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Reading ability in children relates to rhythm perception across modalities

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Abstract

The onset of reading ability is rife with individual differences, with some children termed ‘early readers’ and some falling behind from the very beginning. Reading skill in children has been linked to an ability to remember non-verbal rhythms, specifically in the auditory modality. It has been hypothesized that the link between rhythm skills and reading reflects a shared reliance on the ability to extract temporal structure from sound. Here we tested this hypothesis by investigating whether the link between rhythm memory and reading depends upon the modality in which rhythms are presented. We tested 75 primary school-aged children from 7 to 11 years of age on a within-subjects battery of reading and rhythm tasks. Participants received a reading efficiency task followed by three rhythm tasks (auditory, visual, and audiovisual). Results showed that children who performed poorly on the reading task also performed poorly on the tasks that required them to remember and repeat back non-verbal rhythms. In addition, these children showed a rhythmic deficit not just in the auditory domain, but also in the visual domain. However, auditory rhythm memory explained additional variance in reading ability even once visual memory was controlled for. These results suggest that reading ability and rhythm memory rely both on shared modality-general cognitive processes and on the ability to perceive the temporal structure of sound.

Keywords: reading, rhythm, auditory, visual

1. Introduction

Reading is a foundational skill upon which the ability to be a productive member of society depends. The acquisition of reading and other language skills is one of the most complex human abilities, relying on a vast network of motor, auditory, and cognitive processes. It is likely, therefore, that impairment in any one of these processes can lead to delayed language acquisition (Protopapas, 2014). Ultimately, therefore, successful diagnosis and treatment will rely upon identification of the underlying perceptual, cognitive, and neural mechanisms that make language acquisition possible so that remediation can be targeted to the specific problems causing a child to struggle to learn to read.

Growing evidence suggests that children who struggle to read tend to have difficulty perceiving rhythmic patterns compared to neurotypical children. This rhythmic impairment has been consistently demonstrated in struggling readers of all ages. Young children at risk of developing reading disorders, for example, have difficulties with rhythmic skills, including the ability to discriminate temporal rhythms. [Overy \(2000\) found that a small sample of children at strong risk of developing dyslexia were worse at discriminating rhythms compared to children. In a higher-powered study Dellatolas et al. \(2009\) tested 695 children in kindergarten, and then again in second grade. The ability to reproduce rhythmic sequences in kindergarten predicted reading ability in second grade. Similarly, Lundetræ and Thomson \(2018\) found that the ability to synchronize to a steady beat was poorer in children below the national threshold in word reading and spelling. However, Anvari et al. \(2002\) found somewhat different results: a composite measure of music perception encompassing melody and rhythm skills predicted phonemic awareness and reading in 4-year-olds, but in 5-year-olds rhythm skills predicted phonemic awareness but not reading, while melody skills predicted both phonemic awareness and reading. In addition, rhythmic difficulties have been found in older participants who have already developed reading impairments, including](#)

primary school-aged children (Casini, Pech-Georgel, & Ziegler, 2018; Flaughnacco, et al., 2014; Huss, Verney, Fosker, Mead, & Goswami, 2011; Ozernov-Palchik, Wolf, & Patel, 2018), adolescents (Tierney, White-Schwoch, MacLean, & Kraus, 2017), and adults (Grube, Cooper, & Griffiths, 2013).

This research suggests that there is overlap in the cognitive foundations of reading acquisition and non-verbal rhythm perception. However, the nature of this overlap remains unclear. One possibility, the *auditory timing hypothesis*, is that individual differences in the ability to perceive sound timing help drive variability in both rhythm and reading skills (Tierney & Kraus, 2014). Many types of linguistic structure are cued by subtle differences in the duration of speech sounds; individual differences in duration perception, therefore, could make detection of these structures more difficult, potentially slowing the development of language skills, including reading. For example, English speakers mark boundaries between phrases by elongating phrase-final syllables and by inserting pauses between phrases (Scott, 1982). Detecting these lengthened syllables and pauses helps listeners segment phrases and sentences (Streeter, 1978; Scott, 1982) and parse syntactic structure (Marslen-Wilson, Tyler, Warren, Grenier, & Lee, 1992). Lengthened duration is also one cue to syllable stress (Nakatani & Schaffer, 1977), which can provide lexical information, help convey word emphasis, and direct attention to stressed syllables (Pitt & Samuel, 1990). The importance of speech rhythm perception for language acquisition is further supported by findings that reading skill in children is linked to sensitivity to stress patterns (Anastasiou & Protopapas, 2015; Goswami, Gerson, & Astruc, 2010; Holliman, Wood, & Sheehy, 2008; for a review see Wade-Woolley & Heggie, 2015), the ability to use temporal information to segment speech (Whalley & Hansen, 2006), and the production of durational cues to syntactic structure (Breen, Kaswer, Van Dyke, Krivokapić, & Landi, 2016).

Rhythm perception, however, does not solely rely on the detection of temporal patterns in sound. An alternate explanation for links between rhythm and reading skills is the *cognitive hypothesis*, which suggests that rhythm perception draws on many different cognitive processes that are also important for the acquisition of reading skills. For example, neuroimaging studies have shown links between rhythm perception and activation in the premotor cortex, supplementary motor area and basal ganglia (Grahn & Brett, 2007), suggesting that rhythm perception may draw upon motor planning resources (Patel & Iversen, 2014). Fine motor control tends to be disrupted in a subset of children with reading problems (Ramus, 2003). In addition, children with familial risk for dyslexia who also showed significantly slower motor development had a smaller vocabulary than at-risk children with normal motor development (Viholainen, Ahonen, Cantell, Lyytinen, & Lyytinen, 2002). Rhythm skills have also been shown to require attentional control (Birkett & Talcott, 2012; Tierney & Kraus, 2013), which has been found to be impaired in children with reading problems (Facoetti, Lorusso, Cattaneo, Galli, & Molteni, 2005). Moreover, rhythm discrimination may place stringent demands upon short-term memory, as it correlates with auditory verbal memory span (Saito, 2001), another skill that tends to be impaired in children who struggle to read (Gathercole & Baddeley, 1990). Finally, rhythm performance could reflect the precision of modality-general internal timekeeping, which has been linked to language impairment: children with dyslexia have been shown to have difficulties with both auditory and visual time perception tasks compared to age-matched controls (Casini et al. 2018).

Correlations between rhythm and reading skills are consistent with both the auditory timing and cognitive hypotheses. However, some prior studies examining the link between rhythm and reading skills have attempted to covary for potential cognitive skills which could be driving the rhythm-reading relationship. For example, Anvari et al. (2002) found that in 4-

year-olds, when digit span and phonemic awareness were entered as predictors at step 1, music perception did not predict additional variance in reading scores. Goswami et al. (2002) found that beat detection correlated with a number of language skills, including reading, after age and IQ were controlled for. Dellatolas et al. (2009) reported that rhythm reproduction in kindergarten predicted reading ability in second grade even after a large number of additional variables were controlled for, including short-term memory and visual attention/processing speed. Corriveau and Goswami (2009) found that the ability to synchronize to a metronome accounted for unique variance in language skills (including reading) even when motor dexterity was controlled for. Huss et al. (2011) found that rhythm discrimination predicted reading and spelling even when short-term memory was controlled for. Grube et al. (2013) reported that beat regularity perception correlated with word and non-word reading even after non-verbal IQ was partialled out. Flaugnacco et al. (2014) reported that rhythm discrimination predicted reading ability even after IQ was accounted for. Lundetræ and Thomson (2018) found that synchronization ability was not a significant predictor of reading ability when a variety of other tasks and demographic variables were included as predictors (including letter-sound knowledge, rapid automatized naming, short-term memory, gender, and family risk for reading difficulties). Finally, Ozernov-Palchik et al. (2018) reported that rhythm discrimination predicted additional variance in letter-sound knowledge even after IQ and non-word repetition were controlled for. Notably, none of these studies attempted to control for all of the potential cognitive factors driving rhythm performance, including attentional control, short-term memory, motor control, and domain-general internal timing, and therefore these results cannot conclusively rule out the possibility that the link between rhythm and reading skills is primarily driven by shared cognitive factors.

The ideal way to determine whether the link between rhythm and reading skills is partially driven by the ability to extract temporal structure from sound is to present the same

rhythm tests in multiple modalities. Visual and auditory rhythm reproduction tests, for example, should be similar in their cognitive demands, including all of the potentially relevant cognitive factors listed above. If, therefore, the link between rhythm and reading is partially mediated by cognitive factors, then rhythm perception should relate to reading ability even if rhythms are presented in the visual modality. However, the auditory timing hypothesis predicts that the reproduction of auditory rhythms will explain additional variance in reading ability even once visual rhythm perception performance is accounted for, given that the auditory rhythm reproduction test requires participants to extract temporal structure from sound.

To test these predictions, we asked neurotypical primary school-aged children to repeat back rhythms presented in auditory-only and visual-only conditions and examined the extent to which performance on these two different rhythm tests helped explain variance in their performance on tests of word and non-word reading. We also included an audiovisual rhythm perception condition, to test the hypothesis that this multi-modal test would tap into a third skill relevant to reading acquisition, namely, the ability to draw connections between sounds and visual stimuli. If audio-visual rhythm perception explains additional variance in reading ability even when performance on both single-modality tests is accounted for, this would suggest that domain-general audiovisual integration is foundational for reading development. We chose rhythm sequence reproduction as our primary measure of rhythmic skill because this task places a wide variety of demands on the participant: to reproduce a rhythm one must perceive the difference between interval lengths, extract the underlying tempo, encode and retain in memory the sequence of intervals, and accurately reproduce the temporal sequence at the correct tempo. Auditory rhythm reproduction is linked to activation within a widely distributed neural network, including supplementary motor area, pre-motor cortex, primary auditory cortex, basal ganglia, the left superior frontal gyrus, and right medial

prefrontal cortex (Chapin, Zanto, Jantzen, Kelso, Steinberg, & Large, 2010), suggesting that this task draws on a wide variety of auditory-motor and executive processes.

2. Methods

2.1. Participants

Data from 75 neurotypical children were included in the study. Participants were selected from two primary schools in London, in four separate school years – Years Three, Four, Five, and Six - spanning ages seven to eleven (the entirety of Key Stage 3 in the UK school system). There were 10 Year Three (mean age = 95.6 months (SD = 3.7), 3 females), 17 Year Four (mean age = 107.2 months (SD = 3.3), 7 females), 27 Year Five (mean age = 121.9 (SD = 4.3) months, 11 females), and 21 Year Six students (mean age = 135.7 (SD = 2.8) months, 14 females). Ethical approval was received from the departmental ethics committee, and informed written parental consent was obtained for each participant. As the children were all above the age of 5 years, verbal consent was obtained from the children as well. All participants had normal hearing. All testing was conducted in a quiet room within the participant's school.

2.2. Stimulus Design and Procedure

The children were presented with a battery of tests, individually, in a quiet room in one session, lasting approximately 20 minutes. The tasks were administered in a standard order: first, participants completed the TOWRE-2, then the three Rhythm Perception tasks. The order of the Rhythm Perception conditions, however, was counterbalanced across participants, with all participants receiving all three conditions.

Test of Word Reading Efficiency-Second Edition. Two subtests of the Test of Word Reading Efficiency-Second Edition (TOWRE-2; Torgesen, Wagner, & Rashotte, 2012) were presented: Sight Word Efficiency (“word reading” below) and Phonemic Decoding

Efficiency (“nonword reading”). The stimulus list for the word reading subtest consists of printed English words, whereas the nonword reading list consists of phonologically legal nonwords. The number of words or nonwords a participant could pronounce accurately in 45 seconds was measured. Raw reading scores for each subtest were converted to standard scores prior to analysis.

Rhythm Task. In order to assess auditory, visual, and audiovisual rhythm perception, participants were asked to repeat back rhythmic patterns. The stimuli for the rhythm perception task consisted of three videos (one each for the visual, auditory and auditory-visual conditions). There were ten rhythms in each test, five taken from the “strongly metrical” list in Povel and Essens (1985) and five taken from the “weakly metrical” list. Strongly metrical rhythms contained more drum hits on strong beats, whereas weakly metrical rhythms contained fewer drum hits on strong beats and more drum hits on “off-beats”. Abstract rhythmic sequences were converted to patterns of inter-stimulus-intervals by assigning 200 ms to the shortest interval in each rhythmic pattern, with the result that the rhythms were formed by concatenating intervals of 200, 400, 600, or 800 ms.

All videos featured a white background, in the center of which was a drawing of a ball. During the auditory-only test, the ball did not move, and the rhythms were presented over headphones via a sequence of presentations of a 150-ms conga drum stimulus (acquired at freesound.org). During the visual-only test, the video soundtrack was silent, and to present the rhythms the ball moved in a rectified sinusoidal trajectory, such that the onset of each “hit” in the rhythm was aligned with the point at which the ball reached a horizontal blue line in the middle of the screen, after which it rapidly rebounded. During the audiovisual test, the rhythms were presented via both the audio track and the movement of the ball, and the conga drum hits were aligned with the point at which the ball made contact with the horizontal line. Participants were told that the ball would bounce in a rhythmic pattern, and that they might

see it, hear it, or both see and hear it. Each rhythm was presented three times, after which the researcher paused the video. Participants were then asked to reproduce the rhythm by tapping a pen on the desk at which they were seated. Participants' drumming was recorded using a hand-held sound recorder.

Drumming data were processed in Matlab. First, drum onset times were extracted by setting amplitude thresholds and relaxation times for each participant. Any time point for which the amplitude exceeded the threshold and an amount of time greater than the relaxation time had elapsed since the last drum hit was marked as an onset. The absolute value of the difference between each drum interval and the nearest target interval from the set [200 400 600 800] was then extracted, normalized by dividing by the nearest target interval, and averaged across trials, forming a measurement of *tempo error*. For example, if a participant produced an interval of 220 ms, the tempo error score for this data point would be $\text{abs}(200-220)/200 = 0.1$. Note that a lower score on this measure indicates better performance. To calculate rhythm sequence reproduction accuracy, intervals between drum onsets were then quantized via transformation to the nearest interval in the set [200 400 600 800]. For example, the sequence [187 213 388 413] would become [200 200 400 400]. Next, participants' drumming was transformed into a vector of zeros and ones by assessing, for each 200 ms interval, whether it contained a drum hit (i.e. a one) or a rest (a zero). The same was done for the stimulus sequence, and the resulting vectors were compared to generate a *percent correct* score. For example, if a stimulus sequence was [1110] and the participant drummed [1010], the score assigned would be 75%.

2.3. Analysis

A Jarque-Bera test revealed that portion correct scores on all three conditions were normally distributed ($p > 0.5$). However, tempo error scores were positively skewed, and so were log

transformed prior to analysis. (Descriptive statistics reflect the untransformed values.) An RMANOVA with Greenhouse-Geiser correction for sphericity was used to examine whether performance differed across the rhythm conditions. Post-hoc Bonferroni-corrected paired t-tests were used to test pairwise differences between conditions. Relationships between reading and rhythm performance were investigated in two ways. First, Pearson correlations were calculated between performance in each of the three rhythm conditions (as assessed by both percent correct and tempo error) and word and non-word reading ability. Next, stepwise linear regressions were used to investigate the relative contribution of measures of rhythm reproduction in different sensory modalities to the explanation of variance in reading ability. Two separate regressions were run for each rhythm measure (percent correct versus tempo error), with word reading and nonword reading as the outcome measures. In the first step, visual rhythm reproduction, age, and musical training were entered, followed by auditory rhythm in the second step, and finally by audiovisual rhythm in the third and final step. We reasoned that if visual rhythm reproduction explains variation in reading ability, this would suggest that the relationship between rhythm reproduction and reading is at least partially driven by shared modality-general cognitive processes. On the other hand, if auditory rhythm reproduction explains additional variation in reading ability over and above visual rhythm reproduction, this would suggest that the relationship between rhythm and reading is partially driven by a shared reliance on the ability to extract temporal information from sound.

3. Results

Performance (percent correct) differed across rhythm perception conditions ($F(2,148) = 120.8, p < 0.001$). Post-hoc comparisons revealed that performance in the auditory-only condition ($M = 76.8\%$ correct, $SD = 8.4$) was significantly better than performance in the visual-only condition ($M = 63.8\%$ correct, $SD = 5.7$; $t(74) = 16.0, p < 0.001$). Thus, there was evidence in support of a Modality Effect ($A > V$). Performance in the audiovisual condition

($M = 76.3\%$, $SD = 10.6$) was significantly better than performance in the visual-only condition ($t(74) = 11.7$, $p < 0.001$). However, there was no significant difference between performance in the audiovisual and auditory-only conditions ($t(74) = -0.54$, $p > 0.1$). Thus, there was only evidence in support of a partial Redundancy Effect (i.e. $AV > V$, but $AV = A$).

Tempo error also differed across rhythm memory conditions ($F(2,148) = 38.34$, $p < 0.001$).

Post-hoc comparisons revealed that performance in the auditory-only condition ($M = 0.098\%$, $SD = 0.024$) was significantly better than performance in the visual-only condition ($M = 0.125\%$, $SD = 0.036$; $t(74) = 6.7$, $p < 0.001$). Thus, there was evidence in support of a Modality Effect ($A > V$). Performance in the audiovisual condition ($M = 0.096\%$, $SD = 0.028$) was significantly better than performance in the visual-only condition ($t(74) = 6.7$, $p < 0.001$). However, there was no significant difference between performance in the audiovisual and auditory-only conditions ($t(74) = 1.40$, $p > 0.1$). Thus, there was only evidence in support of a partial Redundancy Effect (i.e. $AV > V$, but $AV = A$).

Pearson's correlations were conducted to analyze the relationship between reading skills and percent correct score on the rhythm reproduction tests (see Figure 1 for scatterplots).

Participants who performed better on the word reading test also performed better on the auditory-only ($r = 0.388$, $p < 0.001$), visual-only ($r = 0.322$, $p = 0.005$), and audiovisual ($r = 0.301$, $p = 0.009$) conditions. Similarly, participants who performed better on the non-word reading test also performed better on the auditory-only ($r = 0.372$, $p < 0.001$) and visual-only ($r = 0.324$, $p = 0.005$) conditions, but there was only a trending relationship between non-word reading ability and performance on the audiovisual condition ($r = 0.218$, $p = 0.060$).

Pearson's correlations were also conducted to analyze the relationship between reading skills and tempo error scores. Participants who performed better on the word reading test more accurately reproduced the stimulus tempo for the auditory-only test ($r = -0.27$, $p = 0.020$) but not the audiovisual ($r = -0.09$, $p > 0.1$) or visual-only ($r = -0.11$, $p > 0.1$) tests. Similarly,

participants who performed better on the non-word reading test more accurately reproduced the stimulus tempo for the auditory-only test ($r = -0.29$, $p = 0.012$) but not the audiovisual ($r = -0.22$, $p > 0.05$) or visual-only ($r = -0.08$, $p > 0.1$) tests.

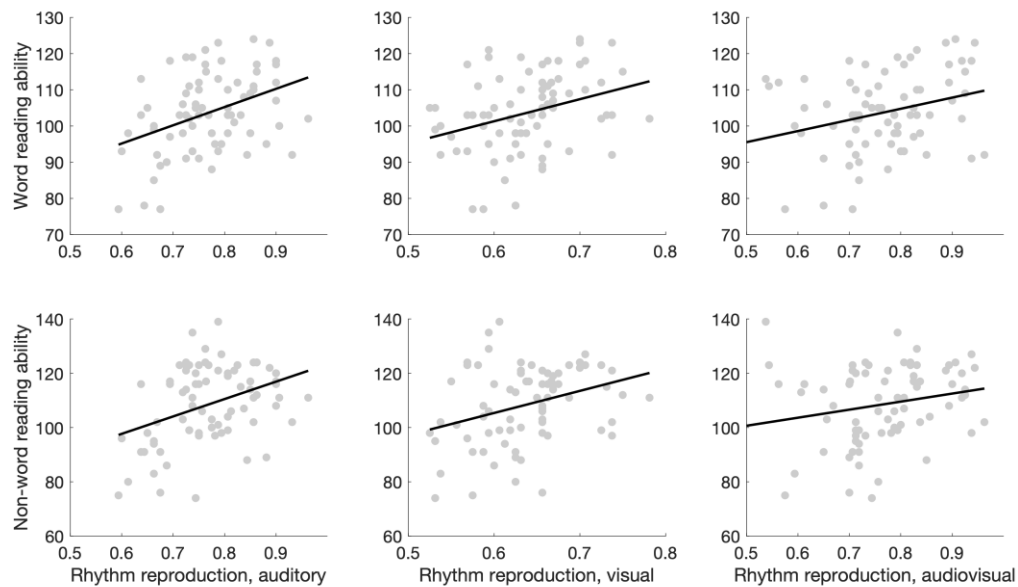


Figure 1. Scatterplot displaying the relationship between performance on three conditions of the rhythm reproduction test (auditory-only, left; visual-only, middle; audiovisual, right) and performance on two reading tests (word reading, top; non-word reading, bottom).

We investigated whether participants who played a musical instrument outperformed participants without musical experience on the rhythm and reading measures, to determine if a confounding relationship with musical experience could be driving our results. Similarly, we investigated the relationship between age and performance on the rhythm measures. Musically trained participants were defined as those who reported being able to play an instrument ($n = 51$, mean age 117.8 (SD = 13.9) months, 23 female), while musically untrained participants reported that they were unable to play an instrument ($n = 24$, mean age 123.5 (SD = 13.9) months, 12 female). Using a series of unpaired t-tests we found no significant differences between the two groups on either word reading ($t(73) = 0.68$, $p > 0.1$)

or nonword reading ($t(73) = 1.78, p > 0.05$). Similarly, we found no significant group differences on the auditory ($t(73) = 1.44, p > 0.1$), visual ($t(73) = 1.07, p > 0.1$), or audiovisual ($t(73) = 1.27, p > 0.1$) conditions of the rhythm test for the percent score, nor were there group differences for tempo error in the auditory ($t(73) = 0.48, p > 0.1$), visual ($t(73) = 0.43, p > 0.1$), or audiovisual ($t(73) = 1.00, p > 0.1$) conditions. We found that age was not significantly related to rhythm performance (percent correct) in either the auditory ($r = -0.13, p > 0.1$), visual ($r = -0.10, p > 0.1$), or audiovisual ($r = -0.01, p > 0.1$) conditions, and was not significantly related to tempo error in either the auditory ($r = -0.18, p > 0.1$), visual ($r = 0.15, p > 0.1$), or audiovisual ($r = -0.19, p > 0.1$) conditions.

To test the auditory timing hypothesis for the relationship between rhythm reproduction (measured as percent correct) and reading, we conducted two stepwise hierarchical regressions with word reading and non-word reading as outcome measures. (Raw scores on the reading tests were used, rather than standard scores, because age was included in the model as a predictor. Because raw scores were not normally distributed according to a Jacque-Bera test ($p < 0.05$) due to being negatively skewed, they underwent reflection followed by log transformation, i.e. a $\log(100-x)$ transformation.) In the first step, visual rhythm reproduction, age, and degree of musical training were entered, explaining 29.9% of the variance in word reading ($F(3,71) = 10.1, p < 0.001$) and 20.5% of the variance in nonword reading ($F(3,71) = 8.6, p < 0.01$). In the second step, auditory rhythm reproduction was entered, explaining an additional 4.3% of the variance in word reading ($F(1,70) = 4.6, p < 0.05$) and an additional 4.3% of the variance in nonword reading ($F(1,72) = 4.0, p < 0.05$). In the third step, audiovisual rhythm reproduction was entered, but it did not significantly explain additional variance in either word reading ($F(1,71) = 0.2, p > 0.1$) or nonword reading ($F(1,71) = 0.2, p > 0.1$). A subsequent analysis was run using the tempo error metric as a measurement of rhythm reproduction performance rather than percent correct. In the first

step, visual tempo error, age, and degree of musical training were entered, explaining 22.7% of the variance in word reading ($F(3,71) = 7.0, p < 0.001$) and 13.8% of the variance in nonword reading ($F(3,71) = 3.8, p < 0.05$). In the second step, auditory tempo error was entered, explaining an additional 10.7% of the variance in word reading ($F(1,70) = 11.2, p < 0.01$) and an additional 8.5% of the variance in nonword reading ($F(1,70) = 7.6, p < 0.01$). In the third step, audiovisual tempo error was entered, but it did not significantly explain additional variance in either word reading ($F(1,69) = 0.8, p > 0.1$) or nonword reading ($F(1,69) = 0.1, p > 0.1$).

4. Discussion

We have shown that children who have difficulty with word and non-word reading also struggle to repeat back non-verbal rhythms. We further show that this rhythmic deficit extends not only to rhythms presented in the auditory modality but to the visual modality as well. However, we find that auditory rhythm reproduction explains additional variance in word and non-word reading after visual rhythm reproduction is accounted for. These findings suggest that the relationship between reading ability and rhythm perception is driven both by shared modality-general cognitive processes and by a shared reliance on the ability to perceive the temporal structure of sound.

Our finding that poor reading is linked to poor visual rhythm reproduction aligns with work showing that children with reading difficulties show temporal deficits in both the auditory and visual modalities (Casini et al., 2018). An open question is what mechanism(s) can account for links between impaired reading and domain-general temporal deficits. One possibility is that decreased entrainment to low-frequency rhythms, which has recently been demonstrated in children who struggle to read (Molinaro, Lizarazu, Lallier, Bourgiognon, & Carreiras, 2016), may extend to the visual system as well as the auditory system. Another

possibility, suggested by Casini et al. (2018), is that reading problems are linked to dysfunction in a domain-general dedicated “internal clock”. Yet another possibility is that both reading and rhythm draw upon general cognitive resources, including attentional control, short-term memory, and motor planning (Foy & Mann, 2013).

Researchers investigating the link between rhythm perception and reading skills have suggested that it is driven by a shared reliance on auditory temporal precision (Huss et al., 2010, Ozernov-Palchick et al., 2018). According to this argument, both speech perception and musical rhythm perception require listeners to precisely perceive the timing of sound events. Amplitude rise time, for example, provides a cue both to the timing of the onsets of musical sounds (Gordon, 1987) and to the distinction between certain consonants (Goswami et al., 2010). Blurry perception of auditory timing, therefore, could lead children to not only have difficulty tracking musical rhythms but also to develop fuzzier speech sound categories, delaying the acquisition of phonological awareness and, consequently, the acquisition of reading. Our data support an explanation for the link between rhythm and reading skills based on auditory temporal precision, since the accuracy of auditory tempo reproduction explained additional variance in word and non-word reading after visual tempo reproduction was accounted for. However, given the link between visual rhythm sequence reproduction and reading, our results also suggest that this cannot be the only factor driving the relationship between reading ability and rhythm skills.

An extensive prior literature has investigated differences in rhythm skills for stimuli presented in the auditory versus visual modalities. For example, participants synchronize more precisely to isochronous rhythms presented in the auditory versus visual systems (Semjen & Ivry, 2001; Chen, Repp, & Patel, 2002; Repp & Penel, 2002; Patel, Iversen, & Chen, 2005; Krause, Pollok, & Schnitzler, 2010). However, this research presented static stimuli (i.e. beeps and flashes), and subsequent research has found that when the visual

stimulus is a dynamic moving object (i.e. a bouncing ball), the auditory advantage disappears, suggesting that visual temporal perception can be as accurate as auditory temporal perception as long as more ecologically valid stimuli are presented (Hove, Fairhurst, Kotz, & Keller, 2013; Iversen, Patel, Nicodemus, & Emmorey, 2015; Ono, 2018). Prior research using static stimuli has also found that performance on rhythm discrimination and reproduction tasks is better for auditory versus visual stimuli (Kolers & Brewster, 1985; Glenberg, Mann, Altman, Forman, & Procise, 1989; Glenberg & Jona, 1991; Collier & Logan, 2000). However, to our knowledge no previous studies have investigated whether the use of dynamic visual stimuli eliminates the auditory advantage for rhythm discrimination or reproduction.

Here we find a strong auditory advantage for rhythm reproduction, even though a dynamic visual stimulus was presented. This finding could be interpreted in two ways. First, temporal processing in the visual system may develop more slowly than in the auditory system. This interpretation is supported by the prior finding that 6-7-year-old children are better able to synchronize to tones than dynamic visual stimuli, but 12-15-year-old children show similar performance across the two modalities (Mu, Huang, Chao, Gu, & Wu, 2018). The second possible interpretation is that the use of dynamic visual stimuli does not eliminate the auditory advantage for rhythm reproduction because the auditory system is better able to encode auditory temporal sequences (c.f. the "auditory scaffolding hypothesis", Conway et al. 2009). This interpretation is supported by findings that both auditory and visual rhythm perception are linked to activation in the dorsal auditory pathway (Karabanov, Blom, Forsman, & Ullén, 2009), and that auditory training can improve visual rhythm perception (Barakat, Seitz, & Shams, 2015), suggesting that listeners re-code visual temporal sequences into the auditory modality. These two interpretations could be disambiguated by future research investigating auditory and visual rhythm reproduction in adults.

Musical rhythm perception/production and reading are both complex multimodal processes that draw upon a wide array of perceptual and cognitive processes. Our results suggest that both explanations based on auditory temporal processing and explanations based on modality-general cognitive processes may help explain the link between these seemingly disparate skills. These findings suggest that the use of multimodal stimuli might help enhance the efficacy of programs attempting to remediate language impairment using rhythmic training (Hallam, 2019).

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