular rhythm, could influence development of reading skills during development. Difficulties in music processing have been reported in DD, and positive correlations between global musical skills (pitch and rhythm processing) and reading skills have been demonstrated (Couvignou et al., 2019). Impaired predictive timing and rhythm is not uniquely a hallmark of DD. Timing deficits can be found across other neurodevelopmental disorders affecting language and reading skills, such as stuttering (Falk et al., 2015; Wieland et al., 2015) and specific language impairment (Corriveau et al., 2007), suggesting a major contribution of beat tracking abilities in language and speech development. However, these abilities as well as cognitive flexibility are impaired in other developmental pathologies which do not affect verbal skills such as ADHD (Puyjarinet et al., 2017). ADHD and DD may share overlapping etiologies, though, as comorbidities between ADHD and DD are found in about 15% to 45% of cases (Germanò et al., 2010).

The ability to synchronize with a musical beat (synchronization consistency) was a marginally significant predictor when adding cognitive flexibility in the model. This finding is consistent with the observed correlation between cognitive flexibility and synchronization consistency. This association suggests that these capacities may partly rely on common mechanisms, in keeping with attention-based theories of DD (Lallier & Valdois, 2012). For example, the SAS hypothesis postulates that the automatic processes engaged in attentional shifting over rapid and sequential stimulus sequences are impaired in DD (Lallier et al., 2010; Stoet et al., 2007). This difficulty may also affect synchronization. The SAS hypothesis assumes that the attentional system in dyslexics cannot disengage from one item to shift attention to the following one. Attentional shifting is a subcomponent of cognitive flexibility (Miller & Cohen, 2001).

In the current study, cognitive flexibility was identified as the best nontemporal determinant of DD. It was tested in a task consisting in counting little creatures one by one and changing the direction of counting when arrows were presented. This sequential task (i.e., counting) is typically realized at a periodic scale close to the one of a musical beat or stressed syllables in language. Children with DD were slower and less precise than control participants, meaning that they struggled to change the direction of counting. The precision index of the cognitive flexibility task (Cognitive flexibility control), which does not take speed into account, was a significant determinant of DD. This result suggests that difficulties in this task in DD reflect actual cognitive flexibility difficulties and not simply an overall slowness that would also affect cognitive flexibility. A lack of attentional resources allocated to successive events may explain these difficulties in counting and could be worsened by changes in the instructions. Note that a similar shifting task has been identified as a determinant of DD in a previous study (Moura et al., 2014), confirming the important role played by cognitive flexibility in DD. In a recent study on ADHD (Puyjarinet et al., 2017), it was also shown that patients who had good beat tracking skills performed better than poor trackers on a cognitive flexibility task. Cognitive flexibility and executive functioning are enhanced in musically trained individuals, who also have enhanced predictive timing skills (Bailey & Penhune, 2010; Zuk et al., 2014). Overall, there is growing evidence that shared mechanisms partially govern these functions.

Structural and functional brain differences between children with DD and controls have been described (Eckert, 2004; Stoodley & Stein, 2013), including in areas involved in the predictive timing circuitries (i.e., the basal ganglia and the cerebellum; Chen et al., 2008; Coull et al., 2011; Grahn & Brett, 2007; Kotz & Schwartze, 2010; Paquette et al., 2017). Cerebellar deficits (Nicolson & Fawcett, 2019) and dysfunctions of the functional networks involving the cerebellum, the motor and premotor cortices, and the basal ganglia are likely to explain difficulties in perceptual (Coull et al., 2011; Grahn & Brett, 2007) and sensorimotor rhythmic skills (Coull et al., 2011; Doyon & Benali, 2005) that have been found in DD. The neuronal networks involved in predictive timing and in cognitive flexibility are mainly independent, but overlap in the premotor cortex; this may explain the link we found between these capacities.

Dysfunctions in oscillatory brain mechanisms are also possible candidates to explain dyslexics' difficulties in language and reading, as suggested by the "temporal sampling" theory of DD (Goswami, 2011). It is considered that neural oscillations allow the allocation of attentional resources to specific points in time to anticipate when an event is likely to occur (Nozaradan et al., 2015). Rhythmic neural entrainment is also crucial in sensory perception of speech to build temporal predictions about speech timing (Giraud & Poeppel, 2012; Kösem et al., 2018). Predictive timing tasks identified as determinants of DD in this study involved stimuli with interbeat intervals of 1.66 Hz (600 ms). Speech involves stressed syllables that occur at similar quasi-periodic intervals (approximately 500 ms, or 2 Hz; Arvaniti, 2009; Goswami, 2011). This implies that verbal and nonverbal predictive timing impairments at this timescale, possibly stemming from dysfunctional brain oscillatory mechanisms, can have negative consequences for the acquisition of reading and language skills in DD.

From the multifactorial view of DD (Pennington, 2006; van Bergen et al., 2014), it is possible that predictive timing and cognitive flexibility account for only a subset of DD profiles (Heim et al., 2008). Reading difficulties in some dyslexic individuals may be better explained by disturbed functions such as visual (Perry et al., 2019) or basic auditory processing skills than phonological core deficits (Hämäläinen et al., 2013). Finally, timing deficits may not be always present in DD, as illustrated by dyslexic musicians, who have equivalent predictive timing skills to musicians without dyslexia (Bishop-Liebler et al., 2014; Weiss et al., 2014; Zuk et al., 2017). In these individuals, disrupted predictive timing skills are not likely to explain reading deficits. Therefore, further investigations are required to identify the predictors of the different profiles of DD.

The findings of this study corroborate recent evidence that training rhythmic skills is important in DD (Bonacina et al., 2015; Flaugnacco et al., 2015; Habib et al., 2016; Thomson et al., 2013) showed that a rhythmic intervention improved children with DD's reading skills in the same proportions as a phoneme discrimination intervention. However, the authors did not address interindividual differences in their study. Each intervention may have been more efficient in a subset of participants. Recently, Cancer and collaborators (Cancer et al., 2020) also showed that a rhythmic intervention program was as efficient as a program combining two yet validated treatments for dyslexia (Bakker's Visual Hemisphere-Specific Stimulation and the Action Video Game Training), even if the effect of each training program was more evident for different aspects of reading. Training executive functions also seems to improve reading skills in DD (Pasqualotto & Venuti, 2020), but the effect has never been compared with that of a rhythmic training program. Further investigations are needed, considering interindividual differences in dyslexia, to tailor interventions to each individual's skills.

Participants in the current study were French speakers. French is considered as a syllable-timed language, meaning that stress syllables are spoken at intervals that are less regular than in stress-timed languages such as English (Scott et al., 1985). One may hypothesize that predictive timing deficits lead to reading and language difficulties only in stress-timed languages, because the timing of syllables is meaningful (Dupoux et al., 1997). However, the results of our study confirm that timing deficits may cause reading and language deficits even in syllable-timed language speakers (Cancer & Antonietti, 2018; Flaugnacco et al., 2014).

In summary, our study clearly identifies the performance in tasks involving sequential processing of stimuli at about 2 Hz as determinants of DD, independently from other cognitive and motor factors. This deficit of predictive timing could partially explain dyslexics' difficulties in processing verbal and nonverbal rhythmic stimuli. Consequently, efforts should be made to develop protocols to train dyslexics' skills in processing rhythmic stimuli around 2 Hz. Such longitudinal studies are also important to confirm the causal link between predictive timing and reading skills. Rhythmic training protocols have already been tested in DD, yielding encouraging results (Bonacina et al., 2015; Thomson et al., 2013). New approaches based, for instance, on tapping or dancing to increasingly complex stimuli (Bégel et al., 2018; Dauvergne et al., 2018), with a focus on musical material, can be used to train perceptual and sensorimotor predictive timing skills. This kind of training would directly target mechanisms identified as determinants of DD in this study. As proposed by recent works (Bégel et al., 2017, 2018; Dauvergne et al., 2018), training can be implemented in video games, which have proven to have a positive impact on DD (Franceschini et al., 2017), and could increase the accessibility of training.

References

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control*, *19*(6), 716–723. https://doi.org/10.1109/TAC.1974.1100705

Arvaniti, A. (2009). Rhythm, timing and the timing of rhythm. *Phonetica*, *66*(1–2), 46–63. https://doi.org/10.1159/000208930

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. https://doi.org/10.1007/s00221-010-2299-y

Bégel, V., Benoit, C.-E., Correa, A., Cutanda, D., Kotz, S. A., & Dalla Bella, S. (2017). "Lost in time" but still moving to the beat. *Neuropsychologia*, *94*, 129–138. https://doi.org/10.1016/j.neuropsychologia.2016.11.022

Bégel, V., Di Loreto, I., Seilles, A., & Dalla Bella, S. (2017). Music games: Potential application and considerations for rhythmic training. *Frontiers in Human Neuroscience*, *11*, 273. https://doi.org/10.3389/fnhum.2017.00273

Bégel, V., Seilles, A., & Dalla Bella, S. (2018). Rhythm workers: A music-based serious game for training rhythm skills. *Music & Science*, *5*(1), 1–7. https://doi.org/10.1177/2059204318794369

Bégel, V., Verga, L., Benoit, C.-E., Kotz, S. A., & Dalla Bella, S. (2018). Test-retest reliability of the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA). *Annals of Physical and Rehabilitation Medicine*, *61*(6), 395–400. https://doi.org/10.1016/j.rehab.2018.04.001

Bekius, A., Cope, T. E., & Grube, M. (2016). The beat to read: A cross-lingual link between rhythmic regularity perception and reading skill. *Frontiers in Human Neuroscience*, *10*, 425. https://doi.org/10.3389/fnhum.2016.00425

Beneventi, H., Tønnessen, F. E., Ersland, L., & Hugdahl, K. (2010). Working memory deficit in dyslexia: Behavioral and FMRI evidence. *International Journal of Neuroscience*, *120*(1), 51–59. https://doi.org/10.3109/00207450903275129

Bishop-Liebler, P., Welch, G., Huss, M., Thomson, J. M., & Goswami, U. (2014). Auditory temporal processing skills in musicians with dyslexia. *Dyslexia*, *20*(3), 261–279. https://doi.org/10.1002/dys.1479

Bonacina, S., Cancer, A., Lanzi, P. L., Lorusso, M. L., & Antonietti, A. (2015). Improving reading skills in students with dyslexia: The efficacy of a sublexical training with rhythmic background. *Frontiers in Psychology*, *6*, 1510. https://doi.org/10.3389/fpsyg.2015.01510

Bonacina, S., Krizman, J., Schwoch, T. W., Nicol, T., & Kraus, N. (2020). Distinct rhythmic abilities align with phonological awareness and rapid naming in school-age children. *Cognitive Processing*, *21*, 575–581. https://doi.org/10.1007/s10339-020-00984-6

Bozdogan, H. (1987). Model selection and Akaike's Information Criterion (AIC): The general theory and its analytical extensions. *Psychometrika*, *52*(3), 345–370. https://doi.org/10.1007/BF02294361

Buhusi, C. V., & Meck, W. H. (2009). Relative time sharing: New findings and an extension of the resource allocation model of temporal processing. *Philosophical Transactions of the Royal Society of London: Series B, Biological Sciences*, *364*(1525), 1875–1885. https://doi.org/10.1098/rstb.2009.0022

Cancer, A., & Antonietti, A. (2018). Rapid automatized naming, verbal working memory, and rhythm discrimination as predictors of reading in Italian undergraduate students with and without dyslexia. *Brain Sciences*, *8*(5), 87. https://doi.org/10.3390/brainsci8050087

Cancer, A., Bonacina, S., Antonietti, A., Salandi, A., Molteni, M., & Lorusso, M. L. (2020). The effectiveness of interventions for developmental dyslexia: Rhythmic reading training compared with hemisphere-specific stimulation and action video games. *Frontiers in Psychology*, *11*, 1158. https://doi.org/10.3389/fpsyg.2020.01158

Casini, L., Pech-Georgel, C., & Ziegler, J. C. (2018). It's about time: Revisiting temporal processing deficits in dyslexia. *Developmental Science*, *21*(2), e12530. https://doi.org/10.1111/desc.12530

Chaix, Y., Albaret, J. M., Brassard, C., Cheuret, E., de Castelnau, P., Benesteau, J., Karsenty, C., & Démonet, J. F. (2007). Motor impairment in dyslexia: The influence of attention disorders. *European Journal of Paediatric Neurology*, *11*(6), 368–374. https://doi.org/10.1016/j.ejpn.2007.03.006

Chen, J. L., Penhune, V. B., & Zatorre, R. J. (2008). Moving on time: Brain network for auditory-motor synchronization is modulated by rhythm complexity and musical training. *Journal of Cognitive Neuroscience*, *20*(2), 226–239. https://doi.org/10.1162/jocn.2008.20018

Corriveau, K., Pasquini, E., & Goswami, U. (2007). Basic auditory processing skills and specific language impairment: A new look at an old hypothesis. *Journal of Speech, Language, and Hearing Research*, *50*(3), 647–667. https://doi.org/10.1044/1092-4388(2007/046)

Coull, J. T., Cheng, R.-K., & Meck, W. H. (2011). Neuroanatomical and neurochemical substrates of timing. *Neuropsychopharmacology*, *36*(1), 3–25. https://doi.org/10.1038/npp.2010.113

Couvignou, M., Peretz, I., & Ramus, F. (2019). Comorbidity and cognitive overlap between developmental dyslexia and congenital amusia. *Cognitive Neuropsychology*, *36*(1–2), 1–17. https://doi.org/10.1080/02643294.2019.1578205

Dalla Bella, S., Białuńska, A., & Sowiński, J. (2013). Why movement is captured by music, but less by speech: Role of temporal regularity. *PLoS ONE*, *8*(8), e71945. https://doi.org/10.1371/journal.pone.0071945

Dalla Bella, S., Farrugia, N., Benoit, C. E., Begel, V., Verga, L., Harding, E., & Kotz, S. A. (2017). BAASTA: Battery for the Assessment of Auditory Sensorimotor and Timing Abilities. *Behavior Research Methods*, *49*(3), 1128–1145. https://doi.org/10.3758/s13428-016-0773-6

Daskalakis, Z. J., Paradiso, G. O., Christensen, B. K., Fitzgerald, P. B., Gunraj, C., & Chen, R. (2004). Exploring the connectivity between the cerebellum and motor cortex in humans. *The Journal of Physiology*, *557*(Pt. 2), 689–700. https://doi.org/10.1113/jphysiol.2003.059808

Dauer, R. M. (1983). Stress-timing and syllable-timing reanalyzed. *Journal of Phonetics*, *11*(1), 51–62. https://doi.org/10.1016/S0095-4470(19)30776-4

Dauvergne, C., Bégel, V., Gény, C., Puyjarinet, F., Laffont, I., & Dalla Bella, S. (2018). Home-based training of rhythmic skills with a serious game in Parkinson's disease: Usability and acceptability. *Annals of Physical and Rehabilitation Medicine*, *61*(6), 380–385. https://doi.org/10.1016/j.rehab.2018.08.002

Démonet, J. F., Taylor, M. J., & Chaix, Y. (2004). Developmental dyslexia. *The Lancet*, *363*(9419), 1451–1460. https://doi.org/10.1016/S0140-6736(04)16106-0

De Smet, H. J., Paquier, P., Verhoeven, J., & Mariën, P. (2013). The cerebellum: Its role in language and related cognitive and affective functions. *Brain and Language*, *127*(3), 334–342. https://doi.org/10.1016/j.bandl.2012.11.001

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Ding, N., Patel, A. D., Chen, L., Butler, H., Luo, C., & Poeppel, D. (2017). Temporal modulations in speech and music. *Neuroscience and Biobehavioral Reviews*, *81*, 181–187. https://doi.org/10.1016/j.neubiorev.2017.02.011

Doyon, J., & Benali, H. (2005). Reorganization and plasticity in the adult brain during learning of motor skills. *Current Opinion in Neurobiology*, *15*(2), 161–167. https://doi.org/10.1016/j.conb.2005.03.004

Drake, C., & Botte, M. C. (1993). Tempo sensitivity in auditory sequences: Evidence for a multiple-look model. *Perception & Psychophysics*, *54*(3), 277–286. https://doi.org/10.3758/BF03205262

Droit-Volet, S. (2013). Time perception in children: A neurodevelopmental approach. *Neuropsychologia*, *51*(2), 220–234. https://doi.org/10.1016/j.neuropsychologia.2012.09.023

Dupoux, E., Pallier, C., Sebastian, N., & Mehler, J. (1997). A destressing "deafness" in French? *Journal of Memory and Language*, *36*(3), 406–421. https://doi.org/10.1006/jmla.1996.2500

Eckert, M. (2004). Neuroanatomical markers for dyslexia: A review of dyslexia structural imaging studies. *The Neuroscientist*, *10*(4), 362–371. https://doi.org/10.1177/1073858404263596

Falk, S., Müller, T., & Dalla Bella, S. (2015). Non-verbal sensorimotor timing deficits in children and adolescents who stutter. *Frontiers in Psychology*, *6*, 847. https://doi.org/10.3389/fpsyg.2015.00847

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/BF03193146

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. https://doi.org/10.1371/journal.pone.0138715

Flaugnacco, E., Lopez, L., Terribili, C., Zoia, S., Buda, S., Tilli, S., Monasta, L., Montico, M., Sila, A., Ronfani, L., & Schön, D. (2014). Rhythm perception and production predict reading abilities in developmental dyslexia. *Frontiers in Human Neuroscience*, *8*, 392. https://doi.org/10.3389/fnhum.2014.00392

Franceschini, S., Trevisan, P., Ronconi, L., Bertoni, S., Colmar, S., Double, K., Facoetti, A., & Gori, S. (2017). Action video games improve reading abilities and visual-to-auditory attentional shifting in English-speaking children with dyslexia. *Scientific Reports*, *7*(1), 5863. https://doi.org/10.1038/s41598-017-05826-8

Germanò, E., Gagliano, A., & Curatolo, P. (2010). Comorbidity of ADHD and dyslexia. *Developmental Neuropsychology*, *35*(5), 475–493. https://doi.org/10.1080/87565641.2010.494748

Giraud, A. L., & Poeppel, D. (2012). Cortical oscillations and speech processing: Emerging computational principles and operations. *Nature Neuroscience*, *15*(4), 511–517. https://doi.org/10.1038/nn.3063

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

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

Goswami, U., Huss, M., Mead, N., Fosker, T., & Verney, J. P. (2013). Perception of patterns of musical beat distribution in phonological developmental dyslexia: Significant longitudinal relations with word reading and reading comprehension. *Cortex*, *49*(5), 1363–1376. https://doi.org/10.1016/j.cortex.2012.05.005

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

Habib, M., & Giraud, K. (2013). Dyslexia. In O. Dulac, M. Lassonde, & H. Sarna (Eds.), *Handbook of clinical neurology* (pp. 229–235). Elsevier. https://doi.org/10.1016/B978-0-444-52891-9.00023-3

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*, 26. https://doi.org/10.3389/fpsyg.2016.00026

Hämäläinen, J. A., Salminen, H. K., & Leppänen, P. H. T. (2013). Basic auditory processing deficits in dyslexia: Systematic review of the behavioral and event-related potential/field evidence. *Journal of Learning Disabilities*, *46*(5), 413–427. https://doi.org/10.1177/0022219411436213

Heim, S., Tschierse, J., Amunts, K., Wilms, M., Vossel, S., Willmes, K., Grabowska, A., & Huber, W. (2008). Cognitive subtypes of dyslexia. *Acta Neurobiologiae Experimentalis*, *68*(1), 73–82.

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. https://doi.org/10.1016/j.cortex.2010.07.010

Jacquier-Roux, M., Lequette, C., Pouget, G., Valdois, S., & Zorman, M. (2010). *BALE: batterie analytique du langage écrit* [English translation: Analytical Battery for Written Language]. UPMF.

Jiang, D., Pepler, D., & Yao, H. (2010). The effect of population heterogeneity on statistical power in the design and evaluation of interventions. *International Journal of Behavioral Development*, *34*(5), 473–480. https://doi.org/10.1177/0165025410375912

Kösem, A., Bosker, H. R., Takashima, A., Meyer, A., Jensen, O., & Hagoort, P. (2018). Neural entrainment determines the words we hear. *Current Biology*, *28*(18), 2867–2875.e3. https://doi.org/10.1016/j.cub.2018.07.023

Kotz, S. A., & Schmidt-Kassow, M. (2015). Basal ganglia contribution to rule expectancy and temporal predictability in speech. *Cortex*, *68*, 48–60. https://doi.org/10.1016/j.cortex.2015.02.021

Kotz, S. A., & Schwartze, M. (2010). Cortical speech processing unplugged: A timely subcortico-cortical framework. *Trends in Cognitive Sciences*, *14*(9), 392–399. https://doi.org/10.1016/j.tics.2010.06.005

Krishnan, S., Watkins, K. E., & Bishop, D. V. M. (2016). Neurobiological basis of language learning difficulties. *Trends in Cognitive Sciences*, *20*(9), 701–714. https://doi.org/10.1016/j.tics.2016.06.012

Lallier, M., & Valdois, S. (2012). Sequential versus simultaneous processing deficits in developmental dyslexia. In T. N. Wydell & L. Fern-Pollak (Eds.), *Dyslexia - A comprehensive and international approach* (pp. 73–108). InTech. https://doi.org/10.5772/39042

Lallier, M., Tainturier, M. J., Dering, B., Donnadieu, S., Valdois, S., & Thierry, G. (2010). Behavioral and ERP evidence for amodal sluggish attentional shifting in developmental dyslexia. *Neuropsychologia*, *48*(14), 4125–4135. https://doi.org/10.1016/j.neuropsychologia.2010.09.027

Lee, D. N., Young, D. S., Reddish, P. E., Lough, S., & Clayton, T. M. H. (1983). Visual timing in hitting an accelerating ball. *The Quarterly*

Journal of Experimental Psychology, *35*(Pt. 2), 333–346. https://doi.org/10.1080/14640748308402138

Lefavrais, P. (1965). Description, definition et mesure de la dyslexie utilisation du test "L'Alouette." [Description, definition and measurement of a test for dyslexia]. *Revue de Psychologie Appliquée*, *15*(1), 33–34.

Leong, V., & Goswami, U. (2014). Assessment of rhythmic entrainment at multiple timescales in dyslexia: Evidence for disruption to syllable timing. *Hearing Research*, *308*, 141–161. https://doi.org/10.1016/j.heares.2013.07.015

Leong, V., Hämäläinen, J., Soltész, F., & Goswami, U. (2011). Rise time perception and detection of syllable stress in adults with developmental dyslexia. *Journal of Memory and Language*, *64*(1), 59–73. https://doi.org/10.1016/j.jml.2010.09.003

Lewandowska, M., Milner, R., Ganc, M., Włodarczyk, E., & Skarżyński, H. (2014). Attention dysfunction subtypes of developmental dyslexia. *Medical Science Monitor*, *20*, 2256–2268. https://doi.org/10.12659/MSM.890969

London, J. (2012). *Hearing in time: psychological aspects of musical meter*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199744374.001.0001

Manly, T., Anderson, V., Nimmo-Smith, I., Turner, A., Watson, P., & Robertson, I. H. (2001). The differential assessment of children's attention: The Test of Everyday Attention for Children (TEA-Ch), normative sample and ADHD performance. *Journal of Child Psychology and Psychiatry*, *42*(8), 1065–1081. https://doi.org/10.1111/1469-7610.00806

McAuley, J. D., Jones, M. R., Holub, S., Johnston, H. M., & Miller, N. S. (2006). The time of our lives: Life span development of timing and event tracking. *Journal of Experimental Psychology: General*, *135*(3), 348–367. https://doi.org/10.1037/0096-3445.135.3.348

Menghini, D., Finzi, A., Benassi, M., Bolzani, R., Facoetti, A., Giovagnoli, S., Ruffino, M., & Vicari, S. (2010). Different underlying neurocognitive deficits in developmental dyslexia: A comparative study. *Neuropsychologia*, *48*(4), 863–872. https://doi.org/10.1016/j.neuropsychologia.2009.11.003

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *24*(1), 167–202. https://doi.org/10.1146/annurev.neuro.24.1.167

Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions: Four general conclusions. *Current Directions in Psychological Science*, *21*(1), 8–14. https://doi.org/10.1177/0963721411429458

Moura, O., Simões, M. R., & Pereira, M. (2014). Executive functioning in children with developmental dyslexia. *The Clinical Neuropsychologist*, *28*(Suppl. 1), S20–S41. https://doi.org/10.1080/13854046.2014.964326

Nicolson, R. I., & Fawcett, A. J. (2019). Development of dyslexia: The delayed neural commitment framework. *Frontiers in Behavioral Neuroscience*, *13*, 112. https://doi.org/10.3389/fnbeh.2019.00112

Nozaradan, S., Zerouali, Y., Peretz, I., & Mouraux, A. (2015). Capturing with EEG the neural entrainment and coupling underlying sensorimotor synchronization to the beat. *Cerebral Cortex*, *25*(3), 736–747. https://doi.org/10.1093/cercor/bht261

Ogden, R. S., Wearden, J. H., & Montgomery, C. (2014). The differential contribution of executive functions to temporal generalisation, reproduction and verbal estimation. *Acta Psychologica*, *152*, 84–94. https://doi.org/10.1016/j.actpsy.2014.07.014

Overy, K., Nicolson, R. I., Fawcett, A. J., & Clarke, E. F. (2003). Dyslexia and music: Measuring musical timing skills. *Dyslexia*, *9*(1), 18–36. https://doi.org/10.1002/dys.233

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

Paquette, S., Fujii, S., Li, H. C., & Schlaug, G. (2017). The cerebellum's contribution to beat interval discrimination. *NeuroImage*, *163*, 177–182. https://doi.org/10.1016/j.neuroimage.2017.09.017

Pasqualotto, A., & Venuti, P. (2020). A multifactorial model of dyslexia: Evidence from executive functions and phonological-based treatments. *Learning Disabilities Research & Practice*, *35*(3), 150–164. https://doi.org/10.1111/ldrp.12228

Pennington, B. F. (2006). From single to multiple deficit models of developmental disorders. *Cognition*, *101*(2), 385–413. https://doi.org/10.1016/j.cognition.2006.04.008

Perry, C., Zorzi, M., & Ziegler, J. C. (2019). Understanding dyslexia through personalized large-scale computational models. *Psychological Science*, *30*(3), 386–395. https://doi.org/10.1177/0956797618823540

Piras, F., & Coull, J. T. (2011). Implicit, predictive timing draws upon the same scalar representation of time as explicit timing. *PLoS ONE*, *6*(3), e18203. https://doi.org/10.1371/journal.pone.0018203

Postuma, R. B., & Dagher, A. (2006). Basal ganglia functional connectivity based on a meta-analysis of 126 positron emission tomography and functional magnetic resonance imaging publications. *Cerebral Cortex*, *16*(10), 1508–1521. https://doi.org/10.1093/cercor/bhj088

Puyjarinet, F., Bégel, V., Lopez, R., Dellacherie, D., & Dalla Bella, S. (2017). Children and adults with Attention-deficit/hyperactivity disorder cannot move to the beat. *Scientific Reports*, *7*(1), 11550. https://doi.org/10.1038/s41598-017-11295-w

Ramus, F. (2003). Developmental dyslexia: Specific phonological deficit or general sensorimotor dysfunction? *Current Opinion in Neurobiology*, *13*(2), 212–218. https://doi.org/10.1016/S0959-4388(03)00035-7

Ravignani, A., Dalla Bella, S., Falk, S., Kello, C. T., Noriega, F., & Kotz, S. A. (2019). Rhythm in speech and animal vocalizations: A cross-species perspective. *Annals of the New York Academy of Sciences*, *1453*, 79–98. https://doi.org/10.1111/nyas.14166

Repp, B. H., & Su, Y.-H. (2013). Sensorimotor synchronization: A review of recent research (2006-2012). *Psychonomic Bulletin & Review*, *20*(3), 403–452. https://doi.org/10.3758/s13423-012-0371-2

Richlan, F., Kronbichler, M., & Wimmer, H. (2013). Structural abnormalities in the dyslexic brain: A meta-analysis of voxel-based morphometry studies. *Human Brain Mapping*, *34*(11), 3055–3065. https://doi.org/10.1002/hbm.22127

Scott, D. R., Isard, S. D., & de Boysson-Bardies, B. (1985). Perceptual isochrony in English and in French. *Journal of Phonetics*, *13*(2), 155–162. https://doi.org/10.1016/S0095-4470(19)30743-0

Stanovich, K. E. (1988). Explaining the differences between the dyslexic and the garden-variety poor reader: The phonological-core variable-difference model. *Journal of Learning Disabilities*, *21*(10), 590–604. https://doi.org/10.1177/002221948802101003

Stoet, G., Markey, H., & López, B. (2007). Dyslexia and attentional shifting. *Neuroscience Letters*, *427*(1), 61–65. https://doi.org/10.1016/j.neulet.2007.09.014

Stoodley, C. J., & Stein, J. F. (2013). Cerebellar function in developmental dyslexia. *Cerebellum*, *12*(2), 267–276. https://doi.org/10.1007/s12311-012-0407-1

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*(1–3), 120–129. https://doi.org/10.1016/j.jphysparis.2008.03.007

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. https://doi.org/10.1111/j.1467-9817.2006.00312.x

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. 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. https://doi.org/10.1016/j.bandl.2012.12.014

Tiffin, J., & Asher, E. J. (1948). The Purdue pegboard; norms and studies of reliability and validity. *Journal of Applied Psychology*, *32*(3), 234–247. https://doi.org/10.1037/h0061266

van Bergen, E., van der Leij, A., & de Jong, P. F. (2014). The intergenerational multiple deficit model and the case of dyslexia. *Frontiers in Human Neuroscience*, *8*, 346. https://doi.org/10.3389/fnhum.2014.00346

van Smeden, M., de Groot, J. A., Moons, K. G., Collins, G. S., Altman, D. G., Eijkemans, M. J., & Reitsma, J. B. (2016). No rationale for 1 variable per 10 events criterion for binary logistic regression analysis. *BMC Medical Research Methodology*, *16*(1), 1–12. https://doi.org/10.1186/s12874-016-0267-3

Vittinghoff, E., & McCulloch, C. E. (2007). Relaxing the rule of ten events per variable in logistic and Cox regression. *American Journal of Epidemiology*, *165*(6), 710–718. https://doi.org/10.1093/aje/kwk052

Wechsler, D. (2002). *Wechsler Preschool and Primary Scale of Intelligence—III*. Psychological Corporation.

Weiss, A. H., Granot, R. Y., & Ahissar, M. (2014). The enigma of dyslexic musicians. *Neuropsychologia*, *54*, 28–40. https://doi.org/10.1016/j.neuropsychologia.2013.12.009

Wieland, E. A., McAuley, J. D., Dilley, L. C., & Chang, S. E. (2015). Evidence for a rhythm perception deficit in children who stutter. *Brain and Language*, *144*, 26–34. https://doi.org/10.1016/j.bandl.2015.03.008

Zuk, J., Benjamin, C., Kenyon, A., & Gaab, N. (2014). Behavioral and neural correlates of executive functioning in musicians and non-musicians. *PLoS ONE*, *9*(6), e99868. https://doi.org/10.1371/journal.pone.0099868

Zuk, J., Bishop-Liebler, P., Ozernov-Palchik, O., Moore, E., Overy, K., Welch, G., & Gaab, N. (2017). Revisiting the "enigma" of musicians with dyslexia: Auditory sequencing and speech abilities. *Journal of Experimental Psychology: General*, *146*(4), 495–511. https://doi.org/10.1037/xge0000281

Appendix A

Sample Size Calculation

The calculation of the sample size was based on a similar study on ADHD (Puyjarinet et al., 2017), another neurodevelopmental disorder affecting rhythmic skills. The sample sizes were calculated in G*Power3 (Faul et al., 2007) using the following parameters: one-tailed test, $\alpha = .05$, power = .80

1. *Duration Discrimination* (*t* test, effect size (*d*) = 1.31): minimum of eight participants per group.
2. *Beat Alignment Test (BAT)* (*t* test, effect size (*d*) = 1.48): minimum of seven participants per group.
3. *Anisochrony Detection With Music* (*t* test, effect size (*d*) = 1.19): minimum of 10 participants per group.
4. *Paced Tapping With a Metronome and Music* (ANOVA mixed design, correlation between the measures (Pearson coefficient) = .82 (authors communication), effect size (η_p^2) = .60): minimum of 4 participants in total.

Sample size for the logistic regression models was calculated based on the "number of events" (i.e., number of subjects in the smaller of two outcome groups) for each regression coefficient estimated (van Smeden et al., 2016). Simulations studies showed that a minimum of five events per predictor variable is sufficient to achieve good statistical power (van Smeden et al., 2016; Vittinghoff & McCulloch, 2007). Considering that in the logistic regression models run in our study there were four predictors, 20 participants in the smaller group were sufficient to achieve good statistical power according to this criterion.

(*Appendices continue*)

Appendix B

Full Tables for Regression Analyses

Term	Estimate	*SE*	Statistic	*p* value
1. Synchronization consistency				
(Intercept)	0.30	0.16	1.80	0.08
BAT	0.58	0.13	4.46	< 0.001
Group	−0.38	0.28	−1.34	0.19
BAT:Group	0.59	0.33	1.77	0.08
Synchronization consistency (model without outliers). Model fit: $R^2 = .57$, $F(3, 40) = 17.45$, $p < .001$				
(Intercept)	0.25	0.17	1.48	0.15
BAT	0.58	0.13	4.34	< 0.001
Group	−0.32	0.31	−1.04	0.30
BAT:Group	0.57	0.35	1.63	0.11
2. BAT				
(Intercept)	0.07	0.23	0.30	0.76
Flexibility (speed)	−0.37	0.17	−2.22	0.03
Group	−0.45	0.32	−1.40	0.17
Flexibility (speed):Group	0.26	0.19	1.41	0.16
BAT (model without outliers). Model fit: $R^2 = .27$, $F(3, 41) = 5.14$, $p < .005$				
(Intercept)	0.11	0.22	0.51	0.62
Flexibility (speed)	−0.37	0.17	−2.16	0.04
Group	−0.48	0.33	−1.44	0.16
Flexibility (speed):Group	0.21	0.21	1.02	0.31
3. Reading nonwords				
(Intercept)	0.00	0.92	0.00	1.00
BAT	3.44	1.47	2.34	0.03
4. Transcription irregular words				
(Intercept)	0.03	0.40	0.07	0.94
BAT	1.48	0.63	2.33	0.03
5. Regular words reading				
(Intercept)	23.34	2.54	9.19	<.001
Flexibility (control)	−2.46	0.55	−4.47	<.001
6. Transcription irregular words				
(Intercept)	−0.87	1.87	−0.47	0.64
Flexibility (control)	0.98	0.43	2.31	0.03

Note. BAT = Beat Alignment Test .

(*Appendices continue*)

Appendix C

Correlations Between Timing and Rhythm Skills Measured With BAASTA and Cognitive Tasks

Pearson correlations

Task	Anisochrony detection (metronome)	Anisochrony detection (music)	Unpaced tapping (mean ITI)	Unpaced tapping (CV ITI)	Paced tapping with music	Paced tapping with metronome	Adaptive tapping (*d′* - large change)	Adaptive tapping (*d′* - small change)	Adaptation index (acceleration)	Adaptation index (deceleration)	Inhibition	Sustained attention	Selective attention	Working memory
Anisochrony detection (Metronome)	1	.26	−.26	.13	.08	.04	−.02	.10	.19	−.08	−.17	−.03	.08	.05
Anisochrony detection (Music)		1	−.12	.12	−.01	−.03	.08	−.10	−.29	−.27	−.19	−.04	−.08	−.10
Unpaced tapping (Mean ITI)			1	−.07	.18	.3*	.16	−.05	−.02	.17	.46***	.22	.2	.32
Unpaced tapping (CV ITI)				1	−.20	−.35*	−.19	−.32*	−.15	−.12	−.30*	−.02	.32*	−.27
Paced tapping with music					1	.41***	.5***	.45***	.21	.06	.34*	.03	−.17	.24
Paced tapping with metronome						1	.32*	.25	.47	−.14	.50	.14	−.10	.35
Adaptive tapping (*d′* - large change)							1	.57***	.12	.19	.28	.26	−.11	.22
Adaptive tapping (*d′* - small change)								1	.01	.04	.09	.02	.03	.33*
Adaptation index (Acceleration)									1	.12	.19	−.04	−.12	−.04
Adaptation index (Deceleration)										1	.12	−.05	−.24	.09
Inhibition											1	.44***	−.19	−.43***
Sustained attention												1	.00	.27*
Selective attention													1	−.1
Working memory														1

Spearman correlations

	Duration discrimination	BAT (*d′*)	Manual dexterity	Divided attention	Cognitive flexibility (Control)	Cognitive flexibility (Speed)
Anisochrony detection (Metronome)	0.36*	−0.04	0.04	0.01	0.06	−0.06
Anisochrony detection (Music)	0.31	−0.05	−0.20	−0.04	0.07	0.10
Unpaced tapping (Mean ITI)	−0.48***	0.07	0.29	−0.27	0.34*	−0.20
Unpaced tapping (CV ITI)	0.21	−0.38*	−0.05	0.15	−0.47***	0.33*
Paced tapping with music	−0.02	0.62***	0.21	−0.16	0.33*	−0.41***
Paced tapping with metronome	−0.14	0.57***	0.23	−0.05	0.43***	−0.45***
Adaptive tapping (*d′* - large change)	−0.13	0.51***	−0.03	−0.30	0.48***	−0.37*
Adaptive tapping (*d′* - small change)	0.03	0.28	0.09	−0.03	0.21	−0.17
Adaptation index (Acceleration)	−0.06	0.37*	0.38***	−0.14	0.23	−0.37*
Adaptation index (Deceleration)	−0.07	0.09	0.10	−0.06	0.09	−0.33*
Inhibition	−0.31	0.42***	0.25	−0.09	0.47***	−0.46***
Sustained attention	−0.45***	0.27	0.14	−0.56***	0.36*	−0.14
Selective attention	−0.16	−0.19	−0.13	−0.13	−0.01	0.35*
Working memory	−0.27	0.43***	0.21	−0.35*	0.42***	−0.25
Duration discrimination		−0.26	−0.43**	0.40*	−0.29	−0.06
BAT (*d′*)			0.18	−0.40***	0.44***	−0.49***
Manual dexterity				−0.22	0.10	−0.29*
Divided attention					−0.45***	−.23
Cognitive flexibility (Control)						0.45***

Note. BAT = Beat Alignment Test; BAASTA = Battery for the Assessment of Sensorimotor and Timing Abilities. Pearson coefficient were calculated when variables were normally distributed; Spearman coefficients were calculated when at least one variable was not normally distributed.

$^{*}p < .05$. $^{***}p < .005$. Noncorrected for multiple comparisons. None of the correlations reached significance ($p > .05$) after correcting for multiple comparisons.

(*Appendices continue*)

Appendix D

Analyses Without Outliers

	Logistic regressions without outliers				
	Null −2LL = −11.79, final −2LL = −30.28, $\chi^2 = 37$, $p < .001$; Nagelkerke $R^2 = 0.76$; AIC = 31.57				
Statistics predictor	β	*SE* (β)	Exp (β)	Wald test	*p*
First model					
Intercept	14.86	6.49	NA	2.29	<.05
Mean ITI	−0.03	0.01	0.96	−2.81	<.005
BAT (*d*′)	−1.77	0.88	0.17	−1.99	<.05
Flexibility (speed)	1.29	0.61	3.63	2.10	<.05
	Null −2LL = −9.66, final −2LL = −30.28, $\chi^2 = 41.24$, $p < .001$; Nagelkerke $R^2 = 0.76$; AIC = 27.33				
Statistics predictor	β	*SE* (β)	Exp (β)	Wald test	*p*
Second model					
Intercept	34.46	12.48	NA	2.76	<.01
Mean ITI	−0.04	0.01	1.15	−2.56	<.05
Tapping Music(Synchronization consistency)	−0.69	0.39	0.50	−1.76	<.1
Flexibility (control)	−2.58	0.95	2.59	−2.71	<.01

Note. AIC = Akaike's information criterion; BAT = Beat Alignment Test; NA = not available.

(*Appendices continue*)

Appendix E

Logistic Regressions Models With the Other Motor and Cognitive Variables

1. Perception models

Null −2LL = −14.37, final −2LL = −32.89, χ^2 = 37.06, $p < .001$; Nagelkerke R^2 = 0.72; AIC = 36.73

Statistics predictor	β	*SE* (β)	Exp (β)	Wald test	*p*
Intercept	22.67	7.44	NA	3.05	<.005
Mean ITI	−0.03	0.01	0.97	−2.91	<.005
BAT (*d′*)	−1.92	0.77	0.15	−2.50	<.05
Manual dexterity	−0.43	0.40	0.65	−1.09	=0.28

Null −2LL = −14.90, final −2LL = −32.89, χ^2 = 35.83, $p < .001$; Nagelkerke R^2 = 0.70; AIC = 37.96

Statistics predictor	β	*SE* (β)	Exp (β)	Wald test	*p*
Intercept	18.42	5.75	NA	3.20	<.005
Mean ITI	−0.03	0.01	0.97	−3.08	<.005
BAT (*d′*)	−2.03	0.76	0.13	−2.66	<.01
Selective attention	−0.11	0.38	0.89	−0.29	=.77

Null −2LL = −14.65, final −2LL = −32.89, χ^2 = 36.49, $p < .001$; Nagelkerke R^2 = 0.71; AIC = 37.30

Statistics predictor	β	*SE* (β)	Exp (β)	Wald test	*p*
Intercept	17.54	5.82	NA	3.01	<.005
Mean ITI	−0.03	0.01	0.74	−3.03	<.005
BAT (*d′*)	−1.82	0.74	0.16	−2.50	<.05
Divided Attention	0.11	0.13	0.89	0.84	=.40

Null −2LL = −14.12, final −2LL = −32.89, χ^2 = 37.43, $p < .001$; Nagelkerke R^2 = 0.73; AIC = 36.36

Statistics predictor	β	*SE* (β)	Exp (β)	Wald test	*p*
Intercept	20.31	6.16	NA	3.29	<.001
Mean ITI	−0.25	0.01	0.78	−2.72	<.01
BAT (*d′*)	−1.56	0.74	0.21	−2.11	<.05
Sustained Attention	−0.13	0.11	0.88	−1.16	=.24

Null −2LL = −14.61, final −2LL = −30.28, χ^2 = 31.36, $p < .001$; Nagelkerke R^2 = 0.68; AIC = 37.21

Statistics predictor	β	*SE* (β)	Exp (β)	Wald test	*p*
Intercept	17.73	5.89		3.01	<.005
Mean ITI	−0.03	0.01	0.97	−2.96	<.005
BAT (*d′*)	−1.73	0.77	0.17	−2.50	<.05
Memory	−0.75	0.17	0.47	−0.43	=.66

Null −2LL = −14.99, final −2LL = −32.89, χ^2 = 35.81, $p < .001$; Nagelkerke R^2 = 0.70; AIC = 37.98

Statistics predictor	β	*SE* (β)	Exp (β)	Wald test	*p*
Intercept	18.37	5.85	NA	3.14	<.005
Mean ITI	−0.03	0.01	0.97	−2.94	<.005
BAT (*d′*)	−1.90	0.79	0.15	−2.40	<.05
Inhibition	−0.05	0.18	0.95	−0.26	=.79

Null −2LL = −4.91, final −2LL = −32.90, χ^2 = 55.97, $p < .001$; Nagelkerke R^2 = 0.92; AIC = 17.82

Statistics predictor	β	*SE* (β)	Exp (β)	Wald test	*p*
Intercept	130.23	72.94		1.79	=.07
Mean ITI	−0.15	0.08	0.86	−1.78	=.07
BAT (*d′*)	−7.25	4.39	0.00	−1.66	=.10
Cognitive flexibility (control)	−7.36	4.15	0.00	−1.77	=.08

2. Production models

Null −2LL = −18.04, final −2LL = −32.89, χ2 = 29.71, p < .001; Nagelkerke R2 = 0.62; AIC = 44.07

Statistics predictor	β	*SE* (β)	Exp (β)	Wald test	*p*
Intercept	17.74	6.13	NA	2.89	<.005
Mean ITI	−0.02	0.01	0.98	−2.76	<.005
Tapping Music (Synchronization consistency)	−0.60	0.31	0.55	−1.91	=.055
Manual dexterity	−0.53	0.35	0.59	−1.50	=.13

(*Appendices continue*)

Appendix E (*Continued*)

	Null $-2LL = -19.33$, final $-2LL = -32.89$, $\chi^2 = 27.13$, $p < .001$; Nagelkerke $R^2 = 0.58$; AIC = 46.66				
Statistics predictor	β	*SE* (β)	Exp (β)	Wald test	*p*
Intercept	11.22	3.77	NA	2.98	<.005
Mean ITI	−0.02	0.01	0.98	−2.91	<.005
Tapping Music (Synchronization consistency)	−0.63	0.31	0.53	−2.05	<.05
Selective attention	0.08	0.35	2.22	0.24	=0.8

	Null $-2LL = -17.17$, final $-2LL = -32.89$, $\chi^2 = 31.46$, $p < .001$; Nagelkerke $R^2 = 0.64$; AIC = 42.33				
Statistics predictor	β	*SE* (β)	Exp (β)	Wald test	*p*
Intercept	10.56	3.75	NA	2.81	<.001
Mean ITI	−0.02	.01	0.98	−2.95	<.001
Tapping Music (Synchronization consistency)	−0.79	0.35	0.45	−2.62	<.05
Divided Attention	0.22	0.11	0.80	1.94	<.05

	Null $-2LL = -15.84$, final $-2LL = -32.89$, $\chi^2 = 34.10$, $p < .001$; Nagelkerke $R^2 = 0.68$; AIC = 39.69				
Statistics predictor	β	*SE* (β)	Exp (β)	Wald test	*p*
Intercept	18.45	5.58	NA	3.30	<.001
Mean ITI	−0.02	0.01	0.98	−2.66	<.001
Tapping Music (Synchronization consistency)	−0.63	0.31	0.53	−2.05	<.05
Sustained Attention	−0.25	0.12	0.78	−2.07	<.05

	Null $-2LL = -17.34$, final $-2LL = -30.28$, $\chi^2 = 25.89$, $p < .001$; Nagelkerke $R^2 = 0.59$; AIC = 42.68				
Statistics predictor	β	*SE* (β)	Exp (β)	Wald test	*p*
Intercept	13.88	4.76	NA	2.92	<.005
Mean ITI	−0.02	0.01	0.98	−2.86	<.005
Tapping Music (Synchronization consistency)	−0.56	0.32	0.57	−1.78	=.0.8
Working Memory	−0.23	0.15	0.79	−1.54	=0.12

	Null $-2LL = -18.37$, final $-2LL = -32.89$, χ2 = 29.06, p < .001; Nagelkerke $R^2 = 0.61$; AIC = 44.73				
Statistics predictor	β	*SE* (β)	Exp (β)	Wald test	*p*
Intercept	13.68	4.65	NA	2.94	<.005
Mean ITI	−0.02	0.01	0.98	−2.64	<.01
Tapping Music (Synchronization consistency)	−0.53	0.30	0.58	−1.78	=0.07
Inhibition	−0.22	0.16	0.80	−1.37	=1.17

	Null $-2LL = -14.91$, final $-2LL = -32.89$, $\chi^2 = 35.96$, $p < .001$; Nagelkerke $R^2 = 0.71$; AIC = 37.83				
Statistics predictor	β	*SE* (β)	Exp (β)	Wald test	*p*
Intercept	9.17	4.50	NA	2.04	<.05
Mean ITI	−0.03	0.01	0.97	−2.84	<.005
Tapping Music (Synchronization consistency)	−0.34	0.35	0.71	−0.95	=.33
Flexibility speed	1.30	0.53	0.27	2.43	<.05

Note. AIC = Akaike's information criterion; BAT = Beat Alignment Test; NA = not available. The fits of these models of these models are lower than the ones presented in the results section (i.e., the AIC is higher).

Received January 7, 2020
Revision received August 5, 2021
Accepted September 21, 2021 ■