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# Clapping in time parallels literacy and calls upon overlapping neural mechanisms in early readers

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**The auditory system is extremely precise in processing the temporal information of perceptual events and using these cues to coordinate action. Synchronizing movement to a steady beat relies on this bidirectional connection between sensory and motor systems, and activates many of the auditory and cognitive processes used when reading. Here, we use Interactive Metronome, a clinical intervention technology requiring an individual to clap her hands in time with a steady beat, to investigate whether the links between literacy and synchronization skills, previously established in older children, are also evident in children who are learning to read. We tested 64 typically developing children (ages 5–7 years) on their synchronization abilities, neurophysiological responses to speech in noise, and literacy skills. We found that children who have lower variability in synchronizing have higher phase consistency, higher stability, and more accurate envelope encoding—all neurophysiological response components linked to language skills. Moreover, performing the same task with visual feedback reveals links with literacy skills, notably processing speed, phonological processing, word reading, spelling, morphology, and syntax. These results suggest that rhythm skills and literacy call on overlapping neural mechanisms, supporting the idea that rhythm training may boost literacy in part by engaging sensory-motor systems.**

**Keywords:** synchronization; rhythm; frequency-following response; reading; auditory processing

## Introduction

Musical training, especially training that focuses on cross-modal integration among visual, auditory, and motor systems, benefits literacy-related language skills, presumably because it enhances the dynamic connection between these different brain areas important for literacy.[1] Indeed, the interaction between sensory and motor systems when synchronizing to an external isochronous (i.e., steady) rhythm has been proposed as the reason why music training can benefit literacy.[2,3] This link between synchronization ability and language/reading skills is well established in both typical and atypical populations.[4–9] However, the mechanisms underlying this link need to be further explored to disentangle the role that different systems involved in rhythm tasks play in shaping specific aspects of auditory processing and literacy.

Synchronizing a movement to a steady beat requires a repeated and stable interaction between the auditory and motor systems with an undoubtedly strong demand of the fine temporal resolution of the auditory system. The frequency-following response (FFR), a predominantly subcortical evoked response to a complex sound, such as speech, that indexes the microsecond precision of auditory processing,[10,11] has been used to study the link between motor and auditory systems. Several parameters can be extracted from the FFR: stability of the brainstem's representation of sound from trial to trial; phase consistency of the neural firing to a specific frequency range of the stimulus; and envelope accuracy, the fidelity of the brainstem response to the envelope of the stimulus. The stability and phase-consistency of the FFR have been found to relate with beat-tapping performance in typically

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developing adolescents[12] and preschoolers.[13] It was also found that the envelope accuracy of the FFR combined with beat-synchronization ability could predict reading readiness[14] in typically developing preschoolers.

The aforementioned studies explored how difficulties in synchronizing a movement to a beat are mirrored in language/reading skills and in neural processing of sound in both quiet and noisy backgrounds. Hearing sounds in noise is a very common situation, inside and outside learning contexts; it requires huge involvement of sensory processing and integration.[15,16] Therefore, considering this scenario—that is, exploring auditory neural processing with noise-masked speech—seems particularly compelling, especially with respect to synchronization ability.

Yet, assessing beat synchronization skills in a rigorous way is a challenging task, which requires precise systems that are able to capture minimal discrepancies between the auditory pacing stimulus and the actual performance. While researchers have come up with a range of settings to tackle these issues, such as developing their own experimental set ups with drums or keyboards, cables and specific recording software (e.g., in Refs. 17 and 18), a seemingly unexplored alternative is provided by Interactive Metronome (IM), a portable clinical assessment and training tool that measures synchronization ability in an automatic and convenient way through a clapping-in-time paradigm. In addition, the IM technology offers the functionality of providing online feedback during the clapping-in-time performance, and it is actually this distinct aspect that has made IM so appealing from both therapeutic and theoretical perspectives.

IM has been investigated largely from a clinical perspective to prove its therapeutic impact on cognitive and motor skills in various populations.[19–21] However, recently, it was also considered from a neuroscience point of view and it revealed its link with cortical speech processing and language skills in typically developed adolescents, especially when visual feedback was provided to help in synchronizing.[22]

The current study aims at deepening the understanding of the biological correlates underlying clapping in time. In particular, by studying typically developing school age children in their initial stage of learning how to read and directly comparing two rhythm tasks, our work adds to previous studies showing links between rhythm and language skills in older children using simple tapping tasks.

We hypothesized that the incorporation of feedback draws on phonological, cognitive, and auditory temporal skills engaging the sensory and motor systems important for reading while only some of them are actively engaged in the no feedback condition. Therefore, we expect that only when all of these systems are involved, clapping in time would be a reflection of reading ability.

## Methods

### *Participants*

Sixty-four children (31 females) aged 5–7 years old (mean = 6.244, SD = 0.61) were recruited from the greater-Chicago area. These children had no history of a neurologic condition, no diagnosis of autism spectrum disorder or learning disabilities, and no second language exposure. Children passed a screening of peripheral auditory function (normal otoscopy, tympanometry, and distortion product otoacoustic emissions at least 6 dB SPL above the noise floor from 0.5 to 4 kHz). Parents or legal guardians provided informed consent and assent was given by the child prior to participation. All study procedures were approved by Northwestern University's Institutional Review Board. Children were monetarily compensated for their participation.

All behavioral and neurophysiological tests were presented in a random order to participants over two to three sessions.

### *Beat synchronization*

Beat synchronization was assessed using IM. IM assesses synchronization ability by having a child clap two hands together in a fluid circular motion against a hand trigger in time with a pacing tone delivered over headphones. Synchronization was performed under two different conditions: first without feedback (no feedback) and then with feedback (feedback). In the feedback condition, a visual indicator is shown on a computer screen, reflecting the asynchrony between their last clap and the "target" beat (ms before or behind the beat). In both conditions, synchronization was performed at a rate of 0.9 Hz for 1 min without any practice period. The goal of IM is to align one's clap with the pacing tone; thus, it is important that not only the clapping rate of 0.9 Hz is maintained but that it happens in phase with the pacing tone (i.e., at 0° phase). The feedback facilitates clapping at the correct rate and phase.

### *Data processing*

Synchronization variability during each condition was calculated as the standard deviation, in ms, of the asynchronies, which are automatically computed and reported by the IM software. We chose it as the main measure of performance on this task, in line with several studies investigating individual differences in synchronization ability.[23] The measure of asynchrony was chosen because it reflects deviations in both time and phase.

## Neurophysiology

### *Stimulus*

FFRs were elicited to a 170 ms [da] stimulus presented at 80 dB SPL and a 4.35 Hz presentation rate. The [da] was a six-formant stop consonant-vowel synthesized at 20 kHz in a Klatt-based synthesizer, with voicing onset at 5 ms, a 50 ms consonant-to-vowel transition, and a 120 ms steady-state vowel. The [da] stimulus was presented amid a background noise consisting of six talkers, four females, speaking English nonsense sentences.[24] The noise was presented as a continuous repeating masking track (45-s duration) and there was no phase synchrony between the onset of the [da] and the noise track. Stimulus presentation was controlled by E-Prime version 2.0 (Psychology Software Tools, Inc., Sharpsburg, PA). The goal was to collect 4000 artifact-free from each child, and so ∼4200 stimulus trials were presented in about 20/25 minutes. For additional details, see Ref. 25.

### *Data collection*

Children sat in a comfortable chair in an electrically shielded and sound-attenuated booth (IAC Acoustics, Bronx, NY) while watching a film of their choice to facilitate a relaxed state. The [da] was presented in alternating polarity monaurally to the right ear via electromagnetically shielded insert earphones (ER-3A, Etymotic Research, Elk Grove Village, IL). The left ear was unoccluded so that children could hear the movie soundtrack (<40 dB SPL in sound field). Responses were recorded differentially with a BioSemi Active2 system (BioSemi, Amsterdam, The Netherlands) with ActiABR module via LabView 2.0 (National Instruments, Austin, TX). A vertical recording montage was used with active at Cz, references at each ear, and CMS/DRL equidistant from Fpz (1 cm on either side). Only ipsilateral responses were used in this analysis. Responses were digitized at 16.384 kHz with an online bandpass filter of 100–3000 Hz (20 dB/decade roll-off). Offset voltages for all electrodes were <±50 mV.

### *Data processing*

Responses were offline amplified in the frequency domain for 20 dB per decade for three decades below 100 Hz. Amplified responses were bandpass filtered from 70 to 2000 Hz (12 dB/octave roll-off, Butterworth filter, zero phaseshift). Responses were epoched from –40 to 210 ms and baseline-corrected relative to the prestimulus period (–40 to 0 ms). Responses exceeding ±35 μV were rejected as artifact. Averages containing 2000 sweeps of each stimulus polarity were created and combined in two ways. First, average responses to the two polarities were added ($FFR_{ENV}$) to emphasize the lower frequency components of the response, including the temporal envelope. Second, the average response to one polarity was inverted before adding to the other response polarity ($FFR_{TFS}$), to emphasize the higher frequency components by maximizing the spectral response.

### *Data analysis*

Previous studies investigating the relationship between synchronization ability and the FFR have found that intertrial stability, intertrial phase-locking consistency, and accuracy of envelope encoding are linked to the ability to synchronize to an external beat. Therefore, the current analyses focused on these three FFR components. All data analyses were performed in MATLAB (2010) and SPSS (version 24).

### *Intertrial phase-locking consistency*

Intertrial phase-locking consistency was assessed using a procedure previously reported.[12,26] It was calculated on consecutive 40 ms Hanning-ramped windows (39 ms overlap), over the 60–170 ms portion of the response waveform. Only responses that fell below the artifact rejection criterion (i.e., ±35 μV) were included in the analyses. In each window, the spectrum was calculated using a fast Fourier transform. This resulted in a vector for each frequency that contained a length, indicating the encoding strength for each frequency, and a phase, which contained information about the timing of the response to that frequency. To examine the timing consistency of the response, each vector was transformed into a unit vector (i.e., a vector with a length of one, discarding the information about encoding strength) and then averaged across sweeps so that the length of the resulting vector provided a measure of the intertrial phase consistency. Mean phase consistency values were computed at multiples of 100 ± 10 Hz, and across all time windows between 60 and 170 milliseconds. The 12 mean phase consistency values between 200 and 1200 Hz were averaged to form a global phase consistency measure. We report results on $FFR_{TFS.}$

### Intertrial stability

Intertrial stability was assessed using a procedure previously reported.[12,27] To calculate the stability of a participant's response to the speech stimulus, 2000 of 4000 trials were randomly selected and averaged. The remaining 2000 trials were also averaged. The two averaged waveforms were then correlated over 0–170 ms to determine their similarity. These steps were repeated 300 times, each with different random samplings of 2000 trials in each average, and the 300 correlation values were averaged to generate a final measure of intertrial neural response stability. Correlation values were Fisher transformed. We report results on $FFR_{TFS.}$

### Speech-syllable envelope encoding accuracy

Envelope encoding accuracy was assessed on $FFR_{ENV}$ using a procedure previously reported.[14] To analyze the fidelity of neural encoding of the stimulus envelope, both the stimulus and response were band-pass filtered from 70 to 200 Hz and then a Hilbert transform was applied to extract the temporal envelope. To calculate the precision of envelope encoding, a cross-correlation was performed between the temporal envelope of the stimulus and response over the vowel (60–170 ms). The maximum correlation within a 5–12 ms lag window is reported ($r$, converted to Fisher's $z$ for statistical purposes).

## Cognitive, language, and reading skills

### Verbal intelligence

Verbal IQ scores were estimated with the Wechsler Preschool and Primary Scale of Intelligence, third edition[28] and with the Wechsler Intelligence Scale for Children, fifth edition.[29] We administered the information subtest to assess verbal IQ.

### Phonological memory

Phonological memory was measured with the Comprehensive Test of Phonological Processing.[30] It is a composite score of Memory for Digits, in which children repeat a series of numbers ranging in length from two to eight digits, and Nonword Repetition in which children repeat nonwords that range in length from 3 to 15 phonemes.

### Phonological awareness

Phonological awareness was measured with CTOPP. It is a composite score of Elision, in which children create a new word by dropping a syllable or phoneme from a spoken word, Blending Words in which children blend spoken syllables to create a new word, and Sound Matching in which children select words with the same initial and final sounds.

### Morphology and syntax

Morphology and syntax were assessed with the Word Structure subtest of the Clinical Evaluation of Language Fundamentals[31] in which children were asked to complete an orally presented sentence that pertains to an illustration.

### Basic reading

Basic reading is a cluster score measured by the Woodcock-Johnson III Test of Achievement[32] and it is composed of the Letter-Word Identification and Word Attack subtests, which are intended to assess sight vocabulary, phonics, and structural analysis. In Letter-Word Identification, children read a list of words of increasing difficulty in isolation; in Word Attack, children pronounce nonsense words of increasing complexity.

### Processing speed

Processing speed was assessed using the Visual Matching subtest of the Woodcock-Johnson III Test of Cognitive Abilities[32] in which children were asked to locate and circle the two identical numbers in a row of six numbers. This task proceeded in difficulty from single-digit numbers to triple-digit numbers, with a 3-min time limit.

One child was not assessed on both phonological memory and awareness, another child on both basic reading and processing speed, and finally another child was not assessed on any of the behavioral tests. Those three children were excluded from the analyses using these measures. Standard scores were used for all cognitive, language, and reading tests.

**Table 1. Summary statistics of all measures (frequency, mean, and standard deviation)**

| | *N* | Mean | SD |
|---|---|---|---|
| Feedback IM variability | 64 | 13.09 | 3.15 |
| No feedback IM variability | 64 | 13.79 | 3.07 |
| Phase-locking consistency | 64 | 0.06 | 0.02 |
| Neural stability | 64 | 0.33 | 0.18 |
| Envelope accuracy | 64 | 0.61 | 0.23 |
| Phonological memory | 62 | 101.89 | 13.56 |
| Phonological awareness | 62 | 110.81 | 15.29 |
| Basic reading | 62 | 118.37 | 15.18 |
| Morphology and syntax | 63 | 11.57 | 2.878 |
| Processing speed | 62 | 105.10 | 15.62 |

## Statistical analyses

Pearson correlations between variables were run to explore the relationships between IM synchronization variability and both neural and behavioral measures. Two independent linear regressions were performed to investigate the unique contribution of FFR measures and literacy measures to synchronization variability under no feedback and feedback conditions, using variability of asynchronies in each condition as the dependent variable. Prior to running the regressions, a factor analysis was run on the FFR and literacy independent variables. It was found that the FFR measures factored onto one variable, while the literacy measures factored onto a separate variable. These factors were used when running the regressions. In addition to the FFR and literacy factors, sex and verbal IQ were included as predictors to partial out their influence. Table 1 reports summary statistics (mean and standard deviation) for each measure considered.

## Results

### *Synchronization variability in the no feedback and feedback IM conditions is related*

Variability of asynchronies did not differ between the two IM conditions ($t_{63} = 1.930$, $P = 0.058$). Variability was correlated ($r_{60} = 0.575$, $P < 0.001$; controlling for participant sex and verbal IQ), indicating a relationship between performance on the no feedback and feedback IM conditions.

### *Synchronization variability in the no feedback and feedback IM conditions correlates with FFR measures*

To determine whether there is a relationship between beat synchronization variability and phase-locking consistency, neural stability, and envelope accuracy, partial correlations controlling for sex and verbal IQ were calculated. We found synchronization variability related with the three FFR measures for both IM conditions; better IM performance (lower variability) was associated with more stable, consistent, and accurate FFRs (*r* values and scatterplots are shown in Fig. 1). Figure 2 further illustrates the relationship between synchronization variability and phase-locking consistency.

### *Synchronization variability in the feedback IM condition relates to literacy skills*

To determine relationships between beat synchronization and literacy skills, partial correlations controlling for sex and verbal IQ were calculated between synchronization variability during the two IM conditions and the phonological awareness, phonological memory, morphology and syntax, basic reading, and processing speed. A modest relationship was seen between the no feedback condition and basic reading, only. However, less synchronization variability (better performance) during the feedback condition significantly correlated with better scores on all of the literacy measures considered which are particularly important in the process of learning how to read (*r* values and scatterplots are shown in Fig. 3).

### *Factor analysis*

To explore the structure of our set of variables and, at the same time, reduce our data set to a more manageable size without losing any information, we ran a factor analysis among all the behavioral and electrophysiological measures. The factor analysis revealed that the measures were best captured by two factors, one for the five behavioral measures (phonological memory, phonological awareness, morphology and syntax, basic reading, and processing speed) and one for the three neural measures (phase-locking consistency, neural stability, and envelope accuracy). All further factors had eigenvalues of less than 1, and the slope of the scree plot decreased dramatically between the second and third factors; therefore, we limited our analysis and interpretation to the first and second factors. These two factors appear to reflect literacy skills and temporal auditory skills (from now on, we will be referred to them, respectively, as "literacy" and "auditory processing" measures).

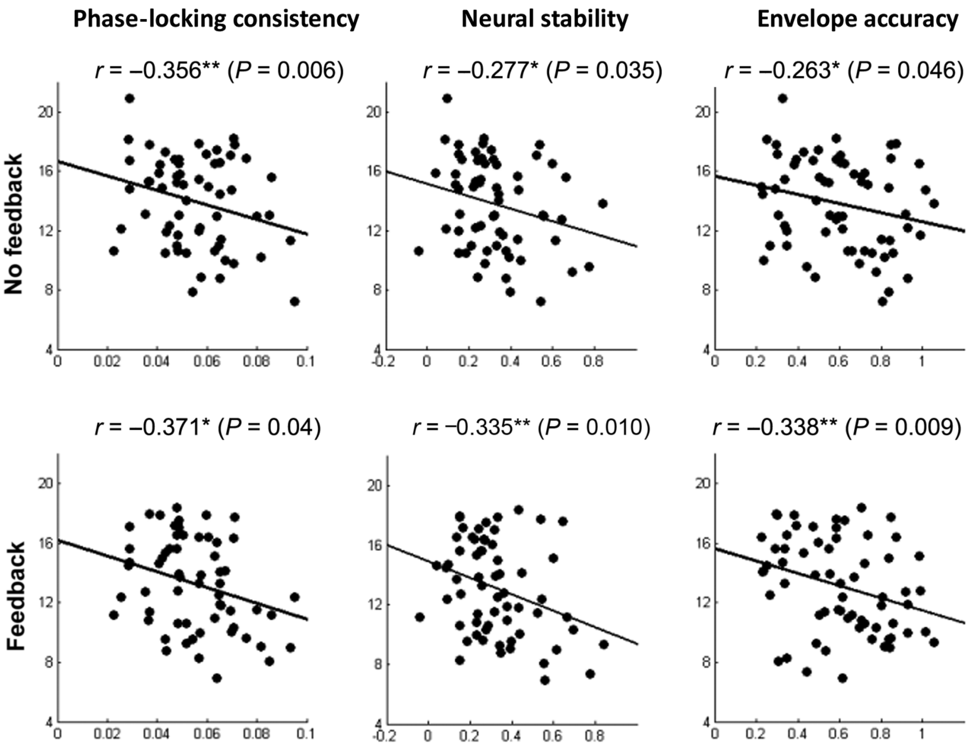


**Figure 1.** The variability of subjects' clapping in time correlates with phase-locking consistency, neural stability, and envelope accuracy across both IM conditions.

The literacy factor accounted for 33.227% of the cumulative variance across the behavioral data set, whereas the auditory processing factor accounted for 25.890% of the cumulative variance across the neural data set. The KMO index was 0.640, indicating an adequate sampling, and Bartlett's test of sphericity returned a significant result ($\chi^2 = 169.175$, $P < 0.001$). Table 2 shows the factor loadings after varimax rotation.

### *Auditory processing and literacy measures contribute independently to asynchrony variability in the feedback condition*

To explore the contributions of auditory processing and literacy predicting beat synchronization ability, we ran two separate linear regressions using the synchronization variability of each condition as the dependent variable. Sex, verbal IQ, auditory processing measure, and literacy measure were considered as predictors. Only the auditory processing measure predicted subjects' synchronization variability in the no feedback condition. In contrast, both auditory processing and literacy independently predicted performance in the feedback condition. Table 3 shows full regression results.

### *Relationship between phonological memory and stability of the auditory system*

In light of the results from the factor analysis and, specifically of phonological memory having a

**Table 2.** Summary of factor loadings after Varimax rotation

| | Auditory processing measures | Literacy measure |
|---|---|---|
| Phase locking consistency | **0.9** | −0.01 |
| Neural stability | **0.918** | 0.007 |
| Envelope accuracy | **0.503** | 0.042 |
| Phonological memory | 0.398 | **0.492** |
| Phonological awareness | 0.023 | **0.859** |
| Basic reading | −0.01 | **0.851** |
| Morphology and syntax | −0.036 | **0.776** |
| Processing speed | 0.063 | **0.592** |

NOTE: Over 0.40 appear in bold.

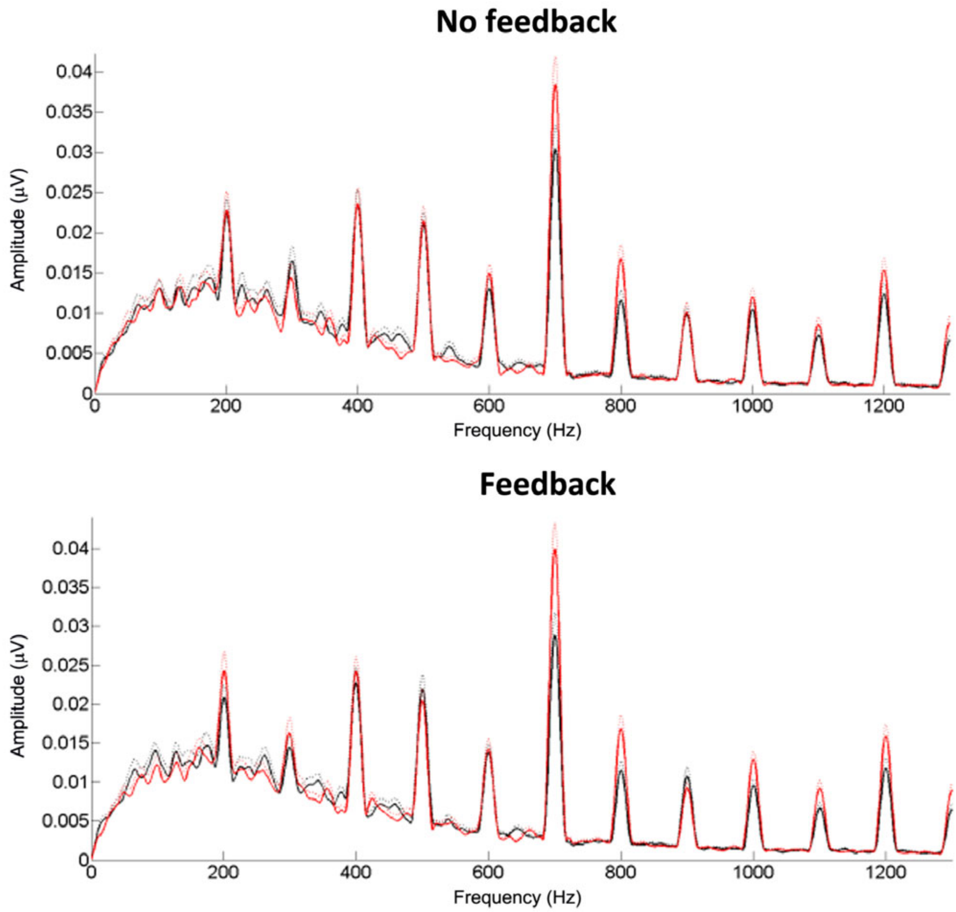


**Figure 2.** To further illustrate the robust relationship between intertrial neural phase-locking and clapping precision, participants were dichotomized as relatively poor ($N = 32$, in black) or good ($N = 32$, in red) synchronizers based on a median split according to their clapping variability. Subjects who show less variability (red) when clapping in time show greater intertrial phase-locking consistency in the FFR to the speech sound/da/, across peaks in the 200–1200 Hz range. The steady state period (60–170 ms) is displayed.

moderate loading onto both factors, we explored relationships among all the auditory processing and literacy measures considered by running partial correlations between these measures controlling for sex and verbal IQ. Table 4 shows all partial correlation results. Only a relationship between phonological memory and neural stability was found, which supports the finding that phonological memory showed partial loading onto both the literacy and auditory Processing factors in the factor analysis.

A summary of the discovered relationships is shown in Figure 4.

**Table 3.** Results of linear regression

| Predictors | Feedback IM $\beta$ | No feedback IM $\beta$ |
|---|---|---|
| Auditory processing measures | $-0.41^{**}$ | $-0.343^{*}$ |
| Literacy measures | $-0.462^{**}$ | $-0.205$ |
| Sex, verbal IQ | √ | √ |
| $R^2$ | 0.39 | 0.238 |

$^{*}P < 0.05$.
$^{**}P < 0.01$.

## Discussion

This study reinforces evidence of relationships between synchronization ability and subcortical auditory processing, as well as literacy skills. For the

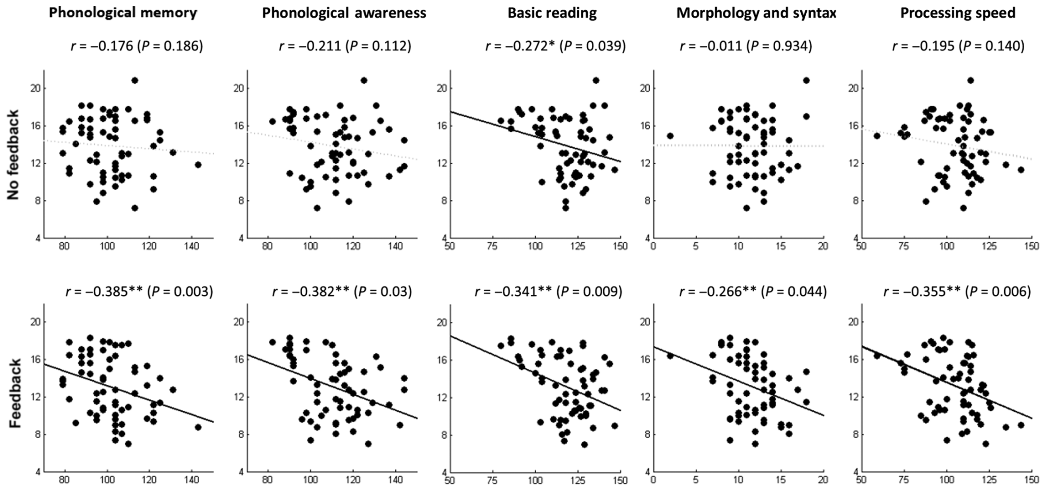


**Figure 3.** The synchronization variability of subjects' clapping in time in the feedback condition correlates with performance on all tests of literacy skills; the synchronization variability of clapping in time in the no feedback condition correlates with basic reading skills only. Each panel is arranged such that better performance is to the right of the *x*-axis.

first time, we extended these links to a clapping-in-time task in a cohort of young typically developing children who were learning how to read. Moreover, we show that these relationships are strengthened with feedback.

Clapping in time represents an activity that almost everyone experiences since childhood. It requires global coordination and interaction between motor and sensory systems and a fine temporal ability to control the entire movement as to be on time. All these characteristics make it an appealing object of study. However, it represents an understudied paradigm in the sensorimotor synchronization literature, perhaps due to the complexity in measuring and controlling all the processes involved in it. Previous studies might have circumvented this issue by relying on simpler tasks such as tapping a finger or hitting a button in time. We were instead able to deal with this complexity using IM technology.

As a beat synchronization task, clapping in time revealed relationships with the FFR measures previously shown to relate with drumming tasks,[12–14] confirming the proposed involvement of the auditory midbrain in integrating precise timing information throughout the auditory system and influencing motor output.

In addition, the IM technology allowed us to take a step further and compare the specific impact of adding a visual component to a beat synchronization task, with the aim of providing real-time feedback on the actual performance. As we reviewed above, the more global integration required by the feedback condition results in stronger links between task performance and both subcortical processing of a speech sound and literacy skills. One possible

**Table 4.** **Partial correlations controlling for sex and verbal IQ among all measures**

| | | Literacy measures | | | | |
|---|---|---|---|---|---|---|
| | | Phonological memory | Phonological awareness | Basic reading | Morphology and syntax | Processing speed |
| Auditory processing measures | Neural stability | 0.268 $P = 0.042$ | 0.049 $P = 0.715$ | 0.046 $P = 0.734$ | 0.058 $P = 0.665$ | 0.086 $P = 0.522$ |
| | Phase-locking | 0.210 $P = 0.113$ | 0.055 $P = 0.697$ | 0.052 $P = 0.696$ | −0.038 $P = 0.774$ | 0.053 $P = 0.693$ |
| | Envelope accuracy | 0.203 $P = 0.127$ | 0.193 $P = 0.146$ | 0.089 $P = 0.508$ | 0.018 $P = 0.894$ | −0.057 $P = 0.673$ |

Note: Values reported are Pearson *r* values.

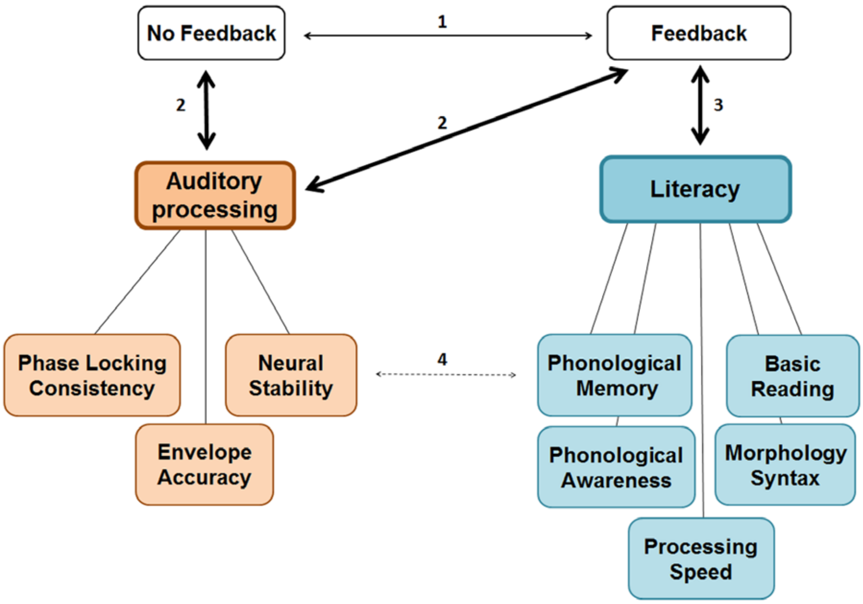


**Figure 4.** Summary of the discovered relationships. This diagram summarizes all the significant relationships among the variables considered. Specifically: 1. No feedback variability and feedback variability are related; 2. Both feedback and no feedback variability are related with "Auditory Processing" (phase-locking consistency, envelope accuracy and neural stability of the FFR as revealed by factor analysis); 3. Feedback variability is related with "Literacy" (phonological memory, phonological awareness, processing speed, basic reading, morphology and syntax are the five variables comprising "Literacy," as revealed by factor analysis); 4. Neural stability and phonological memory are related.

explanation for this result may come from the numerous studies claiming the benefits of music training on the auditory system, and consequently on language development. In fact, by thinking about the experience of taking part in a music education program, it is easy to recognize the dynamic engagement that it requires across visual, auditory, and motor systems. Similarly, the clapping task with feedback seems to parallel most of the auditory-neural and cognitive processing systems activated when learning how to read, where a repeated and flexible interaction between auditory and visual systems precedes and sustains the reading act.

Another related, though different explanation could be that the presence of a visual component with the explicit role of giving feedback may have also motivated school-age children in the task, increasing their level of engagement, with a consequent beneficial impact on temporal processes. This hypothesis can be consistent with our finding that the temporal precision and adaptation activated in the feedback condition appear to be particularly related with phonological memory (the most highly correlated measure), and both seem to depend on the stability of the auditory system.

Overall, the feedback condition seems to help the child to keep an internal temporal consistency and to follow the rhythm. This ability is necessary to organize temporal cues of speech sounds so as to facilitate the automatization of the grapheme-phoneme correspondence in reading. What probably underlies the results is not just the actual involvement of the visual system itself, nor the involvement of the feedback component, but also the combination of both, by making explicit the typical asynchronies and helping in reducing them, or at least making them more consistent.

In light of these findings, the use of IM seems to have potential as a remedial strategy for individuals who struggle with timing-based language learning impairments. We see the present study as providing interesting evidence in this respect, while at the same time it calls for further research. A limitation of this study is its basis on correlations and so we do not know the directionality or cause of these relationships. However, we are currently following longitudinally the children involved in this study to monitor their development and to explore the possibility to predict development from synchronization skills at early ages. Another possible avenue could be conducting intervention studies using the clapping-in-time activities of IM or similar technology to directly investigate its impact on the detailed neural sound processing and on literacy skills.

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## Competing interests

The authors declare no competing interests.

## Author contributions

S.B., J.K., T.W.-S., and N.K. designed research; S.B. performed research; J.K. and T.W.-S. contributed analytic techniques; S.B. analyzed data; and S.B., J.K., T.W.-S., and N.K. wrote the paper.

## References

1. Habib, M., C. Lardy, T. Desiles, *et al.* 2016. Music and dyslexia: a new musical training method to improve reading and related disorders. *Front. Psychol.* **7:** 26.
2. Bhide, A., A. Power & U. Goswami. 2013. A rhythmic musical intervention for poor readers: a comparison of efficacy with a letter-based intervention. *Mind Brain Educ.* **7:** 113–123.
3. Thomson, J., V. Leong & U. Goswami. 2013. Auditory processing interventions and developmental dyslexia: a comparison of phonemic and rhythmic approaches. *Read. Writ.* **26:** 139–161.
4. Anvari, S.H., L.J. Trainor, J. Woodside & B.A. Levy. 2002. Relations among musical skills, phonological processing, and early reading ability in preschool children. *J. Exp. Child Psychol.* **83:** 111–130.
5. Colling, L.J., H.L. Noble & U. Goswami. 2017. Neural entrainment and sensorimotor synchronization to the beat in children with developmental dyslexia: an EEG study. *Front. Neurosci.* **11:** 360.
6. Goswami, U., M. Huss, N. Mead, *et. al.* 2013. Perception of patterns of musical beat distribution in phonological developmental dyslexia: significant longitudinal relations with word reading and reading comprehension. *Cortex* **49:** 1363–1376.
7. Leong, V. & U. Goswami. 2014. Assessment of rhythmic entrainment at multiple timescales in dyslexia: evidence for disruption to syllable timing. *Hear. Res.* **308:** 141–161.
8. Thomson, J.M. & U. Goswami. 2008. Rhythmic processing in children with developmental dyslexia: auditory and motor rhythms link to reading and spelling. *J. Physiol. Paris* **102:** 120–129.
9. Tierney, A., T. White-Schwoch, J. MacLean & N. Kraus. 2017. Individual differences in rhythm skills: links with neural consistency and linguistic ability. *J. Cogn. Neurosci.* **29:** 855–868.
10. Skoe, E. & N. Kraus. 2010. Auditory brainstem response to complex sounds: a tutorial. *Ear Hear.* **31:** 302–324.
11. Kraus, N., S. Anderson, T. White-Schwoch, *et al.* 2017. *The Frequency-Following Response: A Window into Human Communication.* New York: Springer-Nature.
12. Tierney, A. & N. Kraus. 2013. The ability to move to a beat is linked to the consistency of neural responses to sound. *J. Neurosci.* **33:** 14981–14988.
13. Woodruff Carr, K., A. Tierney, T. White-Schwoch & N. Kraus. 2016. Intertrial auditory neural stability supports beat synchronization in preschoolers. *Dev. Cogn. Neurosci.* **17:** 76–82.
14. Woodruff Carr, K., T. White-Schwoch, A.T. Tierney, *et al.* 2014. Beat synchronization predicts neural speech encoding and reading readiness in preschoolers. *Proc. Natl. Acad. Sci. USA* **111:** 14559–14564.
15. Thompson, E.C., K. Woodruff Carr, T. White-Schwoch, *et al.* 2017. Individual differences in speech-in-noise perception parallel neural speech processing and attention in preschoolers. *Hear. Res.* **344:** 148–157.
16. White-Schwoch, T., K.W. Carr, E.C. Thompson, *et al.* 2015. Auditory processing in noise: a preschool biomarker for literacy. *PLoS Biol.* **13:** e1002196.
17. Kirschner, S. & M. Tomasello. 2009. Joint drumming: social context facilitates synchronization in preschool children. *J. Exp. Child Psychol.* **102:** 299–314.
18. Corriveau, K.H. & U. Goswami. 2009. Rhythmic motor entrainment in children with speech and language impairments: tapping to the beat. *Cortex* **45:** 119–130.
19. Kim, H.H., G.H. Bo & B.K. Yoo. 2012. The effects of a sensory integration programme with applied interactive metronome training for children with developmental disabilities: a pilot study. *Hong Kong J. Occup. Th.* **22:** 25–30.
20. Namgung, Y., D.-I. Son & K.-M. Kim. 2015. Effect of interactive metronome® training on timing, attention and motor function of children with ADHD: case report. *J. Korean Soc. Sens. Integr. Ther.* **13:** 63–73.
21. Taub, G.E., K.S. McGrew & T.Z. Keith. 2015. Effects of improvements in interval timing on the mathematics achievement of elementary school students. *J. Res. Child. Educ.* **29:** 352–366.
22. Woodruff Carr, K., A.B. Fitzroy, A. Tierney, *et al.* 2017. Incorporation of feedback during beat synchronization is an

index of neural maturation and reading skills. *Brain Lang.* **164:** 43–52.
23. Repp, B.H. & Y.-H. Su. 2013. Sensorimotor synchronization: a review of recent research (2006–2012). *Psychon. B Rev.* **20:** 403–452.
24. Van Engen, K.J. & A.R. Bradlow. 2007. Sentence recognition in native- and foreign-language multi-talker background noise. *J. Acoust. Soc. Am.* **121:** 519–526.
25. White-Schwoch, T., E.C. Davies, E.C. Thompson, *et al.* 2015. Auditory–neurophysiological responses to speech during early childhood: effects of background noise. *Hear. Res.* **328:** 34–47.
26. White-Schwoch, T., T. Nicol, C.M. Warrier, *et al.* 2017. Individual differences in human auditory processing: insights from single-trial auditory midbrain activity in an animal model. *Cereb. Cortex* **27:** 5095–5115.
27. Anderson, S., A. Parbery-Clark, T. White-Schwoch & N. Kraus. 2012. Aging affects neural precision of speech encoding. *J. Neurosci.* **32:** 14156–14164.
28. Wechsler, D. 1967. *Wechsler Preschool and Primary Scale of Intelligence.* New York: Psychological Corporation.
29. Wechsler, D. 1991. *Wechsler Intelligence Scale for Children: Technical and Interpretive Manual.* New York: Psychological Corporation.
30. Wagner, R.K., J.K. Torgesen & C.A. Rashotte. 1999. *Comprehensive Test of Phonological Processes.* Austin, TX: PRO-ED Inc.
31. Semel, E.M., E.H. Wiig & W. Secord. 1995. *CELF3: Clinical Evaluation of Language Fundamentals.* Psychological Corporation, Harcourt Brace.
32. Woodcock, R.W., K.S. McGrew & N. Mather. 2001. *Woodcock-Johnson III.* Itasca, IL: Riverside Publishing.