ABSTRACT

DYSLEXIA AND MUSICAL APTITUDE

By Elizabeth A. Huss

Some researchers believe music instruction may prove a beneficial intervention for dyslexia. The idea is bolstered by the existence of overlapping neural networks for music and language, studies in which musical training has had positive effects on reading in typically developing children, and studies on the effects of musical training on brain plasticity.

The current study was designed to see if adults with a history of dyslexia find musical timing (rhythm and tempo) and rapid tasks more difficult than adults without a history of dyslexia and if performance on these tasks is associated with literacy-related skills. Participants completed two reading measures and a variety of musical aptitude tasks. Results showed the dyslexia group did not perform more poorly on the rhythm tasks. Results on the tempo tasks were mixed. The dyslexia group was more accurate and less consistent at tempo copying at most speeds. No significant group differences were found for the other tempo tasks or for any of the rapid perception tasks. Performance on some of the musical tasks correlated with reading scores. Overall, the results did not support the conclusion that individuals with dyslexia are impaired on musical tasks.

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by

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To my mother and all parents who read to their children and inspire a desire for learning.

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INTRODUCTION

Approximately 5-17.5% of the population suffers from dyslexia, an inordinate difficulty in learning to read that is not commensurate with either intellectual ability or educational opportunity (Shaywitz, 1998). According to broad conceptual agreement, the proximate cause of most cases of dyslexia is a phonological deficit—difficulty in sounding out words using knowledge of letter-sound relationships because of deficient representation, storage, and/or retrieval of speech sounds at the cortical level. A minority of cases may be due to a visual deficit involving the ability to recognize the visual forms of words. Although the existence of the phonological deficit is not under debate, the origin of the deficit and whether it is the only core deficit in dyslexia are disputed. Some researchers attribute the phonological deficit to rapid auditory processing or beat perception deficits (Farmer & Klein, 1995; Goswami, Thomson, Richardson, Stainthorp, Hughes, Rosen, & Scott, 2002; Tallal, 1980) whereas others do not believe an auditory deficit causes the phonological deficit (Ramus, 2003; Rosen, 2003). Still others argue the auditory deficit is speech specific, and thus reflects phonological rather than auditory processing difficulties (Mody, Studdert-Kennedy, & Brady, 1997). Several researchers contend the phonological deficit cannot explain all of the impairments associated with dyslexia, such as problems with motor coordination, directionality confusion, delayed expression of hand dominance, memory deficits, and impaired performance on temporal sequencing and timing tasks. Additional core deficits, including a rapid naming or lexical retrieval deficit, have also been proposed. The disagreement among researchers as to the origins of the deficits reflect a larger debate regarding whether dyslexia is a language-specific or more pervasive disorder with roots in general sensory, motor, or learning processes (Ramus, Rosen, Dakin, Day, Castellote, White, & Frith, 2003).

Traditionally, developmental dyslexia has been defined as a discrepancy between reading and intellectual ability in the presence of adequate reading instruction. However, some researchers believe dyslexia is a lifelong neuro-developmental syndrome that remains after successful reading remediation and exists prior to the onset of reading difficulties (Rack, 1997). In this view, dyslexia refers to a developmentally varying pattern of underlying strengths and weaknesses. Weaknesses include difficulties in reading, spelling, and writing, general slowness or incoordination on practical tasks, poor phonological awareness, subtle language difficulties including problems with word finding, mispronunciations, and auditory confusions, and impaired verbal working memory (Rack, 1997). Strengths include greater artistic creativity, creative problem solving, and a more innovative thinking style (Everatt, Steffert, & Smythe, 1999).

Rapid Temporal Processing Theory

A classic study by Tallal (1980) assessed the ability of dyslexic children to make same-different discriminations and to temporally order two tones of either the same or different frequency presented at varying interstimulus intervals (ISIs) using the Repetition Test. The Repetition Test (Tallal & Piercy, 1973) was designed to assess nonverbal perceptual abilities in children with specific language impairment (SLI). SLI is characterized by the delayed onset and protracted development of early oral language skills relative to other areas of development and is generally identifiable in preschool-aged children (Tager-Flusberg & Cooper, 1999). The Repetition Test consists of four subtests: association, sequencing, rapid perception, and same-different discrimination. During the association subtest the participant is asked to press one response button when tone 1 is presented and the other when tone 2 is presented. The two tones are presented separately. In the sequencing subtest, the tones are presently successively, separated by a 428 ms ISI. The participant is instructed to press the response buttons according to the order of tone presentation. The rapid perception subtest is the same as the sequencing subtest, except the ISIs vary from 15 to 305 ms. For the same-different discrimination subtest, the participant is instructed to press one button if the two tones are the same and the other if the two tones are different. ISIs vary from 8 to 428 ms. The 20 dyslexic children in Tallal's (1980) study ranged in age from 8 to 12 years with a mean age of 9 years 7 months. Their scores on the rapid perception and same-different subtest at short ISIs were impaired relative to 12 non-dyslexic children aged 8 years 6 months from a previous developmental study, leading to the conclusion that dyslexics have a rapid auditory perception deficit. The performance of the dyslexic children on the same-different discrimination subtest, which requires the ability to detect differences in frequency, was compared to the performance of the dyslexic children on the sequencing and rapid perception tasks, which require both frequency discrimination and temporal order perception. There was no significant difference in overall performance or performance at any ISI studied. Thus, performance in the dyslexic group did not depend on whether or not knowledge of temporal order was necessary. For the dyslexic group, performance on the rapid perception subtest positively correlated with nonsense word reading and a general reading measure, but not with age or intelligence. The control group did not complete reading assessments.

Deficient rapid temporal auditory processing is believed to impact speech perception at the level of formant transitions. For any vowel, the air vibrates at many frequencies at once because of changes in the shape of the vocal tract. The dominant frequency bands, which correspond to specific resonances in the vocal tract, are called formants. Each vowel sound has multiple formants. If a consonant is adjacent to a vowel then the vowel's formants will be slightly bent toward the characteristic frequency range of the consonant (Crystal, 2002). These "bends" are formant transitions. Formant transitions are crucial for discriminating between consonants in consonant-vowel syllables such as /ba/ versus /da/. There is evidence dyslexics may have poorer categorical perception of some phonemic contrasts defined by formant transitions including /ba/-/ga/-/da/ (Ramus, 2003; Sernicalaes, 2006). Proponents of rapid temporal processing theory claim problems in perceiving formant transitions cause phonological code retrieval problems, impaired phonemic awareness, and impeded learning of phoneme-grapheme correspondences. Phonemes are the smallest speech sounds that convey meaning in a language. For example, the word "cat" breaks down into three phonemes: /k/, /ae/, and /t/. Phonemes correspond with graphemes, individual letters or letter combinations.

Tallal (2003) attributes the rapid temporal processing deficit to slowed neural processing in the left temporoparietal lobe. Abnormal neuropsychological responses to various auditory stimuli have been documented in individuals (including newborns) with and at familial risk for dyslexia (Lyytinen, Guttorm, Huttunen, Hämäläinen, Leppänen, & Vesterinen, 2005). Therefore, dyslexia appears to have a strong genetic component. The concordance rate of monozygotic twins ranges from 84 to 100% and that of dizygotic twins from 20 to 35% (Démonet, Taylor, & Chiaz, 2004 as cited in Carlson, 2010).

Critique of rapid temporal processing theory. Individuals with dyslexia are not impaired on all auditory rapid temporal processing tasks. Rosen (2003), in a review of the literature, reported individuals with dyslexia are generally unimpaired on forward masking and gap detection tasks. In forward masking, the participant is instructed to respond to a probe tone. The probe tone is presented after the termination of a masking noise or tone. The likelihood of detecting the probe increases as the time interval or "gap" between the masker and probe increases. The masking effect is due to the persistence of the masker percept and interference between percepts. Impairments on forward and backward masking tasks have traditionally been attributed to deficient temporal resolution although other explanations have been proposed (Hartley & Moore, 2002). Auditory gap detection tasks measure the ability to discriminate between continuous noise bursts/tones and noise bursts/tones containing brief intervals of silence, "gaps".

Some studies fail to show rapid processing inadequacies with Piercy and Tallal's (1973) Repetition Test, the paradigm used in Tallal's (1980) classic study. In a longitudinal investigation of 543 children, Share, Jorm, Maclean, and Matthews (2002) examined the concurrent and predictive relationships between the Repetition Test given in kindergarten and phonological and reading measures administered in kindergarten, grade 1, and grade 2. Children with reading disabilities and matched controls were followed through grade 3. Reading-disabled children were impaired on long ISIs on the Repetition Test administered in kindergarten. This finding is opposite to what rapid temporal processing theory predicts. In addition, long-ISI deficits predicted oral receptive vocabulary and reading comprehension deficits but not phonological weakness. This suggests long-ISI deficits are related to SLI-type deficits. The failure of Share, Jorm, Maclean, and Matthews' study to find a relationship between pre-reading rapid temporal processing and later reading is problematic for rapid temporal processing theory because the theory claims rapid perception deficits cause and therefore precede reading impairment. Of course, rapid temporal processing impairments may have existed during an earlier critical period and resolved before kindergarten entry.

Dyslexic individuals may be impaired on auditory tasks that do not require temporal or rapid processing. Tasks such as frequency and duration discrimination pose difficulties for children and adults with dyslexia (Ahissar, Protopapas, Reid, & Merzenich, 2000; Banai & Ahissar, 2006; Goswami et al., 2002; Thomson, Fryer, Maltby, & Goswami, 2006; Thomson & Goswami, 2008). Individuals with dyslexia are generally impaired on amplitude modulation detection tasks regardless of the modulation rate (Rosen, 2003). Menell, McAnally, and Stein (1999) had adults with and without childhood diagnoses of dyslexia discriminate between amplitude modulated (AM) white noise and unmodulated white noise using a two-interval forced-choice paradigm. Modulation depth, the degree of change in amplitude or loudness within each cycle, was adjusted adaptively. AM detection thresholds were higher for the dyslexic participants at all frequencies tested (10-320 Hz). In a second study, Menell, McAnally, and Stein (1999) measured scalp potentials evoked by AM stimuli. The scalp potentials of the dyslexic participants were significantly smaller than those of the control participants for all frequencies tested (10-160 Hz), indicating dyslexics' AM discrimination difficulties are likely due to AM insensitivity rather than task difficulty. This study is problematic for rapid temporal processing theory because impairments were found at all modulation rates. Of course, it is possible to argue 10 Hz, the minimum frequency modulation rate used, requires rapid processing. The results of Witton, Stein, Stoodley, Rosner, and Talcott (2002) support this argument. They found AM detection was impaired at 20 Hz but not at 2 Hz in participants with dyslexia. However, frequency modulation (FM) detection was impaired at 2 Hz but not at 20 Hz. Impaired detection of 2 Hz FM in individuals with dyslexia has been replicated in several laboratories and is one of the most consistent findings in the auditory deficit literature (Ramus, 2003). Impaired detection of 2 Hz FM cannot be explained by a rapid temporal processing deficit.

The relationship between rapid temporal auditory processing and phonological and literacy measures is not clear. Marshall, Snowling, and Bailey (2001) found dyslexic children were impaired on the Repetition Test but did not find evidence of a direct causal relationship between rapid auditory processing and phonological skill. Performance on the Repetition Test was confounded with hyperactivity. The four dyslexic children who performed at or below the level of the lowest-performing control participant (excluding the control who performed at chance levels) were significantly more hyperactive according to teacher report and needed more training trials to learn to identify the tones and associate them with particular responses than the other dyslexic children. Their scores on the phonological tasks did not differ from those of the other children with dyslexia. Also, rapid temporal processing, as measured by temporal order judgment tasks, is not reliably related to performance on tasks requiring the categorization and discrimination of formant transitions (Ramus, 2003).

The appropriateness of equating formant transitions with tone sequences has been debated (Studdert-Kenxnedy & Mody, 1995). Tones are steady-state events with discrete frequencies. Formant transitions are continuously changing spectral sweeps with components that cannot be distinguished. The ability to distinguish these tones is necessary for a temporal order judgment account. Studdert-Kennedy and Mody argue researchers need to use nonspeech control patterns that are specifically matched to speech stimuli to determine if speech and nonspeech deficits are independent. Traditional tone and speech stimuli are acoustically dissimilar. Therefore, tone and speech perception may not share the same mechanisms. Non-speech control patterns that are acoustically similar to speech stimuli are easy to develop. Vowel sounds have multiple formants. Most information in speech is conveyed by the three formants with the lowest frequencies. The lowest frequency formant is F1, the next is F2, and the third is F3. Isolated formants, usually F2 or F3, or sinewave tones mimicking formants can serve as matched non-speech control patterns (Joanisee & Gati, 2003; Mody, Studdert-Kennedy, & Brady, 1997; Rosen & Manganari, 2001). Isolated formants contain formant transitions. If using sinewave tones, it is possible to mimic a formant transition by having either a brief rise or fall in pitch precede the sinewave tone (Joanisse & Gati, 2003).

Explanations other than a rapid processing deficit may account for impaired performance on temporal order judgment tasks using speech stimuli. For example, Mody (2003) contends impairments on speech temporal order judgment tasks at short ISIs may be due to poorly defined categorical representations that slow down the rate of stimulus identification. According to Mody, the lengthening of speech stimuli results in improved performance not because rapid acoustic events are lengthened but because more time is provided in which to form phonemic representations. Menell, McAnally, and Stein (1999) attribute the improved intelligibility of slowed speech to the fact slowing results in amplification of the AM signal. In their study, participants with dyslexia were impaired at detecting all AM frequencies. Therefore, slowing the modulation rate would not be expected to improve speech intelligibility. Rapid temporal processing proponents advocate the use of slowed speech stimuli in the remediation of dyslexia. Improved comprehension is attributed to the lengthening of rapid acoustic events. Mody (2003) argues it is wrong to attribute the benefits of slowed speech to temporal changes because modifying speech affects both its temporal and spectral properties. The use of slowed speech in dyslexia remediation is controversial (Rosen, 2003).

Rapid auditory temporal processing deficits are believed to underlie specific language impairment (SLI) as well as dyslexia. Tallal believes the two disorders belong to “a continuum of language and learning deficits that includes both oral and written language” which she terms “developmental language learning impairments (Tallal &

Benasich, 2002, p. 560).” This view is in opposition to the general consensus. Dyslexia and SLI are generally considered distinct albeit comorbid disorders (American Psychiatric Association, 1994). Researchers who view dyslexia and SLI as distinct are troubled by the fact that rapid temporal processing theory provides no explanation for why deficits may cause dyslexia in some instances and specific language impairment in others (Rosen, 2003). Findings of rapid temporal processing deficits in dyslexia may be due to comorbid SLI. In a study by Heath, Hogben, and Clark (1999), dyslexic children with oral language delays were impaired on the Repetition Test while dyslexic children without oral language delays were unimpaired relative to non-dyslexic controls.

The Repetition Test may not reflect temporal processing difficulties. As Studdert-Kennedy and Mody (1995) point out, Tallal’s (1980) finding that dyslexic children performed poorly on both same-different discrimination and temporal ordering at short ISIs implies a deficit in discrimination capacity rather than in temporal processing. This was the original conclusion reached by Tallal. Subsequently, in commentaries on Tallal, dyslexics’ difficulties were described as “temporal.” Studdert-Kennedy and Mody suggest the term “rapid” is more appropriate than “temporal” and argue the error, although entirely semantic, has contributed to significant confusion in the research literature. Tomblin and Quinn (1983), based on the observation that participants tend to improve with increased trials, suggest the Repetition Test actually measures perceptual learning rather than temporal resolution abilities.

Attention-related alternative hypotheses. The anchoring deficit hypothesis attributes dyslexics’ difficulties on psychoacoustic tasks involving repeated reference tones (such as the Repetition Test) and on repetitive motor-sequencing tasks to an inability to form internal representations of repeated stimuli (Ahissar, 2007). Usually, individuals perform better on paradigms that use repeated reference stimuli because, over several trials, a stable internal reference or “anchor” is formed. Ahissar found adults with dyslexia were worse than non-dyslexic controls at identifying the higher of two tones if the higher tone was a constant, but were unimpaired if it varied trial by trial. According to the anchoring deficit hypothesis, bottom-up attentional mechanisms are less effective in individuals with dyslexia because the gradual build-up of predictions around repeated stimuli cannot be used to reduce attentional load. An anchoring deficit may explain dyslexics’ superior innovation and creativity as perceptual anchoring reduces the ability to detect the unexpected (Ahissar).

The sluggish attentional shifting hypothesis attributes difficulties in rapid stimulus sequence perception to prolonged chunk duration caused by parietal dysfunction. Hari and Renvall (2001) support their argument for prolonged chunk duration with three experimental tasks: auditory saltation illusion, pitch-streaming, and attentional blink. For the auditory saltation illusion task, participants listened to four left-ear clicks followed by four right-ear clicks. At short ISIs the sounds appear to jump from left to right at equidistant steps. At intermediate ISIs the whole stimulus sequence appears to jump when the first right-ear click is presented, whereas at long ISIs the individual clicks are perceived. Dyslexics perceived the “jump” at significantly longer ISIs than controls, suggesting dyslexics have a “prolonged cognitive integration window during which percepts of successive sounds can interfere” (p. 526). For the pitch-streaming task, high and low tones were presented alternatively. In comparison to controls, individuals with dyslexia perceived separate high and low streams rather than a continuous sequence of high-low-high-low tones at significantly longer ISIs. For the attentional-blink task, letters were presented on the computer screen and the participant had to report white letters and whether an X followed each white letter. Individuals with dyslexia needed a longer ISI between the white letter and the X in order to detect the X. According to Hari and Renvall, chunking abnormalities could contribute to distorted cortical phonological representations and therefore to reading difficulties.

A study by Petkov, O'Conner, Benmoshe, Baynes, and Sutter (2005) suggests the impairment in dyslexia involves suppressing the effects of distracting stimuli rather than sluggish attentional shifting. Petkov et al. employed an auditory perceptual grouping paradigm in which participants listened for a "middle" frequency tone within a stream of background tones. A deviant "high" frequency tone was sometimes presented either immediately before or after the "middle" frequency tone. The "high" tone served as an invalid attentional cue, shifting attention away from the spectral region containing the "middle" tone. Participants had to indicate whether they heard one or two tones outside of the repetitive background tone's frequency. Adults with dyslexia were significantly worse at the task when the discrepancy in frequency between the high and middle tones was large. The results are inconsistent with the sluggish attentional shifting hypothesis, which would predict greater impairment when the high tone precedes the middle tone, because there was no group by order interaction. Petkov et al. therefore concluded individuals with dyslexia are simply more prone to the effects of distracting stimuli.

Beat Perception

Goswami, Thompson, Richardson, Stainthorp, Hughes et al. (2002) argue the phonological deficit in dyslexia is due to impaired beat or rhythm perception. In music, beat refers to the tempo, pace, or time it takes to play a piece, and is often demarcated by a metronome. Rhythm is the length and accent given to a series of notes in a piece. The distinction between beat and rhythm is often not made in the literature on speech perception in dyslexia. Physically, the beat in speech is due to amplitude modulation, in particular amplitude envelope onsets or rises. An amplitude envelope is the overall amplitude structure of a sound. Rise is the change in the amplitude envelope at onset, and rise time is the time over which a sound reaches its full amplitude. Unlike formant transitions that occur over tens of milliseconds, amplitude envelope onsets in speech occur over hundreds of milliseconds. Amplitude envelope onsets may denote the point in time at which a vowel or syllable is perceived (Muneaux, Ziegler, Truc, Thomson, & Goswami, 2004).

Speech rhythm serves as a cue for segmenting the continuous speech stream (Cutler & Norris, 1988). Word onsets tend to be aligned with the onsets of metrical units. Sensitivity to the lexical rhythm of speech may be necessary for successful progression to phonemic awareness and reading. Findings of lexical rhythmic deficits in poor readers are consistent with this idea. Wood and Terrell (1998) showed poor readers were less accurate than age-matched controls but not reading-matched controls at matching the metrical structure of a low-pass filtered sentence with a spoken phrase.[1] This kind of speech rhythm sensitivity is a strong predictor of reading. In English, speech rhythm is defined by alternating strong and weak syllables. Strong syllables contain full vowels (such as eye, pill, and crypt) and weak syllables contain "reduced" vowels (such as the second syllables in ion, pillow, and cryptic). Performance on a speech rhythm task predicted reading attainment in 5- and 6-year-olds after controlling for age, vocabulary, and phonological awareness (Holliman, Wood, & Sheehy, 2008).

Goswami et al. (2002) found significant group differences between dyslexic children and non-dyslexic controls on an amplitude modulated beat-perception task. During training, the children learned to associate a 15-ms rise time amplitude-modulated sinusoidal carrier with the sound of Tigger and Eeyore on a swing and a 300-ms rise time amplitude-modulated sinusoidal carrier with the sound of Pooh going down a slide. The 15-ms rise time sinusoidal carrier is perceived as having a beat and the 300-ms rise time sinusoidal carrier is perceived as one continuous sound. For the experimental trials, amplitude modulated sinusoidal carriers with rise times between 15 and 300 ms were presented. For each presentation, the children were asked whether Tigger and Eeyore swinging or Pooh going down the slide made the sound. Children with dyslexia perceived one continuous sound, Pooh going down the slide, at significantly shorter rise times than non-dyslexic children. Thus, the dyslexic children were less able to detect a beat. After controlling for age, non-verbal IQ, and vocabulary, beat sensitivity explained variance in oddity (identifying the word that differed in terms of onset or rime), reading,

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[1] A low-pass filter is a filter that passes low frequencies but reduces the amplitude of frequencies higher than some cutoff frequency.

phonological short-term memory, non-word reading, and spelling. Adults with dyslexia were also impaired on the same Tigger/Eeyore and Pooh beat detection task, which is a five-ramp rise time task (Pasquini, Corriveau, & Goswami, 2007). The number of ramps in a task indicates the number of times the total amplitude of the sinusoidal carrier wave, measured from the negative peak to the positive peak, rises and falls. Sinusoidal carrier waves have negative and positive components. When graphed with time on the abscissa and amplitude on the ordinate, the abscissa divides an amplitude-modulated sinusoidal carrier into symmetrical halves.

Pasquini, Corriveau, and Goswami (2007) did not find significant group differences on one- and two-ramp rise-time tasks in their adult sample. However, on the one-ramp task, 47% of the dyslexic participants performed below the 5th percentile of control performance. The one-ramp task involved identifying which of two modulated pure tones had the shorter rise time. Participants were asked to choose the tone that was “sharpest” in the beginning (p. 270). Performance on the one-ramp task explained additional variance in phoneme deletion, nonword reading rate, and spelling after controlling for age and full scale IQ. The stimuli for the two-ramp task were amplitude-modulated sinusoidal carriers. Participants were asked to identify the sound with the “sharper” beat, shorter rise times (p. 270). Another study found significant group differences on the same one- and two-ramp tasks in dyslexic and non-dyslexic adults (Thomson et al., 2006). Pasquini, Corriveau, and Goswami provide no explanation for the inconsistent findings. Both used the same tasks and had similar samples in terms of number and composition. However, the data analysis techniques used in the two studies differed. Pasquini, Corriveau, and Goswami eliminated outliers from their analyses. Data from two participants in the two-ramp task and three participants in the one-ramp task were excluded. Thomson et al. did not remove outliers and did not report the number of outliers on each task.

Critique of the beat perception hypothesis. Metrical structure, a cue used in the segmentation of the speech stream, is language specific. English is a stress-timed language. The most noticeable structural characteristic of spoken English is its alternating strong and weak syllables. Most English words begin with strong syllables. Cutler and Norris (1988) proposed a segmentation strategy model for English in which strong syllables trigger the segmentation of the speech signal. Strong syllables in English are defined by the quality of the vowel. Timbre[2] is a near synonym for quality and is dependent on the amplitude envelope (Hirsh & Watson, 1996). Thus, the amplitude envelope may be important to speech segmentation in English speakers. In particular, amplitude envelope onsets or rises may provide an important onset-rime segmentation cue since amplitude envelope onsets typically correspond with vowel onsets (Muneaux et al., 2004). Onset, with regards to syllables, signifies the phoneme(s) preceding the vowel. Rime is the vowel and subsequent phonemes.

In addition to English, Goswami and colleagues have found rise time perception deficits in French and Finnish speaking dyslexics (Hämäläinen, Leppänen, Torppa, Müller, & Lyytinen 2005; Muneaux et al., 2004). The role of rise time perception in French and Finnish speech segmentation is not clear. French speakers are believed to

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[2] In music, the quality of a tone that is distinctive to a particular instrument.

rely primarily on syllable boundaries for speech segmentation. Syllabic structure is more regular and intuitive in French than in English. Finnish is a fixed-stress language. Word-initial syllables are stressed. Suomi, McQueen, and Cutler (1997) argue stress is not likely an important segmentation cue for Finnish because vowel quality and syllable duration do not vary between stressed and unstressed syllables as they do in English and because the amplitude and fundamental frequency differences between syllables are not large. They provide evidence for vowel harmony mismatch being an important segmentation cue. Finnish vowels belong to three sets: front, back, and neutral. Front and back vowels cannot co-occur in a native Finnish word. The presence of a back and front vowel thus signals a possible word boundary. Hämäläinen et al. (2005) suggest rise time may be a suprasegmental cue in Finnish. Suprasegmentals are phonetic properties that transcend the segment and require the comparison of successive segments. Pitch, duration, and loudness are examples of suprasegmental properties.

While rise-time perception may be expected to be universally impaired in dyslexia, it should be more strongly related to phonological skill and literacy in individuals who speak languages where rise time is a critical cue. Yet, relationships were strong in the French and Finnish speaking samples. Performance on the Tigger/Eeyore and Pooh beat perception task explained 36% of the variance in reading, 17% of the variance in oddity, 14% of the variance in nonword reading accuracy, 26% of the variance in nonword reading rate, 7% of the variance in short term memory, and 19% of the variance in rapid naming in the French sample. Performance on an 80-ms rise time, 400-ms ISI, task explained additional variance in pseudoword/word choice and rhyme recognition in the Finnish sample. The psuedoword/word choice task involved deciding if a printed word was a real word or a pseudoword. Participants were asked to pick the word that rhymed with the target word or psuedoword in the rhyme recognition task. These findings suggest rise time perception may play a role in speech segmentation in non-stress based languages, perhaps by signaling onset-rime boundaries. Indeed, multiple segmentation cues are available in speech and are used in combination (Sanders & Neville, 2000). Alternatively, the relationships between rise time perception, literacy, and phonological processing could be due to a confounding third variable. Rise time perception insensitivity may simply be another manifestation of a general auditory deficit associated with dyslexia.

In languages where rise time is critical to speech segmentation, rise time sensitivity should correlate with literacy and phonological skills both within and across groups. Rosen (2003), in his re-analysis of Goswami et al. (2002), found that significant correlations between rise time sensitivity and both nonword reading and spelling were maintained in the age-matched control group but not in the reading-level control or dyslexia groups when the groups were treated as independent. Significant correlations would be expected in English-speaking dyslexics given that rise-time is known to play a role in speech segmentation in English. The lack of any significant correlations suggests individuals with dyslexia may employ other speech segmentation strategies and raises doubts about the existence of a causal relationship between rise time sensitivity and literacy impairment in dyslexia.

The Cerebellar Deficit Hypothesis

The cerebellum controls motor, sensory, perceptual, and higher-level functions. It may be involved in the sharpening of sensory input, providing feedback for fine adjustment of speech production, temporal processing for motor and perceptual functions, and creating “internal models” for prediction, including models for articulation containing articulation-phonological mappings (Callan, Kawato, Parsons, & Turner, 2007). Studies reveal anatomical, functional, and metabolic cerebellar differences between controls and individuals with dyslexia (Laycock, Wilkinson, Wallis, Darwent, Wonders, Fawcett, Griffiths, & Nicolson, 2008). Deficits on tasks involving balance, motor skills, timing, and automaticity are interpreted as evidence of cerebellar dysfunction.

Advocates of the cerebellar deficit hypothesis maintain that mild cerebellar dysfunction is consistent with the cognitive, information processing, and motor skill impairments commonly observed in individuals with dyslexia (Nicolson, Fawcett, & Dean, 2001). The cerebellar deficit hypothesis also attributes the phonological deficit to cerebellar impairment. Specifically, the phonological deficit is ascribed to impoverished articulatory representations. Nicolson, Fawcett, and Dean assert motor impairment in dyslexia makes articulation more effortful and slower. This effectively reduces working memory and requires the commitment of greater conscious resources. In a clarification of the cerebellar deficit hypothesis, Nicolson and Fawcett (2006), state dyslexia is caused by abnormalities in the verbal regions of the cerebellum. Other cerebellar regions are not necessarily impaired. This clarification accounts for why indicators of cerebellar dysfunction are not universal in dyslexia.

Motor skills. Individuals with dyslexia have subtle difficulties with sequential motor movements, especially when interlimb coordination is involved (Farmer & Klein, 1995). Wolff, Michel, Drake, and Ovrut (1990) conducted a bimanual tapping study with adolescent and adult samples. Participants began tapping to a metronome and continued tapping after the metronome was turned off. Tapping variability, left- to right-index finger tap ratios,[3] and errors after the metronome was turned off were analyzed. Dyslexic adolescents and adults were unimpaired when asked to tap both index fingers in synchrony to the beat. Performance of dyslexic adolescents was more variable than age-matched controls when alternating between index fingers. Performance of both dyslexic groups was more variable than age-matched controls on the asynchronous condition.

Ramus, Pidgeon and Firth (2003) found children with dyslexia were slower at bead threading and at the finger to thumb task. The finger to thumb task involves placing the index finger of one hand onto the thumb of the other hand and vice versa and then, while keeping the top thumb and finger together, rotating one hand clockwise and the other counter-clockwise until the finger and thumb touch again (i.e., the “Eentsy Weentsy Spider” fingerplay). Children in another study were not impaired on the same tasks (White, Milne, Rosen, Hansen, Swettenham, Frith, & Ramus, 2006). Motor impairment

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[3] When tapping with both fingers together (synchronous condition) or tapping one beat with the left and the next with the right (alternating condition) the correct ratio is 1:1, that is, for every left-index tap there is a right-index tap. When tapping every beat with one index finger and every second beat with the other (asynchronous condition), the ratio should be 2:1 or 1:2.

is believed to be directly responsible for the poor handwriting of some individuals with dyslexia and indirectly responsible for the phonological deficit through impaired articulation.

The prevalence of motor deficits in individuals with dyslexia is unclear. Some studies fail to find motor impairments whereas others find impairments in a minority of individuals. Impairments may be due to the comorbidity of dyslexia with ADHD and dyspraxia (developmental coordination disorder). Dyslexic children with comorbid ADHD or dyspraxia are more likely to display motor impairments and tend to be more severely impaired (Ramus, Pidgeon, & Firth, 2003). Moreover, several studies indicate motor skill is not related to phonological or literacy skills (Ramus, Pidgeon, & Firth, 2003; Savage, 2002; White et al., 2006; Wolff et al., 1990). The motor theory of speech was generally abandoned following the discovery of normal phonological development in individuals with severe dysarthria (a neurological injury-induced motor speech disorder) and speech apraxia (Ramus, Pidgeon, & Firth).

Timing. Impairments on unimanual tapping performance tasks have been attributed to a general time perception deficit (Nicolson, Fawcett, & Dean, 1995). Wolff (2002) had children with dyslexia and non-dyslexic right-handed controls perform a variety of tapping tasks. All participants almost always anticipated (i.e., tapped before) the metronome signal on the synchronous bimanual and right-handed unimanual tasks. The mean anticipation time of non-dyslexic readers was significantly shorter for both conditions. Another task measured the ability to recalibrate after a change in the rate of the metronome. Participants were informed the metronome rate would change and were instructed to try to stay in unison with the metronome. Individuals with dyslexia took significantly longer to recover after the change. The third task involved the reproduction of simple rhythmic patterns consisting of five equal-length taps separated by 500 ms and 250 ms inter-tap intervals (ITIs). Three individuals with dyslexia were unable to correctly reproduce the pattern. The ITIs of the remaining dyslexic children were more widely distributed than the ITIs of the non-dyslexic readers. Participants who could correctly reproduce the pattern were asked to repeat it ten times in succession under the following three conditions: at the preferred rate without a metronome signal, with the metronome set at the preferred rate, and with the metronome set at 25% faster than the preferred rate. Children with dyslexia had greater difficulty when the metronome was present at the preferred rate than when it was not. Non-dyslexic readers' performance at the preferred rate was similar with and without the metronome. When the metronome was set at 25% faster than the preferred rate, non-dyslexic readers preserved the serial order of long and short inter-tap intervals. By comparison, the performance of the children with dyslexia was "essentially undecipherable" (p. 195).

Performance on tapping tasks may be affected by ADHD, which is significant given the substantial comorbidity of ADHD and dyslexia. Adolescents with ADHD exhibited greater intra-individual variability than controls on a tapping task (Toplak & Tannock, 2005). Tiffin-Richards, Hasselhorn, Richards, Banaschewski, and Rothenberger (2004) found dyslexic children with and without comorbid ADHD were significantly less accurate at reproducing complex rhythms than either unimpaired controls or children with ADHD. No group differences were found for the following unimanual tasks: maintenance of a self-chosen free tapping rate, tapping to a metronome, continuing tapping after termination of the metronome’s signal, and simple rhythm reproduction.

The finding of time perception deficits in dyslexics is not reliable. Ramus, Pidgeon, and Firth (2003) found no impairment on an auditory duration discrimination task. Some studies find deficits on unimanual tapping tasks whereas others do not. Tapping performance deficits are difficult to interpret because they can be due to motor timing output deficits, motor deficits, or time perception deficits. Geuze and Kalverboer (1994) had special education teachers in the Netherlands provide them with the names of children with reading problems, with motor problems, and with neither reading nor motor problems. The researchers then administered a standardized reading fluency test, the short-form of the Wechsler Intelligence Scale for Children-Revised (Weschler, 1974), and the Test of Motor Impairment (TOMI; Stott, Moyes, & Henderson, 1984) to the identified children. Children who were less than one year behind in reading ability and scored below the 15th percentile on the TOMI were classified as clumsy. Children who were more than 1.5 years behind in reading and who scored above the 15th percentile on the TOMI were classified as dyslexic. They then compared the tapping performance of the dyslexic, clumsy, and control children (i.e., children who were less than one year behind in reading and who scored above the 15th percentile on the TOMI). Performance of the children in the dyslexic group was more variable than that of the control group on all unimanual tapping tasks. The only significant difference between the dyslexic and clumsy children was in right-handed performance on the bimanual 1:2 asynchronous task. This was attributed to left-hemispheric dysfunction.

Automaticity. Automatization is the ability to become fluent at a task through practice so it no longer requires conscious control. Common automatic tasks include driving, typing, and reading. Nicolson and Fawcett (1990) used a dual-task paradigm to investigate the automatization of balance-related skills in children with and without dyslexia. Five different motor balance tasks were devised: 60 s beam balance on both feet, 30 s beam balance on the right foot, 30 s beam balance on the left foot, walking back and forth five times on the beam while looking down, and walking back and forth five times on the beam while looking straight ahead. Participants completed each balance task twice, once as a single task and once concurrently with a secondary task (either backwards counting or an auditory choice reaction task). For the auditory choice reaction task, a high or low tone was presented every 2 s. Participants had to press one button to respond to the high tone and another to respond to the low tone. No group differences existed for the balance tasks in the single-task condition. However, the dyslexic children were significantly impaired on all balance tasks in the dual-task condition except balancing on the beam with both feet. These results were interpreted as suggesting children with dyslexia invest significantly more conscious resources in balance monitoring and are therefore adversely affected by any secondary task requiring attentional resources. Nicolson and Fawcett further argue the automatization deficit in dyslexia is general, applies to all learned tasks, but is typically undetected because of conscious compensation. Dual-task studies are thought to inhibit the use of conscious compensation and thus reveal subtle automatization deficits. With regards to reading and spelling, the automatization deficit may make the acquisition of verbal forms more difficult.

Evidence for a general automatization deficit is mixed. Wimmer, Mayringer, and Raberger (1999) failed to replicate the results of Nicolson and Fawcett (1990) in a German population. Dual-task balancing deficits were restricted to dyslexic children with higher ADHD ratings. Kelly, Griffiths, and Frith (2002) found adults with dyslexia were unimpaired at implicit motor and spatial sequence learning. A single-task implicit learning paradigm was used in place of a dual-task paradigm because resource allocation is a potential confound in dual tasks and implicit learning should preclude conscious compensation. The implicit learning paradigm was the Serial Reaction Time task, which requires participants to press buttons in response to stimuli on a computer screen. Implicit learning is indicated by the presence of faster reaction times to old than to new or random stimulus sequences. Although Kelly, Griffiths, and Frith (2002) found no evidence of implicit learning impairment in individuals with dyslexia, Stoodley, Harrison, and Stein (2006) did find impairments using the same paradigm. It is unclear whether implicit learning studies measure the same aspects of skill learning as dual-task studies. Critics of the general automatization deficit account argue broader intellectual deficits would be expected in the case of a general automatization deficit, and also raise the question of why non-literacy tasks are more successfully compensated for than literacy tasks (Savage, 2002).

The evidence for a deficit in making word-reading skills automatic is much stronger than for other automatization deficits (Savage, 2002). In fact, there is widespread agreement for the existence of naming speed deficits in dyslexia (Wolf & Bowers, 1999). The controversy lies in how rapid naming deficits should be categorized and whether they simply reflect slowed general processing. Traditionally, naming speed has been subsumed under phonological processes and portrayed as either phonological recoding or the retrieval of phonological codes. Wolf and Bowers (1999) suggest that naming speed is a separate core deficit in dyslexia.

The General Magnocellular Deficit Hypothesis

The general magnocellular deficit hypothesis integrates rapid auditory processing, visual, and cerebellar hypotheses. It claims all magnocells are impaired in individuals with dyslexia (Stein, 2001). Magnocells are supposedly involved in the processing of rapidly changing stimuli in the sensory and motor systems. Evidence exists for impaired magnocellular functioning in the visual, auditory, and tactile domains. Behaviorally, findings of impaired visual motion sensitivity and reduced contrast sensitivity at low spatial frequencies and luminance in individuals with dyslexia are cited as evidence of visual magnocellular impairment. Anatomically, post-mortem studies indicate the visual magnocellular layers of the lateral geniculate nucleus are distorted, and individual magnocells are up to 30% smaller in individuals with dyslexia (Galaburda & Livingstone, 1993; Livingstone, Rosen, Drislane, & Galaburda, 1991). The visual magnocellular system is responsible for timing visual events. Visual magnocellular impairment may cause visual confusions—letter transpositions, distortions, blurring, and superimpositions—and orthography deficits (Stein & Walsh, 1997).

Auditory magnocells in the medial geniculate nucleus relay auditory signals to the cerebral cortex. Galaburda, Menard, and Rosen (1994) found auditory magnocells in the medial geniculate nucleus were disordered and smaller in the brains of individuals with dyslexia than in controls. Auditory magnocellular impairment is believed to be responsible for reduced sensitivity to rapidly changing auditory stimuli, auditory attention deficits, and the phonological deficit through impaired speech perception. Magnocells are also involved in detecting flutter and vibration in the skin. Mild tactile deficits have been found in individuals with dyslexia (Stein, 2001). Magnocellular deficits may extend to other systems such as the motor system.

Slight impairments at the level of individual magnocells are thought to multiply to produce significant impairments in regions receiving magnocellular input (Stein & Walsh, 1997). One such region is the cerebellum. The cerebellum receives heavy magnocellular projections from sensory and motor systems and contains magnocellular neurons (Stein, 2001).

Critique of the general magnocellular deficit hypothesis. Many of the previously raised criticisms of the rapid auditory temporal processing and cerebellar deficit hypotheses apply to the general magnocellular deficit hypothesis since this hypothesis predicts rapid auditory processing and cerebellar deficits. Additionally, the general magnocellular deficit hypothesis predicts impairments on visual magnocellular tasks. Visual magnocellular deficits have only been observed in a minority of individuals with dyslexia. In one study, 2 out of 16 participants with dyslexia had visual deficits consistent with magnocellular impairment (Ramus et al., 2003). Another study found visual impairments in 6 out of 23 dyslexic participants (White et al., 2006). However, only 2 participants were impaired on the visual measure of magnocellular functioning. According to Amitay, Ben-Yehudah, Banai, and Ahissar (2003), individuals who are impaired on magnocellular tasks may have broader impairments, and may also be impaired on tasks unrelated to magnocellular functioning. The 6 dyslexics in their study with magnocellular deficits were impaired on all psychophysical tasks administered. Failures to find visual magnocellular deficits and motor deficits cannot be as easily dismissed as failures to find auditory deficits. These negative findings pose a significant problem for the general magnocellular deficit hypothesis. Whereas auditory deficits during infancy may negatively impact later speech perception and phonological skills, visual and motor deficits remedied before school age should not have adverse effects on reading.

Music and Dyslexia

Together, the theories outlined above strongly suggest individuals with dyslexia may experience music perception and performance difficulties, especially in regards to rapid and timing skills. While the theories may one day be proven false, they are all based on observed impairments in individuals with dyslexia: deficits in rapid auditory processing, beat perception, time estimation, automaticity, and motor skills. All of these difficulties are relevant to either music production or perception.

Musical difficulties have been observed in individuals with dyslexia. Atterbury (1985) found reading-disabled children between the ages of 7 and 9 performed worse than age-matched controls at a clapping task. The reading-impaired children in the 7- and 8-year-old groups performed worse than controls at tonal discrimination as measured by the Primary Measures of Music Audiation Tonal Test (Gordon, 1979). For this test, children must decide whether pairs of tonal patterns they hear sound the same or different. No group differences existed in the ability to discriminate 1-measure-long rhythmic patterns. Another study found that performance on the Seashore Rhythm Test could reliably discriminate between impaired readers and aged-matched controls in grades 1-3 (McGivern, Berka, Languis, & Chapman, 1991). The Seashore Rhythm task is very similar to the Rhythm Test of the Primary Measures of Music Audiation, only standardized for individuals age 15 years and older. The authors concluded this test might be useful in identifying children at risk for developing reading impairment. Forgeard, Schlaug, Norton, Rosam, and Iyengar (2008) found children with dyslexia performed worse on melody and rhythm tasks than age-matched controls.

Overy, Nicolson, Fawcett, and Clarke (2003) examined timing and rapid skills in their study of musical abilities in children with dyslexia. Their assessment battery contained measures of rhythm skills, meter skills, rapid skills, pitch skills, and other musical skills. A significant group difference was found on the composite created from the rapid skill measures: note order detection (a pitch temporal order judgment task), note number detection, and note number discrimination, with the dyslexic group performing more poorly than the control group. Unexpectedly, the children with dyslexia performed significantly better than the controls on the pitch discrimination task. This could be due to the somewhat greater musical experience of children in the dyslexic group, or to the fact that the right hemisphere is predominately involved in pitch processing. The most consistent "neural signature" of dyslexia is the failure of left-hemisphere posterior systems to function properly during reading (Shaywitz, Mody, & Shaywitz, 2006). Though insignificant, trends toward poorer performance in the dyslexic group existed for all of the rhythm skills: rhythm copying, rhythm discrimination, and song rhythm (clapping the rhythm of and singing "Happy Birthday"). Song rhythm performance was significantly related to scores on the Wechsler Objective Reading Dimensions Spelling subtest in the control group but not in the dyslexic group. Both the song rhythm task and spelling partially rely on syllable segmentation skills. The lack of a relationship between spelling and song rhythm performance in the dyslexic group was interpreted as indicating the children with dyslexia were less likely to use syllable segmentation as a strategy in spelling. This is consistent with the hypothesized cause of the phonological deficit espoused by Goswami and colleagues (Goswami et al, 2002): impaired syllable segmentation skills due to rhythm perception insensitivity.

Music and Language Processing

Traditionally, language processing was believed to predominately occur in the left hemisphere and music processing in the right hemisphere. More recent evidence points to the existence of shared as well as functionally distinct processing components (Peretz & Zatorre, 2005). In particular, the fine-tuning of pitch appears to rely on music-specific areas in the right hemisphere (Peretz & Hyde, 2003). The processing of musical time relations is more widespread, bilateral, and relies on the cerebellum, parietal cortex, pre-motor cortex, and motor cortex (Peretz & Zatorre). Grouping and meter appear to be functionally dissociated. Meter is predominately processed in the right hemisphere and grouping in the left hemisphere.

There is growing evidence musical training has general effects on brain plasticity (Habib & Besson, 2009). Musical experience appears to influence brain anatomy in regions not exclusively devoted to music processing. Anatomical differences between musicians and nonmusicians have been found in the motor cortex, cerebellum, Hesch's gyrus, planum temporale, and corpus callosum (Peretz & Zatorre, 2005). Musical training improves pitch discrimination for both musical and linguistic stimuli (Lamb & Gregory, 1993) and alters the brain's response to pitch incongruities (Besson, Schön, Moreno, Santos, & Magne, 2007). Gaab, Tallal, Kim, Lakshimnarayanan, Archie, Glover, and Gabrieli (2005) found musicians were more accurate, quicker to respond, and utilized different brain areas (including areas traditionally associated with language processing such as Broca's Area), than nonmusicians when completing a tone sequence reproduction task.

Music Instruction as an Intervention for Dyslexia

Music training has been found to benefit children without reading impairments. Forgeard et al. (2008) found non-dyslexic children who received, on average, 14 additional months of musical training improved significantly more than children without musical experience on Word Attack, a standardized measure of nonsense word reading from the Woodcock Reading Mastery Tests-Revised. Musical skills accounted for almost all of the variance in Word Attack in the music group. At baseline, both melodic and rhythmic discrimination performance were significant predictors of Word Attack. Rhythm discrimination performance was a near-significant predictor of improvement on Word Attack ($p < .07$). In another sample, improvement in phonemic awareness from baseline to 31 months later was predicted by improvement on Gordon's Primary Measures of Music Audiation Tonal subtest and a melody discrimination task, but not by performance on rhythmic tasks (Forgeard et al.).

Rauscher and her colleagues performed a study to examine the relationship between music instruction and phonemic awareness in five-year-old children (Rauscher, Mosley, & Almane, 2009). Phonemic awareness, the ability to aurally discriminate between speech sounds, is strongly related to reading ability. Seventy-five children were administered the Predictive Assessment of Reading (2005) before and after either four months of weekly 40-min violin instruction, weekly 40-min swimming instruction, or no special training. Four sub-tests were given to each child individually: (1) Letter-Word Calling, in which the child is asked to read out loud a list of progressively difficult words; (2) Picture Naming, in which the child is asked to state out loud the names of progressively difficult pictures; (3) Phonemic Awareness (i.e., Initial Consonant Different, in which the child must indicate which of a series of words read by the test administrator has a different initial consonant, and Strip First Sound, in which the test administrator reads a word (e.g., PARK) and then asks the child to take away the first sound and indicate what word is left (i.e., ARK)), and (4) Rapid Naming, in which the child is asked to read a series of letters/digits out loud as quickly as possible. All sub-tests are predictive of reading ability in later grades. Results indicated that there were no differences between groups in the pre-test scores. However, the post-test scores of the music and control groups were significantly different on the Letter-Word Calling and Phonemic Awareness sub-tests, with children in the music group scoring higher than children in the control groups. This work suggests a relationship between some of the auditory skills used in learning to read and certain elements of music perception, supporting the notion that early music instruction may influence reading acquisition.

Findings of impairments in dyslexics on music-related tasks, the existence of shared neural networks for music and language processing, the positive effects of music instruction on non-dyslexic children's reading abilities, and the demonstrated effects of music on brain plasticity suggest musical training may be beneficial for individuals with dyslexia. Few studies have examined this possibility. Register, Darrow, Standley, and Swedberg (2007) implemented an intensive short-term music-reading curriculum for children with and without dyslexia. Intact classrooms were assigned to each condition. All children with dyslexia were in the treatment condition. The control group received normal reading instruction and the treatment group received music reading instruction. The children with dyslexia improved from pre-test to post-test on all subtests of the Gates-MacGinite Reading Test. However, the non-dyslexic control children also improved. The non-dyslexic children in the treatment group only improved more than the non-dyslexic children in control group on the word knowledge subtest. Due to the fact the music condition consisted of vocal music with lyrics specifically designed to improve reading, the effects of traditional music training cannot be determined.

Overy (2003) measured the impact of one hour per week of classroom singing-based music instruction on literacy-related skills in children categorized as at “no,” “low,” and “strong” risk of developing reading problems according to scores on the Dyslexia Screening Test. Due to the lack of a control group, standard scores were used for analyses to account for expected improvements in performance due to development. All three groups showed significant improvement in phonologic segmentation from the beginning to the end of the school year. The “low” and “strong” risk groups improved in spelling. However, none of the groups improved in reading. This study has several confounds. Since vocal music was used, the effects of the lyrics versus the music cannot be determined. Also, the absence of a control group is troubling, as factors other than the music instruction may have contributed to the improvements. In a second study reported in Overy (2003), 9 boys with dyslexia were given additional music lessons. Improvement over the 15-week period prior to the intervention was compared to improvement over the 15-week intervention period during which the boys received three additional 20-minute music lessons per week. In comparison to the control period, the boys improved significantly more on rhythm copying, rapid auditory processing, phonological ability, and spelling ability measures, but not on reading during the music intervention period.

Overview of the Current Study

The current research was designed to serve several purposes. First, while low-level auditory perception and timing studies have been conducted with dyslexic adults, higher-level music perception and production abilities have only been investigated in children with dyslexia. The documentation of musical impairments in adults with dyslexia is critical given the potential role of music in remediation. If musical deficits are not present in adults with dyslexia, then music may not be a useful intervention for adults *or* children with dyslexia. If musical difficulties are present in dyslexic children but not in dyslexic adults, this would suggest that the development of musical and literacy skills follow different trajectories, and musical training may be less likely to impact reading ability. Another reason to investigate music abilities in dyslexic adults rather than dyslexic children is that rhythm perception appears to become more important to reading as increasing numbers of polysyllabic words are encountered accompanied by an increased need to segment them (David, Wade-Woolley, Kirby, & Smithrim, 2007). Therefore, the relationship between musical timing and literacy may be stronger in adults than in beginning readers.

As with Overy et al. (2003), this study emphasizes timing and rapid music skills. Timing and rapid skills were chosen because timing deficits are predicted by the cerebellar deficit hypothesis, the beat perception hypothesis, and the general magnocellular deficit hypothesis, and rapid skill deficits are predicted by the rapid auditory temporal processing theory and the general magnocellular deficit hypothesis. Also, further studies suggest the neural processing of musical timing is less music-specific than the processing of musical pitch and indicate grouping processes rely heavily on the left hemisphere. Additionally, speech rhythm perception is involved in syllable segmentation, and therefore literacy.

Overy et al. (2003) found dyslexic children were significantly impaired on a rapid skill composite. There were also trends toward impairment on all of the rhythmic and some of the meter tasks. The small sample size and low trial-to-task ratio may have limited Overy's ability to find significant effects. The current study, although also suffering from a small sample size, increased statistical power by increasing the trial-to-task ratio. Overy's ability to find significant effects on the rapid skills measures may also have been limited by the fact not all ISIs were "rapid". Some ISIs in Overy's study were as long as 1000 ms. By comparison, the longest ISI used on the rapid perception subtest of Repetition Test and in this study was 305 ms.

In addition to looking at group differences, this study adopted a "multiple-case study" approach in which the number of outliers on each task relative to the control group mean is reported. This has recently become a convention in research on dyslexia due to limited sample sizes and the heterogeneity of the dyslexic population. A minority is normally impaired on any given task, excepting phonological tasks, even when significant group differences are found.

Third, this study investigated the relationships between music perception and performance and word and nonword reading. This study also investigated the impact of comorbid ADHD through the use of an ADHD self-report measure. Overy et al. (2003) did not report the incidence of or screen for comorbidities in their sample.

A majority of the musical tasks were taken from Overy et al. (2003). Minor adjustments were made. The trial-to-task ratio was increased as well as task difficulty to render the tasks more suitable for adults. Unfamiliar songs were used in place of “Happy Birthday” for the song beat and song rhythm tasks. In addition, a novel task, tempo identification, was piloted. Tempo identification involves listening to 2 repetitions of the same song segment with different metronome overlays and identifying the repetition where the metronome overlay is in synch with the beat.

Hypotheses. Hypothesis 1: Individuals with dyslexia will perform more poorly than individuals without dyslexia on the rhythm tasks: rhythm copying, rhythm discrimination, and song rhythm.

Hypothesis 2: Individuals with dyslexia will perform more poorly on tasks involving meter: song beat, tempo identification, tempo copying, and tempo discrimination.

Hypothesis 3: Individuals with dyslexia will perform more poorly than individuals without dyslexia on the rapid tasks—note order detection, note number detection, and note number discrimination.

Hypothesis 4: Individuals with ADHD or dyspraxia will be worse at motor timing skills: tempo copying, rhythm copying, song tempo, and song rhythm.

Hypothesis 5a: Musical timing and rapid skills will positively correlate with Word Identification and Word Attack.

Hypothesis 5b: The positive relationships between musical timing skills and Word Attack will be of greater magnitude than the positive relationships between musical timing skills and Word Identification.

Hypothesis 6: Musical experience will positively correlate with performance on the music tasks.

Hypothesis 7: A minority of individuals with dyslexia will be impaired on musical tasks where significant group differences are found.

METHODS

Participants

Participants were 32 undergraduate male and female students at the University of Wisconsin Oshkosh with and without self-reported histories of dyslexia. They were either enrolled in psychology classes at the University of Wisconsin Oshkosh or members of Project Success, a remedial program for University of Wisconsin Oshkosh students with language-based learning disabilities. All of the control participants were enrolled in psychology classes. One of the participants with dyslexia was a member of Project Success, 4 were enrolled in psychology classes, and 7 were members of Project Success and enrolled in psychology classes. Participants received their choice of $15 or class credit for participating. One participant in the dyslexia group and 2 participants in the control group chose to receive $15.

Nine participants were dropped from the final data analyses. One participant was dropped from the dyslexia group because he identified himself as reading disabled but not dyslexic and did not meet the Word Identification and Word Attack inclusion criteria. Participants had to score at or below the 25th percentile on both Word Attack and Word Identification and report a history of dyslexia to be included in the dyslexia group. Control group inclusion criteria included the absence of a history of dyslexia, learning disability, neurological disorder, and/or ADHD, and performance at or above the 40th percentile on both Word Attack and Word Identification. Eight participants did not meet these criteria. One participant was dropped from the control group because he had an

ADHD diagnosis. Seven participants were dropped from the control group because they did not score at or above the 40th percentile on both Word Attack and Word Identification. This left 11 participants in the dyslexia group and 12 in the control group.

There were 4 female participants in each group. The groups did not significantly differ according to age, $t(21) = 1.18$, $p = .25$, $d = .49$, two-tailed. The mean age of participants in the dyslexia group was 21.91 ($SD = 4.51$). The control group mean was 20.20 ($SD = 2.12$). Similar numbers in both groups had some musical training ($p = .41$, Fisher's exact test); 5 in the dyslexia group and 8 in the control group. The groups significantly differed according to the type of musical training ($p = .03$, Fisher-Freeman-Halton test). Two participants in the dyslexia group had instrumental training alone and 3 had both instrumental and vocal training. Seven participants in the control group had instrumental training alone and 1 had vocal training alone. The groups did not significantly differ according to age at musical training initiation, Levene's test, $F = 10.67$, $p < .01$, $t(8.25) = .70$, $p = .51$, $d = .35$, two-tailed, or duration of musical training, $t(11) = .74$, $p = .47$, $d = .44$, two-tailed. The mean age at which participants in the dyslexia group who received musical training began their training was 10.00 ($SD = .71$) with a minimum value of 9.12. The mean duration of musical training for these participants was 6.80 years ($SD = 2.17$) with a maximum value of 8. The mean age at which participants in the control group who received musical training began their training was 9.25 ($SD = 2.92$) with a minimum value of 5. The mean duration of musical training for these participants was 5.63 years ($SD = 3.07$) with a maximum value of 10. All participants reported normal hearing or corrected to normal hearing. All participants in the control group spoke English as their native language. One participant in the dyslexia group spoke English as a second language. All participants in the dyslexia group were right handed. One participant in the control group was left handed. Participants reported no neurological disorder, specific language impairment, or dyspraxia diagnoses. One participant in the dyslexia group reported comorbid ADHD, 2 reported comorbid learning disabilities, and 2 reported both comorbid ADHD and learning disabilities. The participants in the dyslexia group who did not belong to Project Success did not receive classroom or testing accommodations from the university through Disability Services.

The groups significantly differed on Word Identification, $t(21) = -7.09$, $p < .001$, $d = 2.74$, two-tailed, and Word Attack $t(21) = -5.29$, $d = 2.20$, $p < .001$, two-tailed. The mean Word Identification standard score was 89.36 ($SD = 4.65$) for the dyslexia group and 101.33 ($SD = 4.08$) for the control group. The mean standard score for Word Attack for the dyslexia group was 88.36 ($SD = 6.87$). The mean standard score for Word Attack for the control group was 104.00 ($SD = 7.36$).

The groups did not significantly differ according to total score, $t(21) = 1.67$, $p = .11$, two-tailed, $d = .69$; hyperactivity subscale score, $t(21) = .83$, $p = .41$, $d = .34$, two-tailed; or impulsivity subscale score, $t(21) = .46$, $p = .65$, $d = .19$, two-tailed, on the ADHD scale (Caterino, Gómez-Benito, Balluerka, Amador-Campos, & Stock, 2009). The dyslexia group was marginally more inattentive than the control group, $t(21) = 2.05$, p = .05, $d = .84$, two-tailed. The mean total score was 66.00 ($SD = 27.19$) for the dyslexia group and 50.67 ($SD = 15.82$) for the control group. The mean subscale scores for the dyslexia group were 33.00 ($SD = 16.42$) for the inattention subscale, 23.09 ($SD =$

10.44) for the hyperactivity subscale, and 9.91 (*SD* = 4.59) for the impulsivity subscale. The mean subscale scores for the control group were 21.83 (*SD* = 9.02) for the inattention subscale, 19.83 (*SD* = 8.35) for the hyperactivity subscale, and 9.00 (*SD* = 4.86) for the impulsivity subscale.

The researcher was blind except to the group assignments of 4 participants. Three participants in the dyslexia group self-disclosed their dyslexia status: 1 while completing the informed consent, 1 before Word Identification, and 1 after Word Identification. The assignment of 1 control participant was known prior to the session because the researcher had to cancel and reschedule the participant's session.

Materials

Woodcock Reading Mastery Tests-Revised-Normative Update (WRMT-R/NU; Woodcock, 1998). The WRMT-R/NU is a comprehensive battery designed to assess a wide range of reading skills. It is used in school systems, the diagnosis of reading disabilities, educational planning, and research. Norms are available for individuals between the ages of 5 and 75. The WRMT-R/NU measures a unitary construct, reading, and has two highly correlated factors (Williams, Eaves, & Cox, 2001). The Basic Skills Cluster consists of Word Attack and Word Identification. For Word Attack, the individual must read nonsense words out loud according to phonic rules. Some of the items are actually obscure English words. The items are presented in order of increasing difficulty. The subtest is not timed. For Word Identification, the individual reads real words in isolation. Familiarity with the words is unnecessary. The test measures decoding and sight recognition skills. The items are presented in order of increasing difficulty. The subtest is not timed. The Reading Comprehension Cluster consists of Word Comprehension and Passage Comprehension. Total Reading Scores can be calculated from the Basic Skills Cluster and Reading Comprehension Cluster measures.

Only the Word Attack and Word Identification subtests were administered in this study. Two judges scored performance on the subtests. The researcher was the first judge, scoring performance while administering the test. The second judge scored participants from an audio recording of their performance. The Word Identification raw scores of judge 1 significantly correlated with the Word Identification raw scores provided by judge 2, $r = 1.00$, $n = 23$, $p < .001$. The raw scores for Word Attack were also highly consistent, $r = .99$, $n = 23$, $p < .001$. The scores of judge 2 were used in all analyses.

ADHD scale (Caterino, Gómez-Benito, Balluerka, Amador-Campos, & Stock, 2009). The ADHD Scale (APPENDIX D) was designed to supplement clinical interviews in the diagnosis of ADHD in young adults. There are two parallel forms. Form A was used in this study. Each parallel form has 18 items corresponding to the 18 DSM-IV behavioral diagnostic criteria for ADHD. There are 9 inattention items, 6 hyperactivity items, and 3 impulsivity items. The ADHD Scale thus yields a total ADHD score as well as inattention, hyperactivity, and impulsivity subscores. The items are presented in the form of statements. Respondents are asked to indicate how well each statement describes them using a Likert-type scale where “0” indicates a little, “1” some, and “2” a lot. Each statement is rated for the following settings: as a child, at home, at work or school, and in social settings. The ADHD Scale has high content validity, representational validity (i.e., dimensionality, internal consistency, and equivalent forms reliability), and elaborative validity (i.e., the degree to which a measure discriminates known groups and predicts theoretically relevant behavior).

Musical aptitude tests.

Rhythm skills.

Rhythm copying. Participants copied a total of 15 rhythmic patterns (1 practice trial, 14 experimental trials) by tapping the space bar on a laptop keyboard with the index finger of their dominant hand. Seven “simple” patterns consisted of 6 tapping units separated by long (500 ms) and short (250 ms) inter-tap intervals. Seven “difficult” patterns consisted of 6 tapping units of equal duration separated by 750-ms, 500-ms, and 250-ms inter-tap intervals. All patterns consisted of computer generated 50-ms long drumbeats. A computer program recorded the timing of the participants’ taps at the ms level.

Performance on the rhythm copying test was quantified in 3 ways: mean base interval estimate, number of exact matches, and intra-individual variability. To determine the mean base interval estimate, the rhythmic stimulus patterns were first redefined in terms of 250 ms units. Inter-tap intervals of 250 ms were labeled as 1, 500-ms intervals as 2, and 750-ms intervals as 3 (e.g. the stimulus pattern 500, 250, 500, 750, 250 became 2, 1, 2, 3, 1). The number of 250-ms units in each stimulus pattern was determined (e.g. the example has 9 units). The sum time between taps was calculated for each participant and trial and then divided by the number of 250-ms units in the trial to yield the base interval estimate for the trial. The arithmetic average of the estimates for all 14 trials is the mean base interval estimate.

The first step in determining both the number of exact matches and intra-individual variability was, for each tap, to subtract when the participant should have tapped from when the participant actually tapped. Differences of 0 were "exact matches". To calculate intra-individual variability, the absolute value of the difference between when the participant tapped and should have tapped was determined for each tap. Then, the arithmetic mean of the absolute difference values for all taps was calculated.

Rhythm discrimination. Participants listened to 15 pairs of rhythmic patterns (1 practice trial, 14 experimental trials). For each pair, participants indicated whether the patterns were the same or different by clicking on a response box on the computer screen labeled "same" or "different". The seven "simple" pairs consisted of 6 50-ms long drumbeats separated by 500-ms and 250-ms inter-stimulus intervals. The seven "difficult" pairs consist of 6 50-ms long drumbeats of equal duration separated by 750-ms, 500-ms, and 250-ms inter-stimulus intervals. Rhythm discrimination was scored in terms of the number correct.

Song rhythm. Participants tapped to the rhythm of a 60-sec selection from "Home Among the Gum Trees" using the index finger of their dominant hand and the laptop keyboard space bar. The laptop recorded the timing of participants' taps. Measures included the number of missed taps and an index calculated by custom software. The algorithm for the software determined which time interval each tap fell into (which note in the song each tap corresponded to) and assigned each tap a score based on its accuracy. The arithmetic mean of the accuracy scores is the song rhythm index.

Tempo skills.

Tempo copying. A steady beat of 12 units was presented at each of six speeds: 40, 60, 80, 100, and 120, and 160 (practice trial) beats per minute. The units were 50-ms-long computer generated drumbeats. Participants were asked to tap the space bar on a laptop keyboard with the index finger of their dominant hand in synchrony with the beat and to continue tapping after the cessation of the beat until asked to stop. The computer recorded the timing of each participant's first 12 taps after the cessation of the beat. For each speed, the mean inter-tap interval (time between taps) and inter-tap interval intra-individual variability were calculated. The total number of tapping errors was calculated for each participant. A tapping error is an inter-tap interval within a trial that exceeds a participant's mean inter-tap interval for that trial by 2 or more intra-individual standard deviations.

Tempo discrimination. Two different 12-beat-long tempos were presented in each of 15 trials (1 practice, 14 experimental). Participants identified the faster tempo by clicking on response boxes on the laptop screen labeled "the first was faster" and "the second was faster". Speeds varied from 64 to 800 beats per minute. Beats were 50 ms-long computer generated drumbeats. Tempo discrimination was scored in terms of the number correct.

Tempo identification. For each of 6 trials (1 practice, 5 experimental) 20 s of an instrumental piece was played twice with different metronome overlays each time.

Participants were asked to identify the presentation in which the metronome overlay coincided with the beat by clicking on response boxes labeled “the first was correct” and “the second was correct” which appeared on the laptop screen. Tempo identification was scored in terms of the number correct.

Song beat. Participants tapped to the beat of the 60-sec selection from “Home Among the Gum Trees” using the index finger of their dominant hand. The laptop recorded the timing of participants’ taps. Measures included the number of missed taps and an index calculated by custom software. The software assigned each tap a score based on the difference between when the tap occurred and should have occurred. The arithmetic mean of these scores is the song beat index.

Rapid skills.

Note order detection. First, the ability to recognize C5 as a high pitch and C2 as a low pitch was established. Then, both notes were presented at interstimulus intervals varying from 15 to 305 ms: 10, 20, 30, 45, 60, 150, and 305. Two trials, one with the high note preceding the low note and one with the low note preceding the high note, occurred at each of the seven ISIs. The ordering of the trials was random. Participants reported the order of presentation of the high note by clicking on response boxes labeled “the first was higher” and “the second was higher” which appeared on the laptop’s screen. The notes were 50 ms in duration. Note order detection was scored in terms of number correct.

Note number detection. Participants indicated the number of drumbeats heard by using the mouse to select a number from a scroll bar and then clicking on a response box labeled “okay”. The number of drumbeats varied from two to eight. Interstimulus intervals varied from 15 to 305 ms. The drumbeats were 50 ms in length. There were 14 experimental trials and 1 practice trial. Note number detection was scored in terms of the number of correct trials.

Note number discrimination. Two groups of taps, each consisting of two to eight computer-generated drumbeats, were presented. Participants indicated whether the two groups were the same or different in terms of the number of drumbeats by clicking on “same” and “different” response boxes which appeared on the computer screen. The drumbeats were 50 ms in duration. Interstimulus intervals varied from 15 to 305 ms. There were 14 experimental trials and 1 practice trial. Note number discrimination was scored in terms of number correct.

Procedure

Testing was conducted individually in 45 to 60 min sessions with breaks as requested by the participant. Testing occurred in a small room with a table surrounded by three chairs. The researcher waited for the participant outside and led the participant into the room where he/she was asked to sit in a designated chair. Pens and two turned-over copies of the consent form lay on the table in front of the participant. A turned-away laptop with headphones and mouse sat on the table to the right of the participant. There was a chair across from and a chair to the right of the participant. The researcher sat across from the participant, introduced herself, and explained the study before asking the participant to read the consent form (APPENDIX B). If the participant agreed to take part in the study, which all participants did, he/she signed one copy of the consent form and placed it in an envelope labeled “consent form.” The second copy was offered to the participant to take at the completion of the study.

The musical aptitude tasks were administered first. The researcher moved to the seat next to the participant so the researcher could better explain the tasks and monitor performance during the practice trials (APPENDIX C). Tasks were presented in the order above on a laptop running custom software. The auditory stimuli were presented through headphones. All participant responses were recorded by the software and saved on the laptop under the participant’s randomly assigned identification number.

After the musical aptitude tests, the researcher closed and removed the laptop and gave the participant a copy of the ADHD scale (APPENDIX D). The researcher said she would leave the room to give the participant privacy while completing the scale. The participant was asked to place the completed scale in an envelope labeled with his/her participant number and then to open the door to let the researcher know he/she was finished.

The researcher then administered the WRMT-R/NU subtests. The researcher sat across from the participant with the testing easel and an audio recorder between her and the participant. An audio recording was made of the participant’s performance for scoring by a second judge. The researcher scored them while administering them and put the score sheet in the envelope labeled with the participant’s identification number. The participant was then asked to complete the demographics questionnaire (APPENDIX E). The researcher left the room while the questionnaire was being filled out. The participant was asked to open the door to the room after completing the questionnaire, placing it in the envelope, and sealing the envelope. After returning to the room, the researcher debriefed the participant (APPENDIX F), asked if the participant had any questions, and thanked the participant.

RESULTS

Group Differences

Independent-samples *t* tests were conducted to determine if between-group mean differences on the musical tasks were significant. An alpha level of .05 was used. Dyslexic participants with comorbid learning disabilities and/or ADHD were excluded from *t* tests involving variables for which they were outliers relative to the dyslexic group's mean. Outliers were defined as at least 1.65 SD away from the mean. Levene's test for equality of variances is only reported if significant.

Rhythm. Group differences were significant for some rhythm copying test variables but not others. The groups did not significantly differ in regards to mean base interval estimate, *t(*21) = -.40, *p* = .69, *d* = .17, two-tailed. The stimulus base interval was 250 ms. The mean base interval estimate for the dyslexia group was 320.95 ms (*SD* = 79.28) and for the control group was 336.73 ms (*SD* = 105.21). The number of exact matches was significantly different between groups, *t*(21) = 2.78, *p* = .011, *d* = 1.17, two-tailed. The mean number of exact matches for the dyslexia group (*M* = 2.50, *SD* = 1.18) was significantly greater than for the control group (*M* = 1.33, *SD* = .78). One dyslexic participant with comorbid ADHD and learning disability was an outlier on the exact matches variable and was excluded from the analysis. Intra-individual variability, the mean time interval from when the participant tapped to when the participant should have tapped, did not significantly differ between groups, t(18.20) = -.41, *p* = .69, *d* = .17, two-tailed. Intra-individual variability variance was significantly different between groups, Levene's test, *F* = 5.14, *p* = .03. The control group (*M* = 200.53, *SD* = 169.09) was more variable than the dyslexia group (*M* =176.83, *SD* = 101.05). Corrections for heterogeneity of variance were made to the independent *t* test.

Mean performance on the rhythm discrimination test was not significantly different between groups, *t*(15.49) = -.52, *p* = .61, *d* = .22, two-tailed. However, the groups significantly differed in regards to variance, Levene's test, *F* = 4.55, *p* = .05. The performance of the dyslexia group (*M* = 10.45, *SD* = 2.11) was significantly more variable than that of the control group (*M* = 10.83, *SD* = 1.19). The rhythm discrimination independent *t* test was corrected for violation of the homogeneity of variance assumption.

No significant group differences were found for the song rhythm task. Group differences for song rhythm as measured by the song rhythm index were not significant, *t*(20) = .46, *p* = .65, *d* = .18, two-tailed. The mean song rhythm index score was .33 (*SD* = .06) for the dyslexia group and .32 (*SD* = .05) for the control group. The groups did not significantly differ according to the number missed taps on the song rhythm task, *t*(20) = -.48, *p* = .64, *d* = .21, two-tailed. The mean number of missed taps was 61.20 (*SD* = 15.37) for the dyslexia group and 64.75 (*SD* = 18.57) for the control group. All participants had missed taps. As an outlier, one dyslexic participant with a comorbid learning disability was excluded from the above analyses.

Tempo. Significant group differences were found for some tempos on the tempo copying test. Group differences in mean inter-tap interval at 40 BPM were not significant, *t*(21) = 1.09, *p* = .29, *d* = .45, two-tailed. The mean inter-tap interval at 40

BPM (1500 ms) was 1566.05 ms (*SD* = 397.27) for the dyslexia group and 1439.58 ms (*SD* = 12.84) for the control group. One-sample *t* tests were performed to compare the mean inter-tap intervals of the dyslexia and control groups to the stimulus value, 1500 ms. The mean inter-tap interval of the dyslexia group did not significantly differ from 1500 ms, *t(*10) = .55, *p* = .59, *d* = .17, two-tailed. The mean inter-tap interval of the control group did significantly differ from 1500 ms, *t*(11) = -2.84, *p* = .016, *d* = 4.71, two-tailed. An independent *t* test revealed the between groups difference in mean inter-tap interval intra-individual variability at 40 BPM was not significant, *t*(10.17) = 1.49, *p* = .17, *d* = .64, two-tailed. The groups significantly differed in regards to variance on the intra-individual variability variable, Levene's test, *F* = 5.46, *p* = .03. The dyslexia group had greater variability in inter-tap interval intra-individual variability (*M*=161.69, S*D* = 208.88) than the control group (*M* = 67.34, *SD* = 19.96). Corrections for heterogeneity of variance were made to the independent *t* test for inter-tap interval intra-individual variability.

No significant group differences in mean inter-tap interval, *t*(20) = 2.74, *p* =.013, *d* = 1.17, two-tailed, or inter-tap interval intra-individual variability, *t*(20) = .73, *p* = .48, *d* = .30, two-tailed, were found for 60 BPM. The mean inter-tap interval at 60 BPM (1000 ms) was 993.87 ms (*SD* = 40.26) for the dyslexia group and 969.30 ms (*SD* = 66.85) for the control group. One-sample *t* tests for the dyslexia group, *t*(9) = -.48, *p* = .64, *d* = .15, two-tailed, and the control group, *t*(11)= -1.59, *p* = .14, *d* = .46, two-tailed, revealed neither group significantly differed from the stimulus value of 1000 ms. The mean inter-tap interval intra-individual variability at 60 BPM was 56.07 ms (*SD* = 27.56) for the dyslexia group and 49.20 ms (*SD* = 16.23) for the control group. One dyslexic participant with comorbid ADHD and learning disability was eliminated from the analyses at 60 BPM due to being an outlier.

Group differences in mean inter-tap interval at 80 BPM were significant, *t*(21) = 2.31, *p* =.03, *d* = .96, two-tailed. The mean inter-tap interval at 80 BPM (750 ms) was 750.60 ms (*SD* = 32.34) for the dyslexia group and 721.65 ms (*SD* = 27.81) for the control group. One-sample *t* tests revealed the mean inter-tap interval of the dyslexia group did not significantly differ from 750 ms, *t*(10) = .06, *p* = .95, *d* = .02, two-tailed, whereas the mean inter-tap interval of the control group did significantly differ, *t*(11) = -3.53, *p* = .005, *d* = 1.02, two-tailed. No significant differences were found for inter-tap interval intra-individual variability at 80 BPM, *t(*21) = .73, *p* = .47, *d* = .30, two-tailed. The mean inter-tap interval intra-individual variability at 80 BPM was 40.86 ms (*SD* = 19.47) for the dyslexia group and 35.87 ms (*SD* = 12.84) for the control group.

The mean inter-tap interval at 100 BPM differed significantly between groups, *t*(20) = 2.74, *p* =.013, *d* = 1.17, two-tailed. A one-sample *t* test revealed the mean inter-tap interval for the dyslexia group (*M* = 599.24, *SD* = 15.60) was not significantly different from the stimulus value of 600 ms, *t*(9) = -.16, *p* = .88, *d* = .05, two-tailed. The mean inter-tap interval for the control group (*M* = 581.00, *SD* = 15.51) significantly differed from the stimulus value, *t*(11) = -4.24, *p* = .001, *d* = 1.23, two-tailed. One dyslexic participant with comorbid ADHD and learning disability was eliminated from the mean inter-tap interval analyses at 100 BPM as he was an outlier. A significant group difference was also found for inter-tap interval intra-individual variability at 100 BPM, *t(*21) = 1.98, *p* = .06, *d* = .82, two-tailed. The mean inter-tap interval intra-individual variability of the dyslexia group (*M* = 39.27, *SD* = 16.07) was significantly greater than the control group's (*M* =28.41, *SD* = 9.71).

No significant group differences in mean inter-tap interval, *t*(21) = 1.60, *p* = .13, *d* = .66, two-tailed, or inter-tap interval intra-individual variability, *t*(21) = -.94, *p* = .36, *d* = .39, two-tailed, were found for 120 BPM. The mean inter-tap interval at 120 BPM (500 ms) was 498.50 ms (*SD* = 23.22) for the dyslexia group and 485.33 ms (*SD* = 16.04) for the control group. The mean inter-tap interval intra-individual variability was 25.10 ms (*SD* = 10.93) for the dyslexia group and 29.29 ms (*SD* = 10.43) for the control group. One-sample *t* tests comparing the obtained mean inter-tap intervals to the stimulus value of 500 ms revealed the mean inter-tap interval for the dyslexia group was not significantly different from 500 ms, *t(*10) = -.22, *p* = .83, *d* = .06, two-tailed, but the mean for the control group was significantly different, *t*(11) = -3.17, *p* = .009, *d* = .91, two-tailed.

Tapping errors, inter-tap intervals within a trial that exceed a participant's mean inter-tap interval for that trial by at least 2 SD, were calculated for the tempo copying trials (Wolff et al., 1990). An independent *t* test revealed no significant group difference in the mean number of tapping errors when all trials were combined, *t(*21) = - .09, *p* = .93, *d* = .04, two-tailed. The mean number of tapping errors was 1.45 (*SD* = 1.21) for the dyslexia group and 1.50 (*SD* = 1.17) for the control group.

Analysis revealed no significant group difference on the tempo discrimination test, *t*(21) = -.16, *p* = .88, *d* = .06, two-tailed. The mean number correct out of 14 was 10.73 (*SD* = 2.11) for the dyslexia group and 10.83 (*SD* = 1.19) for the control group.

The mean performance of the groups on the tempo identification test did not significantly differ, *t* (15.52) = -1.2, *p* = .24, *d* = .50, two-tailed. Variance was significantly different between groups, Levene's test, *F* = 6.10, *p* = .02. The performance of the dyslexia group (*M* = 4.55, *SD* = .69) on the tempo identification test was significantly more variable than that of the control group (*M* = 4.83, *SD* = .39). Corrections for heterogeneity of variance were made to the independent *t* test.

No significant group differences were found for the song beat task. Song beat index performance was not significantly different between groups, *t*(18) = -.83, *p* = .41, *d* = .40, two-tailed. The dyslexia group's mean song beat index score was .36 (*SD* = .10) and the control group's mean song beat index score was .40 (*SD* = .10). The groups did not significantly differ in regards to the number of taps missed on the song beat task, *t*(18) = .634, *p* = .53, *d* = .28, two-tailed. The mean number of missed taps was 33.11 (*SD* = 25.92) for the dyslexia group and 25.82 (*SD* = 25.34) for the control group. All participants had missed taps. The song beat performance of 2 dyslexic participants and 1 control participant was not measured due to software malfunction.

Rapid perception. No significant group differences were found for the note order detection test, *t*(21) = -.35, *p* = .73, *d* = .15, two-tailed. The mean number correct out of 14 was 13.09 (*SD* = 1.22) for the dyslexia group and 13.25 (*SD* = .97) for the control group.

Analysis revealed no significant group differences on the note number detection test, *t* (20) = .23, *p* = .82, *d* = .09, two-tailed. The mean number correct out of 14 was 1.00 (*SD* = .67) for the dyslexia group and .92 (*SD* = 1.00) for the control group. One dyslexic participant with a comorbid learning disability was excluded from the analysis, as he was an outlier.

No significant group differences were found for the note number discrimination test, *t*(21) = .27, *p* = .79, *d* = .11, two-tailed. The mean number correct out of 14 was .82 (*SD* = .75) for the dyslexia group and .75 (*SD* = .45) for the control group. Performance on the note number detection test was significantly less than chance (7 out of 14) for the sample, one sample *t*(22) = -49.72, *p* < .001, two-tailed.

Correlations

Zero-order correlations. Zero-order correlations were performed to examine relationships between the main predictor variables: Word Identification standard score, Word Attack standard score, duration of musical training (in years), ADHD scale total score, inattention subscale score, hyperactivity subscale score, and impulsivity subscale score. Table 1 shows correlations for the entire sample. Table 2 displays correlations for the dyslexia group. Table 3 contains correlations for the control group. An alpha level of .05 was used for all correlations.

Table 1

Zero-order Correlations for the Entire Sample: Predictor Variables

		Word Attack	Musical Training	ADHD Total	Inattention	Hyperactivity	Impulsivity
Word ID	*r*	**.724*****	-.104	.009	.017	-.027	.049
	p	**.000**	.637	.967	.939	.903	.825
	N	**23**	23	23	23	23	23
Word Attack	*r*		.078	-.026	-.173	.159	.075
	p		.724	.907	.429	.469	.735
	N		23	23	23	23	23
Musical Training	*r*			-.174	-.339	.019	.129
	p			.428	.114	.933	.557
	N			23	23	23	23

* p < .05 (two-tailed), ** p < .01 (two-tailed), *** p < .001 (two-tailed)

Table 2

Zero-order Correlations for the Dyslexia Group: Predictor Variables

		Word Attack	Musical Training	ADHD Total	Inattention	Hyperactivity	Impulsivity
Word ID	*r*	.389	-.296	**.718***	**.803****	.394	.483
	p	.237	.377	**.013**	**.003**	.231	.133
	N	11	11	**11**	**11**	11	11
Word Attack	*r*		-.279	.592	.452	**.763****	.156
	p		.407	.055	.163	**.006**	.647
	N		11	11	11	**11**	11
Musical Training	*r*			-.260	-.302	-.209	.018
	p			.440	.366	.537	.959
	N			11	11	11	11

* p < .05 (two-tailed), ** p < .01 (two-tailed), *** p < .001 (two-tailed)

Table 3

Zero-order Correlations for the Control Group: Predictor Variables

		Word Attack	Musical Training	ADHD Total	Inattention	Hyperactivity	Impulsivity
Word ID	*r*	.182	-.237	.066	.207	-.072	-.046
	p	.572	.458	.840	.519	.823	.888
	N	12	12	12	12	12	12
Word Attack	*r*		.308	.292	.061	.258	.395
	p		.330	.357	.851	.418	.204
	N		12	12	12	12	12
Musical Training	*r*			.009	-.416	.322	.248
	p			.977	.179	.307	.437
	N			12	12	12	12

* p < .05 (two-tailed), ** p < .01 (two-tailed), *** p < .001 (two-tailed)

Relationships between the predictor variables and performance on the musical aptitude tasks were examined with zero-order correlations. Table 4 shows correlations for the entire sample, Table 5 for the dyslexia group, and Table 6 for the control group.

Table 4

Zero-order Correlations between Predictor Variables and Musical Aptitude Tasks for the Entire Sample

		Word ID	Word Attack	ADHD Total	Inattention	Hyperactivity	Impulsivity	Years of Training
Rhythm Copying Base Interval Est.	*r*	.095	.055	-.128	-.053	-.156	-.155	.033
	p	.668	.803	.561	.811	.476	.480	.880
	N	23	23	23	23	23	23	23
Rhythm Copying Exact Matches	*r*	-.298	-.340	.315	.301	.179	.286	.171
	p	.167	.113	.143	.164	.413	.185	.434
	N	23	23	23	23	23	23	23
Rhythm Copying Variability	*r*	.087	-.044	-.179	-.179	-.099	-.143	.112
	p	.693	.843	.413	.414	.652	.514	.612
	N	23	23	23	23	23	23	23
Rhythm Discrimination Test	*r*	.307	.276	.311	.207	.289	.325	.196
	p	.155	.203	.148	.343	.181	.130	.370
	N	23	23	23	23	23	23	23
Song Rhythm Index	*r*	.251	.070	-.039	-.083	-.088	.236	.108
	p	.248	.751	.861	.708	.688	.279	.622
	N	23	23	23	23	23	23	23
Song Rhythm Missed	*r*	-.231	-.069	.119	.134	.183	-.184	-.122
	p	.289	.754	.588	.542	.405	.401	.580
	N	23	23	23	23	23	23	23
Mean ITI 40 BPM	*r*	-.011	-.207	.075	.078	.143	-.155	.174
	p	.959	.343	.734	.723	.514	.480	.426
	N	23	23	23	23	23	23	23
Intra-individual Variability 40 BPM	*r*	-.212	-.372	-.146	-.195	.069	-.270	.193
	p	.331	.080	.505	.372	.754	.213	.376
	N	23	23	23	23	23	23	23
Mean ITI 60 BPM	*r*	-.145	.047	**.413***	**.473***	.245	.113	-.249
	p	.508	.832	**.050**	**.023**	.260	.608	.251
	N	23	23	**23**	**23**	23	23	23
Intra-individual Variability 60 BPM	*r*	-.202	.011	.233	.265	.203	-.057	-.232
	p	.356	.961	.284	.222	.353	.797	.287
	N	23	23	23	23	23	23	23
Mean ITI 80 BPM	*r*	-.399	**-.423***	.244	**.413***	-.014	-.015	-.203
	p	.060	**.044**	.262	**.050**	.948	.946	.353
	N	23	**23**	23	**23**	23	23	23
Intra-individual Variability 80 BPM	*r*	-.185	-.194	-.288	-.252	-.226	-.203	-.204
	p	.397	.374	.182	.245	.301	.352	.350
	N	23	23	23	23	23	23	23

Mean ITI 100 BPM	*r*	**-.461***	-.215	.261	.326	.137	.023	.230
	p	**.027**	.324	.230	.128	.532	.918	.292
	N	**23**	23	23	23	23	23	23
Intra-individual Variability 100 BPM	*r*	-.335	-.360	-.191	-.239	.003	-.226	.230
	p	.118	.091	.382	.272	.990	.299	.292
	N	23	23	23	23	23	23	23
Mean ITI 120 BPM	*r*	-.128	.000	**.429***	**.540****	.223	.035	-.101
	p	.559	.999	**.041**	**.008**	.306	.874	.647
	N	23	23	**23**	**23**	23	23	23
Intra-individual Variability 120 BPM	*r*	.113	.049	**-.429***	**-.529****	-.082	-.354	.011
	p	.607	.826	**.041**	**.009**	.710	.098	.962
	N	23	23	**23**	**23**	23	23	23
Tempo Copying Tapping Errors	*r*	.159	.274	.010	-.025	.082	-.040	.109
	p	.469	.206	.963	.910	.708	.855	.622
	N	23	23	23	23	23	23	23
Tempo Discrimination Test	*r*	-.015	-.168	-.061	-.004	-.118	-.049	**.428***
	p	.944	.443	.782	.984	.591	.825	**.042**
	N	23	23	23	23	23	23	**23**
Tempo Identification Test	*r*	.188	.189	.157	.135	.050	.263	.001
	p	.389	.387	.476	.539	.821	.225	.997
	N	23	23	23	23	23	23	23
Song Beat Index	*r*	.172	.240	.161	.081	-.017	**.553***	.396
	p	.468	.307	.499	.733	.943	**.011**	.084
	N	20	20	20	20	20	**20**	20
Song Beat Missed	*r*	-.120	-.245	-.155	-.119	.061	**-.509***	-.358
	p	.613	.298	.515	.617	.798	**.022**	.121
	N	20	20	20	20	20	**20**	20
Note Order Detection	*r*	.140	.036	-.046	-.051	.061	-.198	**.556****
	p	.525	.872	.834	.819	.782	.365	**.006**
	N	23	23	23	23	23	23	**23**
Note Number Detection	*r*	.075	-.235	.222	.227	.225	-.046	-.022
	p	.734	.280	.309	.298	.301	.836	.920
	N	23	23	23	23	23	23	23
Note Number Discrimination	*r*	-.091	-.317	-.229	-.288	-.065	-.128	.107
	p	.679	.140	.294	.183	.767	.562	.628
	N	23	23	23	23	23	23	23

* p < .05 (two-tailed), ** p < .01 (two-tailed), *** p < .001 (two-tailed)

Table 5

Zero-order Correlations between Predictor Variables and Musical Aptitude Tasks for the Dyslexia Group

		Word ID	Word Attack	ADHD Total	Inattention	Hyperactivity	Impulsivity	Years of Training
Rhythm Copying Base Interval Est.	*r*	-.116	.197	.056	.298	-.263	-.139	-.404
	p	.734	.562	.871	.373	.435	.684	.218
	N	11	11	11	11	11	11	11
Rhythm Copying Exact Matches	*r*	-.065	.010	.155	.172	-.016	.344	.248
	p	.849	.977	.648	.614	.962	.301	.462
	N	11	11	11	11	11	11	11
Rhythm Copying Variability	*r*	-.165	-.189	-.142	.035	-.344	-.184	-.346
	p	.628	.579	.677	.919	.301	.589	.297
	N	11	11	11	11	11	11	11
Rhythm Discrimination Test	*r*	.357	.428	.318	.334	.220	.190	.168
	p	.280	.189	.340	.315	.516	.576	.621
	N	11	11	11	11	11	11	11
Song Rhythm Index	*r*	.258	.090	-.159	-.193	-.207	.217	-.078
	p	.445	.792	.640	.570	.542	.521	.821
	N	11	11	11	11	11	11	11
Song Rhythm Missed	*r*	-.111	-.085	.244	.240	.334	-.175	.007
	p	.745	.805	.470	.477	.316	.606	.983
	N	11	11	11	11	11	11	11
Mean ITI 40 BPM	*r*	.450	-.003	-.001	-.015	.166	-.328	.277
	p	.164	.993	.999	.966	.626	.324	.410
	N	11	11	11	11	11	11	11
Intra-individual Variability 40 BPM	*r*	.128	-.354	-.335	-.431	.012	-.472	.380
	p	.708	.286	.313	.186	.973	.143	.250
	N	11	11	11	11	11	11	11
Mean ITI 60 BPM	*r*	.165	**.628***	.453	.539	.275	.131	-.335
	p	.628	**.038**	.161	.087	.413	.700	.314
	N	11	**11**	11	11	11	11	11
Intra-individual Variability 60 BPM	*r*	.063	.568	.176	.302	.078	-.212	-.345
	p	.854	.069	.604	.366	.821	.532	.299
	N	11	11	11	11	11	11	11
Mean ITI 80 BPM	*r*	-.030	.218	.266	.389	.086	-.011	-.567
	p	.930	.520	.429	.237	.802	.974	.069
	N	11	11	11	11	11	11	11
Intra-individual Variability 80 BPM	*r*	-.301	-.372	-.566	**-.638***	-.360	-.256	-.202
	p	.369	.259	.069	**.035**	.277	.448	.550
	N	11	11	11	**11**	11	11	11
Mean ITI 100 BPM	*r*	.045	.421	.186	.126	.255	.070	.310
	p	.895	.198	.584	.712	.450	.837	.354
	N	11	11	11	11	11	11	11
Intra-individual Variability 100 BPM	*r*	-.054	-.209	-.524	-.485	-.390	-.480	.130
	p	.876	.537	.098	.130	.236	.135	.703
	N	11	11	11	11	11	11	11

Mean ITI 120 BPM	*r*	.345	.587	**.676***	**.695***	.548	.267	-.035
	p	.300	.058	**.023**	**.017**	.081	.428	.919
	N	11	11	**11**	**11**	11	11	11
Intra-individual Variability 120 BPM	*r*	-.318	-.533	**-.606***	**-.604***	-.347	**-.636***	-.009
	p	.341	.091	**.048**	**.049**	.296	**.036**	.980
	N	11	11	**11**	**11**	11	**11**	11
Tempo Copying Tapping Errors	*r*	.410	.542	.206	.286	.067	.044	-.031
	p	.210	.085	.543	.394	.844	.898	.927
	N	11	11	11	11	11	11	11
Tempo Discrimination Test	*r*	.218	.284	.089	.196	-.024	-.121	.552
	p	.520	.397	.795	.563	.944	.723	.079
	N	11	11	11	11	11	11	11
Tempo Identification Test	*r*	-.099	.208	.353	.461	.062	.302	-.135
	p	.771	.540	.287	.154	.856	.366	.691
	N	11	11	11	11	11	11	11
Song Beat Index	*r*	-.415	.343	-.044	.012	-.275	.314	.236
	p	.267	.366	.910	.975	.473	.410	.541
	N	9	9	9	9	9	9	9
Song Beat Missed	*r*	.412	-.357	.073	.013	.297	-.286	-.318
	p	.270	.346	.852	.973	.437	.455	.405
	N	9	9	9	9	9	9	9
Note Order Detection	*r*	.099	-.028	-.024	.110	-.110	-.284	.471
	p	.772	.934	.944	.748	.746	.398	.143
	N	11	11	11	11	11	11	11
Note Number Detection	*r*	.173	-.001	.273	.386	.214	-.251	-.459
	p	.610	.997	.416	.241	.526	.456	.156
	N	11	11	11	11	11	11	11
Note Number Discrimination	*r*	-.094	-.528	-.441	-.503	-.176	-.411	-.029
	p	.784	.095	.175	.115	.604	.209	.933
	N	11	11	11	11	11	11	11

* $p < .05$ (two-tailed), ** $p < .01$ (two-tailed), *** $p < .001$ (two-tailed)

Table 6

Zero-order Correlations between Predictor Variables and Musical Aptitude Tasks for the Control Group

		Word ID	Word Attack	ADHD Total	Inattention	Hyperactivity	Impulsivity	Years of Training
Rhythm Copying Base Interval Est.	*r*	.163	-.154	-.312	-.418	-.050	-.155	.329
	p	.612	.634	.323	.176	.877	.631	.297
	N	12	12	12	12	12	12	12
Rhythm Copying Exact Matches	*r*	.334	-.143	.335	.125	.387	.192	.221
	p	.288	.658	.288	.698	.214	.550	.490
	N	12	12	12	12	12	12	12
Rhythm Copying Variability	*r*	.148	-.162	-.220	-.397	.081	-.116	.362
	p	.647	.614	.493	.201	.804	.720	.247
	N	12	12	12	12	12	12	12
Rhythm Discrimination Test	*r*	.424	.114	.536	.124	.526	**.611***	.237
	p	.170	.725	.072	.701	.079	**.035**	.458
	N	12	12	12	12	12	**12**	12
Song Rhythm Index	*r*	.542	-.010	.308	.254	.139	.292	.370
	p	.069	.975	.330	.425	.666	.357	.237
	N	12	12	12	12	12	12	12
Song Rhythm Missed	*r*	**-.593***	.043	-.208	-.169	-.082	-.220	-.282
	p	**.042**	.894	.517	.600	.799	.491	.375
	N	**12**	12	12	12	12	12	12
Mean ITI 40 BPM	*r*	-.050	-.356	-.040	-.054	-.148	.225	.083
	p	.878	.256	.902	.868	.646	.483	.797
	N	12	12	12	12	12	12	12
Intra-individual Variability 40 BPM	*r*	.043	.355	-.073	-.130	.055	-.089	-.395
	p	.894	.257	.823	.687	.865	.782	.204
	N	12	12	12	12	12	12	12
Mean ITI 60 BPM	*r*	.251	.174	-.017	-.090	.050	.025	-.070
	p	.431	.589	.958	.782	.878	.938	.829
	N	12	12	12	12	12	12	12
Intra-individual Variability 60 BPM	*r*	-.036	-.108	.074	-.545	**.592***	.235	.080
	p	.911	.739	.820	.067	**.043**	.463	.806
	N	12	12	12	12	**12**	12	12
Mean ITI 80 BPM	*r*	-.092	-.502	-.176	.096	-.364	-.125	.236
	p	.775	.097	.585	.767	.245	.700	.460
	N	12	12	12	12	12	12	12
Intra-individual Variability 80 BPM	*r*	.216	.206	.097	.362	-.094	-.195	-.188
	p	.500	.522	.764	.247	.771	.544	.558
	N	12	12	12	12	12	12	12
Mean ITI 100 BPM	*r*	-.104	.311	-.088	.156	-.244	-.156	-.419
	p	.749	.325	.786	.628	.444	.628	.175
	N	12	12	12	12	12	12	12
Intra-individual Variability 100 BPM	*r*	.042	.040	-.007	-.462	.514	-.050	.561
	p	.897	.902	.982	.131	.087	.878	.058
	N	12	12	12	12	12	12	12

Mean ITI 120 BPM	*r*	.141	.189	-.362	-.060	-.431	-.326	-.132
	p	.662	.555	.247	.853	.162	.301	.682
	N	12	12	12	12	12	12	12
Intra-individual Variability 120 BPM	*r*	.151	.171	-.070	-.366	.308	-.079	-.007
	p	.638	.595	.829	.242	.330	.808	.982
	N	12	12	12	12	12	12	12
Tempo Copying Tapping Errors	*r*	.076	.264	-.285	-.544	.112	-.112	.242
	p	.813	.406	.369	.068	.729	.729	.448
	N	12	12	12	12	12	12	12
Tempo Discrimination Test	*r*	-.346	**-.728****	-.253	-.257	-.207	.011	.326
	p	.270	**.007**	.428	.419	.518	.973	.301
	N	12	**12**	12	12	12	12	12
Tempo Identification Test	*r*	.038	-.349	.049	-.267	.186	.336	.158
	p	.906	.266	.879	.401	.562	.285	.624
	N	12	12	12	12	12	12	12
Song Beat Index	*r*	.420	.026	**.636***	.372	.305	**.846****	.498
	p	.198	.941	**.035**	.261	.361	**.001**	.119
	N	11	11	**11**	11	11	**11**	11
Song Beat Missed	*r*	-.374	-.122	**-.630***	-.467	-.229	**-.769****	-.366
	p	.257	.721	**.038**	.148	.499	**.006**	.268
	N	11	11	**11**	11	11	**11**	11
Note Order Detection	*r*	.185	-.038	-.018	-.297	.344	-.097	**.656***
	p	.565	.906	.956	.348	.274	.765	**.020**
	N	12	12	12	12	12	12	**12**
Note Number Detection	*r*	**.634***	-.310	.015	-.204	.184	.113	.463
	p	**.027**	.327	.962	.525	.567	.727	.130
	N	**12**	12	12	12	12	12	12
Note Number Discrimination	*r*	-.049	-.300	.191	.100	.108	.248	.340
	p	.879	.343	.553	.757	.738	.437	.280
	N	12	12	12	12	12	12	12

* $p < .05$ (two-tailed), ** $p < .01$ (two-tailed), *** $p < .001$ (two-tailed)

Partial correlations. Significant zero-order correlations between musical aptitude tasks and Word Identification, Word Attack, and duration of musical training were followed up with partial correlations controlling for the total score on the ADHD scale.

All of the relationships with significant zero-order correlations involving the entire sample remained significant after controlling for scores on the ADHD scale. The relationship for the entire sample between Word Attack and mean inter-tap interval at 80

BPM remained significant after adjusting for the effect of scores on the ADHD scale, *pr* = -.44, *n* = 23, *p* = .04. For the entire sample, Word Identification scores significantly correlated with mean inter-tap interval at 100 BPM after controlling for ADHD scale scores, *pr* = -.47, *n* = 23, *p* = .03. Performance on the note order detection task was significantly related to the duration of musical training in the entire sample after controlling for ADHD scale scores, *pr* = .56, *n* = 23, *p* < .01.

The only correlation involving the dyslexia group did not remain significant after adjusting for the effects of ADHD scores. Word Attack performance did not significantly correlate with mean inter-tap interval at 60 BPM in the dyslexia group after controlling for scores on the ADHD scale, *pr* = .49, *n* = 11, *p* = .15. The value of the correlation coefficient decreased from .63. The loss of statistical significance thus appears to be due, at least in part, to the fact the magnitude of the relationship between Word Attack performance and mean inter-tap interval at 60 BPM is decreased by controlling for ADHD scores rather than solely due to the fact that partial correlations have fewer *df* than zero-order correlations.

Most relationships involving the control group remained significant after controlling for ADHD scale scores. Musical training duration was significantly related to performance on the note order detection task in the control group when ADHD was controlled for, *pr* = .66, *n* = 12, *p* = .03, two-tailed. After adjusting for the effects of scores on the ADHD scale, Word Attack and tempo discrimination task performance were significantly correlated in the control group, *pr* = -.74, *n* = 12, *p* = .01, two-tailed. Word Identification and note number detection performance remained significantly correlated in the control group after controlling for ADHD scores, *pr* = .66, *n* = 12, *p* = .03, two-tailed. The relationship between Word Identification scores and the number missed on the song rhythm task became marginally significant once the effects of ADHD scores were adjusted for, *pr* = - .57, *n* = 12, *p* = .07, two-tailed. The correlation coefficient decreased from -.59.

Outliers

The number of lower performing outliers on each task was determined. Tempo copying mean inter-tap interval and tempo copying inter-tap interval intra-individual variability outliers were calculated relative to the mean for the entire sample. Outliers on all other measures were calculated relative to the control mean. The mean for the entire sample was used for the tempo copying mean inter-tap interval and inter-tap interval intra-individual variability variables because the dyslexia group outperformed the control group on some of them. Lower performing outliers were defined as 1.65 SD below the designated mean if higher scores indicated better performance, 1.65 SD above the mean if higher scores indicated worse performance, and 1.65 SD away from the mean in either direction if performance quality was not inherently related to direction (e.g. mean inter-tap interval). There were no outliers on tempo identification, song beat index, song beat missing taps, note order detection, note number detection, or note number discrimination. The number and frequency of dyslexic and control outliers on the mean inter-tap interval and inter-tap interval intra-individual variability variables for tempo copying are shown in Table 7. The number and frequency of dyslexic and control outliers on all other variables with outliers are shown in Table 8. The number of tasks each participant was an outlier on was calculated. An independent-*t* test revealed no significant group difference in mean number of outliers, *t*(9) = 1.11, *p* = .30, *d* = .66, two-tailed. The mean number of outliers for the dyslexia group was 4.09 (*SD* = 3.02). The mean for the control group was 2.75 (*SD* = 2.83).

Table 7

Number and Frequency of Mean Inter-tap Interval and Inter-tap Interval Intra-individual Variability Outliers Relative to the Mean for the Entire Sample

BPM		Dyslexia	Control	Fisher's Exact Test 2-sided
40	Mean	3 (27.27%)	1 (8.33%)	.32
	Variability	4 (36.36%)	1 (8.33%)	.16
60	Mean	3 (27.27%)	2 (16.67%)	.64
	Variability	3 (27.27%)	2 (16.67%)	.64
80	Mean	4 (36.36%)	2 (16.67%)	.37
	Variability	3 (27.27%)	2 (16.67%)	.64
100	Mean	1 (9.09%)	2 (16.67%)	1.00
	Variability	4 (36.36%)	1 (8.33%)	.16
120	Mean	2 (18.18%)	1 (8.33%)	.59
	Variability	2 (18.18%)	1 (8.33%)	.59

Table 8

Number and Frequency of Outliers Relative to the Control Mean on Select Musical Aptitude Tasks

Test	Measure	Dyslexia	Control	Fisher's Exact Test 2-sided
Song Rhythm	Index	1 (9.09%)	2 (16.67%)	1.00
	Missed	3 (27.27%)	3 (25.00%)	1.00
Rhythm Copying	Base Interval Estimate	2 (18.18%)	3 (25.00%)	1.00
	Exact Matches	2 (18.18%)	1 (8.33%)	.59
	Intra-individual Variability	1 (9.09%)	2 (16.67%)	1.00
Rhythm Discrimination	Number Correct	3 (27.27%)	2 (16.67%)	.64
Tempo Copying	Tapping Errors	2 (18.18%)	2 (16.67%)	1.00
Tempo Discrimination	Number Correct	2 (18.18%)	3 (25.00%)	1.00

DISCUSSION

Hypothesis 1 was not supported. The dyslexia group did not perform more poorly than the control group on the rhythm tasks. The only significant group difference on the rhythm tasks involved the number of exact matches in rhythm copying. The dyslexia group outperformed the control group with a greater mean number of exact matches. Group differences in mean performance on the other rhythm variables were not significant. There were trends toward better dyslexia group performance on the following: mean base interval estimate for rhythm copying (d = .17), song rhythm index (d = .18), and song rhythm missed taps (d = .21). Trends were for better performance of the control group with regards to rhythm copying intra-individual variability (d = .17) and rhythm discrimination (d = .22). Significant differences in variance were found for rhythm copying intra-individual variability and rhythm discrimination. Variance on rhythm coping intra-individual variability was higher for the control group whereas variance on rhythm discrimination was higher for the dyslexia group.

Performance on the tempo tasks was mixed (Hypothesis 2). The dyslexia group was more accurate at tempo copying as measured by the mean inter-tap interval. The mean inter-tap interval for the dyslexia group did not significantly differ from the stimulus value at any tapping rate. The mean inter-tap interval of the control group significantly differed from the stimulus value at 40, 80, 100, and 120 BPM. In all instances, the mean tapping rate of the control group was faster than the stimulus rate. Group differences in inter-tap interval intra-individual variability were only significant at

100 BPM. Interestingly, 100 BPM is often reported as the natural tapping rate (Clarke, 1999 as cited in Overy et al., 2003). Thus, measures of tapping at and around 100 BPM may be particularly sensitive (Overy et al, 2003). At 100 BPM, the mean inter-tap interval intra-individual variability of the dyslexia group was significantly greater than the control group's. Together with the findings regarding mean inter-tap interval, this means the dyslexia group was more accurate but less consistent than the control group at 100 BPM. This pattern of high accuracy and low consistency in tempo copying is consistent with trends at other tapping rates.

No significant group differences were found for the following variables: tempo copying tapping errors, tempo identification, song beat index, and number of missed taps on the song beat task. Trends were toward poorer performance of the dyslexia group with regards to inter-tap interval intra-individual variability at 40 (d = .64), 60 (d = .30), and 80 BPM (d = .30), tempo discrimination (d = .06), tempo identification (d = .50), song beat index (d = .40), and mean number of missed taps on the song beat task (d = .28). The control group tended to perform more poorly with regards to inter-tap interval intra-individual variability at 120 BPM (d = .39) and tempo copying tapping errors (d = .04). Variance significantly differed between groups on tempo copying inter-tap interval intra-individual variability at 40 BPM and the tempo identification test. In both cases, the dyslexia group had the greater variance.

No significant group differences were found on the rapid perception tasks (Hypothesis 3). Trends were toward better dyslexic group performance on the note order detection (d = .15) and note number discrimination (d = .11) tests and better control group performance on the note number detection test (*d* = .09). Interestingly, performance on the note number discrimination test was significantly less than chance. Identifying participants' strategies on the note number discrimination test may be enlightening. Did participants attempt to count the notes in each group of notes or were they basing their judgments on time elapsed?

The discriminative capacity of the rapid perception tasks was low. Most participants scored near ceiling on the note order detection test and near floor on the note number detection and note number discrimination tests. This is interesting since all three used 50 ms-long auditory stimuli and had the same ISIs. Task requirements were of course different. Participants had to make an order judgment on the note order detection task and either count or make a time same-different judgment for the note number detection and note number discrimination tasks. Despite their low discriminative capacity, the rapid perception tasks were still meaningful indicators as evidenced by significant correlations between performance on the rapid tasks and other measures.

ADHD was not associated with poorer performance on tasks measuring motor timing skills: tempo copying, rhythm copying, song beat, and song rhythm (Hypothesis 4). In fact, for the entire sample, all significant correlations between scores on the ADHD scale and the musical aptitude variables (for which direction is indicative of performance) showed higher ADHD scores were related to better musical performance. For the entire sample, mean ADHD and inattention scores were negatively correlated with inter-tap interval intra-individual variability at 120 BPM. Impulsivity scores were positively correlated with the song beat index and negatively correlated with missed taps on the song beat task. These findings could be due to a confounding third variable, dyslexia status. If this is the case, positive relationships between ADHD scores and musical task performance should not be maintained within the dyslexia and control groups. However, higher ADHD scores were associated with better musical task performance in both subsamples. In the dyslexia group, total scores on the ADHD scale and scores on the inattention subscale negatively correlated with inter-tap interval intra-individual variability at 120 BPM. Inattention negatively correlated with inter-tap interval intra-individual variability at 80 BPM. In the control group, total scores on the ADHD scale and scores on the impulsivity scale were positively correlated with song beat index scores and negatively with number missed on the song beat task. There was only one relationship in which higher ADHD scores were significantly associated with poorer musical performance. Scores on the hyperactivity subscale positively correlated with inter-tap interval intra-individual variability at 60 BPM in the control group.

This study's findings of positive associations between ADHD symptoms and musical task performance are not consistent with previous research. ADHD has been associated with a general reduction in performance on auditory tasks involving temporal cues in children with and without dyslexia (Breier, Fletcher, Foorman, Klaas, & Gray, 2003) and with difficulties in the timing of motor output (Ramus, Pidgeon, & Firth, 2003). One explanation for the current discrepant findings is the relationship between ADHD and musical performance changes with maturation. Most studies have involved children. Another difference between this and previous studies is scores on a continuous measure of ADHD symptomology were used instead of separate groups of participants with and without ADHD. Positive relationships may exist between ADHD symptomology and musical task performance in subclinical populations.

The existence of significant relationships between ADHD symptomology and musical task performance means the presence of ADHD needs to be accounted for in studies of musical task performance, particularly when the relationships between tasks are evaluated. This is especially true for this study. Significant relationships not only existed between ADHD scores and musical task performance but between ADHD scores and Word Identification and Word Attack in the dyslexia group. Word Identification scores positively correlated with the total score on the ADHD scale and scores on the inattention subscale. Scores on the hyperactivity subscale positively correlated with Word Attack scores. The finding of higher reading scores in individuals with dyslexia who have higher ADHD scores is unexpected based on the literature. In a recent study, Rommelse, Altink, Fliers, Martin, Buschgens, Hartman, Buitelaar, Faraone, Sergeant, and Oosterlaan (2009) found a positive relationship between ADHD severity and reading disability severity in children with comorbid dyslexia/ADHD. Dyslexic children without ADHD diagnoses were not included. One possible explanation for the findings in this study is individuals with less severe reading disabilities may be more likely referred for assessment and thus more likely to obtain a dyslexia diagnosis if they also exhibit ADHD symptoms.

Performance on a few of the musical tasks was associated with Word Identification and Attack scores (Hypothesis 5a). For the entire sample, the mean inter-tap interval at 80 BPM negatively correlated with Word Attack scores and the mean inter-tap interval at 100 BPM with Word Identification scores. These findings may be attributable to the dyslexia group's greater accuracy at tempo copying as measured by the mean inter-tap interval. The examination of within-group correlations is more enlightening as the confounding effects of dyslexia status are removed. In the dyslexia group, only one musical performance variable was significantly related to reading. Mean inter-tap interval at 60 BPM positively correlated with performance on Word Attack. A greater number of significant relationships were found for the control group. In the control group, Word Identification negatively correlated with the number missed on the song rhythm task and positively with note number detection. Word Attack performance was negatively related to performance on the tempo discrimination task. Psychoacoustic task performance is typically more correlated with reading in the control group than in the dyslexia group (Ahissar et al., 2000; Rosen, 2003). Researchers have attributed this to greater variability within the dyslexia group, auditory skill not being as important to reading in dyslexics as in controls, and to improved reading performance among dyslexics making reading performance not what would be predicted by auditory performance. The results of this study are consistent with the first explanation; variances tended to be greater in the dyslexia group. The last explanation seems untenable, as there were large between group differences in reading performance but not in musical task performance.

Musical timing skills were more strongly related to Word Attack performance than to Word Identification performance in the control group but not the entire sample (Hypothesis 5b). The small number of significant correlations makes it difficult to reach any conclusion. There were only two significant correlations between reading scores and musical timing variables in the entire sample. The correlation coefficient for the correlation between the mean inter-tap interval at 100 BPM and Word Identification was of greater magnitude than the correlation coefficient for the relationship between the mean inter-tap interval at 80 BPM and Word Attack. For the control group, performance on the tempo discrimination test was more strongly related to Word Attack performance than the number missed on song rhythm was to Word Identification performance.

Musical experience was associated with significantly better performance on some musical tasks (Hypothesis 6). In the entire sample, years of musical training positively correlated with scores on the tempo discrimination and note order detection tests. The correlation between years of musical training and note order detection was maintained in the control group. None of the musical aptitude variables significantly correlated with duration of musical training in the dyslexia group. The low number of significant correlations between musical experience and performance may be due to differences in the quality of musical training

The number of dyslexic outliers on any musical aptitude task was small and never significantly exceeded the number of control outliers (Hypothesis 7). In conclusion, the results of this study do not support the conclusion individuals with dyslexia are impaired on musical tasks except with regards to intra-individual variability in tempo copying at certain tempos. Performance on other musical variables was not impaired at the group level or in a significant subset of the dyslexia group. Musical performance deficits may have existed earlier and been resolved in individuals in the dyslexia group. The existence of large group differences in reading but not the musical aptitude tasks and the lack of significant correlations, especially within the dyslexia group, raise doubts about the existence of a causal relationship between tempo, rhythm, or rapid perception and reading impairment in adult dyslexia and therefore the utility of music based intervention for dyslexic adults.

APPENDIX A

Project Success Recruitment Poster

Want to participate in a psychology study?

We are looking for individuals with current or childhood diagnoses of dyslexia to participate in a 50- to 60-minute study on **dyslexia and musical task performance**

All information collected will be kept confidential.

Receive your choice of $15 *or* research participation credit

If you are interested in participating, please email: study010a@uwosh.edu. If you are currently enrolled in a psychology class that gives course credit or extra credit for participating in experiments, you can sign up on the SONA website (http://uwosh.sona-systems.com). The study is listed as 010 A.

The researcher you interact with will be unaware of your dyslexia status. All sessions are individual. Individuals with and without dyslexia are participating.

The Institutional Review Board for the protection of human participants has approved this study.

Study 010 A on SONA
study010a@uwosh.edu

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study010a@uwosh.edu

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APPENDIX B

Consent Form

Consent Form University of Wisconsin Oshkosh

The Department of Psychology supports the practice of protecting human participants in research. The following information is provided so that you can decide whether you wish to participate in the present study. Your participation is solicited but is strictly voluntary.

I, Elizabeth Huss, am a graduate student in the experimental psychology program working under the supervision of Professor Frances Rauscher. For this study you will be asked to complete a series of computerized music-related tasks and to read real and made up words. An audio recording will be made of your word reading. Finally, you will be given two questionnaires. The first asks you to rate how well statements about behaviors and mental states describe yourself. The second asks for basic demographic information and about psychological/medical conditions that could impact task performance. You may feel some of these questions are personal. We assure you all information will be confidential.

To ensure confidentiality, you will be assigned a random 3-digit number. This number will be used to label your responses instead of your name. No record will be kept of name-number correspondences. Your musical task performance information will be saved onto CDs as will the audio recording of your word reading. The questionnaires will be stored in a sealed envelope. Envelopes will not be opened until a substantial number of individuals have participated.

Please keep in mind that if you agree to participate, you will be free to withdraw at any time. If you decide not to participate in this study, at any time or for any reason, please let the researcher know and she or he will excuse you from the study. You will not be penalized should you decide not to participate. You do not need to tell the researcher your reasons for choosing not to participate. If you decide to withdraw from the study, any information collected from you up to that point will be destroyed. Only your signed consent form will be kept for our records.

Once the study is completed, we would be glad to give the results to you. In the meantime, if you have any questions, please contact:
Elizabeth Huss / husse47@uwosh.edu / 920-364-0235

If you have any complaints or concerns about your treatment as a participant in this study, please contact:
Chair, Institutional Review Board for Protection of Human Participants
c/o Grants Office
UW Oshkosh
920-424-1415

Although the chairperson may ask for your name, all complaints are kept in confidence.

Consent Statement: I have received an explanation of the study and agree to participate. I understand that my participation in this study is strictly voluntary, and that I may withdraw at any time without penalty. By signing this, I confirm that I am at least 18 years old and can give consent.

Printed Name	Signature	Date

Audio Recording Consent Statement: By signing this, I give my consent to be audio recorded.

Printed Name	Signature	Date

APPENDIX C

Participant Instructions for the Musical Aptitude Tasks

Rhythm Copying

You will hear a rhythmic pattern. After listening to the pattern, please copy it by tapping the space bar with the index finger of the hand you write with.

Rhythm Discrimination

You will hear two rhythmic patterns and will be asked whether the patterns are the same or different.

Song Rhythm

First presentation of song. Please listen to the song.

Second presentation of song. While the song is playing, please tap the space bar to the *rhythm* of the song with the index finger of the hand you write with.

Tempo Copying

A series of equally spaced beats will be presented. Please tap the space bar with the index finger of the hand you write with in time with the beats. Continue tapping after the beats are no longer presented. The researcher will let you know when to stop tapping.

Tempo Discrimination

You will hear two different tempos and will be asked to identify the faster tempo.

Tempo Identification

A song segment will be played twice with different metronome overlays each time. You will be asked to identify the presentation in which the metronome overlay is in time with the beat.

Song Beat

First presentation of song. Please listen to the song.

Second presentation of song. While the song is playing, please tap the space bar with the index finger of the hand you write with to the *beat* of the song.

Note Order Detection

A high note and a low note will be presented. You will be asked if the high note was before or after the low note.

Note Number Detection

A number of taps will be presented. You will be asked to report the number of taps.

Note Number Discrimination

Two groups of taps will be presented. You will be asked if the groups were the same or different in terms of the number of taps.

APPENDIX D

ADHD Scale

Caterino, Gómez-Benito, Balluerka, Amador-Campos, & Stock, 2009

How well do these sentences describe you when you were a child and now? **For each setting, write a 0, 1, or 2 depending on whether a sentence describes you a little (0), some (1), or a lot (2).**	As a Child	These Days		
		At My Home	At Work or School	In Social Situations
1. I avoid tasks that require a lot of mental effort.				
2. I am not organized.				
3. I forget things I ought to do and need to be reminded.				
4. Sometimes I plan actions and then do not finish them.				
5. I can't seem to relax and be quiet.				
6. I seem to lose a lot of objects				
7. I interfere with people when they are busy.				
8. It is hard for me to be still				
9. I often blurt out answers before questions are completely asked.				
10. It is hard to keep focused on tasks.				
11. I seem to talk all the time.				
12. It's hard to listen even if someone talks directly to me.				
13. I make many careless errors.				
14. I often get up even when I should stay seated.				
15. I am always going at my top speed.				
16. I am easily distracted by things around me.				
17. I cannot stand to wait for things.				
18. I feel restless—like I want to run all over the place.				

APPENDIX E

Demographics Questionnaire

For the following questions, please mark the appropriate boxes or write responses on the lines provided.

Today's Date ____________________/ 2010
mm / dd / yyyy

Date of Birth ____________________
mm / dd / yyyy

Sex:
☐ Male ☐ Female

Year in College:
☐ Freshman ☐ Sophomore ☐ Junior ☐ Senior ☐ Other

Dominant Hand:
☐ Right ☐ Left ☐ Ambidextrous

If ambidextrous, which hand do you write with?
☐ Right ☐ Left

Ethnicity:
☐ African-American
☐ Asian
☐ Caucasian (White)
☐ Hispanic
☐ Middle Eastern
☐ Native American
☐ Multi-racial (Please also mark all ethnicities you identify with)
☐ Other, please specify:________________________________

Is English your native language?
☐ Yes ☐ No

Do you have any hearing impairments?
☐ Yes ☐ No

If yes, do you use assistive devices such as hearing aids?
☐ Yes ☐ No

Have you ever had any formal musical instruction?
☐ Yes ☐ No

If yes…
What type of lessons?
☐ Private ☐ Group

What type of instruction?
☐ Instrumental ☐ Vocal

At what age did you start taking lessons?____________

Are you still taking lessons?
☐ Yes ☐ No

If no, at what age did you stop taking lessons?_______

Have you ever been diagnosed with any of the following (please mark all that apply)?
Dyslexia / Reading Disability
☐ Yes ☐ No

ADHD / ADD
☐Yes ☐ No

Specific Language Impairment (receptive and expressive oral language disorder, not the same as dyslexia)
☐Yes ☐ No

Learning Disability OTHER THAN DYSLEXIA
☐ Yes ☐ No

Dyspraxia / Developmental Coordination Disorder
☐ Yes ☐ No

Neurological Disorder
☐ Yes, please specify: ____________________________________
☐ No

If you have ever been diagnosed with dyslexia…
Are you a member of Project Success?
☐ Yes ☐ No

If not a member of Project Success, have you been approved for classroom or testing accommodations by Disability Services?

☐ Yes ☐ No

APPENDIX F

Debriefing

In this study we are interested in the relationship between music and literacy-related skills in individuals with and without a history of reading disability. The screening questions you answered when you set up your research participation account were used to recruit individuals with and without a history of reading disability. **The researcher you worked with today was not aware of your disability status**.

It has been suggested that music instruction may be a beneficial intervention for reading disability. This is supported by the existence of overlapping neural networks for music and language, studies finding musical training has positive effects on reading abilities in children without reading disabilities, and the effects of musical training on brain plasticity. Despite this, few studies have examined musical abilities in individuals with reading disabilities. All previous studies have involved children. Reading disabled children have difficulties with musical timing skills such as rhythm copying, discriminating between rhythms, clapping a beat, and identifying the longer of two notes. Some researchers believe cerebellar dysfunction causes these musical difficulties as well as reading disability. Other researchers argue difficulties in perceiving speech rhythm cause reading disability. Speech rhythm is used to segment speech into smaller units such as syllables. Developmentally, awareness of syllables and phonemes (the smallest meaningful units of speech) precedes reading. Some studies find reading disabled individuals have problems with rapid perception tasks (i.e. reporting the order of the high note). Rapid temporal processing theory proponents believe reading disability is caused by impaired perception of rapidly changing speech features. In this study, we wish to see if adults with a history of reading disability find musical timing and rapid tasks difficult and if performance on these tasks is associated with literacy-related skills.

Please accept our apologies for not telling you all of our purposes right from the beginning. We did not tell you everything about the study ahead of time as the information might have unconsciously affected your task performance. For this reason, we ask that you **not tell other students who might be participating in our research this semester what the specific purposes of this study are.** We thank you in advance for your help.

If you would like additional information concerning the study or the relationship between music and literacy, please feel free to contact the researcher (Elizabeth Huss, email: husse47@uwosh.edu).

Thank you so much for participating!

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