Sensorimotor and working memory systems jointly support development of perceptual rhythm processing

Hyun-Woong Kim[1-3], Kyung Myun Lee[5,6], & Yune S. Lee[1-4]

[1]School of Behavioral and Brain Sciences, [2]Callier Center for Communication Disorders, [3]Center for BrainHealth, [4]Department of Speech, Language, and Hearing, The University of Texas at Dallas, TX 75080, United States

[5]School of Humanities and Social Sciences, [6]Graduate School of Culture Technology, Korea Advanced Institute of Science and Technology, Daejeon 34141, South Korea

Correspondence

Yune S. Lee, School of Behavioral and Brain Sciences, The University of Texas at Dallas

Email: yune.lee@utdallas.edu

Kyung Myun Lee, School of Humanities and Social Sciences, Korea Advanced Institute of Science and Technology

Email: kmlee2@kaist.ac.kr

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Conflict of Interest Statement

The authors have no conflict of interest.

Data sharing and data accessibility

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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Research highlights

- Rhythm discrimination ability in children aged 7 to 12 years was predicted by both sensorimotor (beat tapping) and auditory working memory (digit span) abilities.
- Beat tapping consistency at slower tempos (60 and 100 BPM) was more predictive of rhythm discrimination performance than faster ones (120 and 180 BPM).
- Beat tapping consistency predicted rhythm discrimination only in 7- to 9-year-olds, but not in 10- to 12-year-olds.
- In 10- to 12-year-olds, only digit span accounted for rhythm discrimination, suggesting a shift from sensorimotor to working memory in relation to perceptual rhythm processing.

Abstract

We studied the role of sensorimotor and working memory systems in supporting development of perceptual rhythm processing with 119 participants aged 7 to 12 years. Children were assessed for their abilities in sensorimotor synchronization (beat tapping), auditory working memory (digit span), and rhythm discrimination (same/different judgment on a pair of musical rhythm sequences). Multiple regression analysis revealed that children's rhythm discrimination performance was independently predicted by higher beat tapping consistency and greater digit span score, with all other demographic variables (age, sex, socio-economic status, music training) controlled. The association between rhythm discrimination and beat tapping was more robust in the slower tempos (60 and 100 BPM) than faster ones (120 and 180 BPM). Critically, the relation of beat tapping to rhythm discrimination was moderated by age. Rhythm discrimination performance was predicted by beat tapping consistency in younger children (age: 7-9 years), but not in older children (age: 10-12 years). Digit span was the only predictor of rhythm discrimination in older children. Together, the current findings demonstrate that the sensorimotor and working memory systems jointly support rhythm discrimination processing during middle-to-late childhood and that the degree of association between the two systems and perceptual rhythm processing is shifted before entering into early adolescence.

Keywords: rhythm, beat synchronization, sensorimotor, working memory, digit span, development

Introduction

Rhythmicity is pervasive in a myriad of auditory objects including speech, music, and other everyday sounds. Rhythmic structures of auditory events provide useful clues for prediction (Nobre & van Ede, 2018), lending perceptual and attentional advantages in auditory timing and detection (Haegens & Zion Golumbic, 2018; Large & Jones, 1999; Schroeder et al., 2010). Although rhythm processing is an integral part of auditory information processes, development of rhythm perception and its relations with other neurocognitive systems remain poorly understood. In the present study, we address this question by measuring multiple rhythm skills, working memory, and demographic indices from a large cohort of children aged 7 to 12 years.

One of the core elements supporting rhythm perception might be the sensorimotor (or motor) system comprising basal ganglia, cerebellum, supplemental motor area, and premotor cortex, which is responsible for temporal coordination of motor actions to an external rhythm (Repp, 2005; Repp & Su, 2013). According to Patel and Iversen's (2014) *Action Simulation for Auditory Perception* (ASAP) hypothesis, the sensorimotor system is thought to play an important role in beat perception by implicitly analyzing temporal regularities of acoustic events. Indeed, both cortical and subcortical motor circuitries are activated in response to rhythm sequences even in the absence of explicit motor task (Bengtsson et al., 2009; Chen et al., 2008; Thaut et al., 2014). In particular, the basal ganglia activation has been associated with the degree of temporal regularity of rhythmic structures, rendering a sense of beat or pulse in a rhythm (Grahn & Brett, 2007; Grahn & Rowe, 2009, 2013). Although the sensorimotor system can be recruited during passive listening, overt motor tasks toward rhythmic sequences (e.g., a series of isochronous tones) would further aid rhythm perception. For example, tapping to a rhythmic sequence improves precision in judging whether a probe tone following the sequence is on the beat (Manning et al., 2017), and helps find the underlying beat by actively adjusting tapping to the beat timings (Su & Pöppel, 2012). In addition, tapping to an isochronous tone sequence accompanied by distracting tones with random intervals facilitates tracking of the isochronous target tones (Morillon et al., 2014; Zalta et al., 2020). These findings support the notion that the motor system is engaged in perceptual rhythm processing (Morillon et al., 2015; Rimmele et al., 2018).

Another crucial element supporting rhythm perception may be the (auditory) working memory system (Kraus et al., 2012). Indeed, numerous behavioral studies have found a positive association between working memory and perceptual rhythm skills (Anvari et al., 2002; Hansen et al., 2013; Politimou et al., 2019; Strait et al., 2011; Swaminathan & Schellenberg, 2019). Importantly, in Saito and Ishio (1998), subvocal articulation of vowels during retention of rhythmic patterns impaired the subsequent reproduction performance, suggesting that participants relied on articulatory rehearsal process of working memory to maintain a representation of rhythmic configuration.

Rhythm perception emerges early in infancy (Bergeson & Trehub, 2006; Trehub & Thorpe, 1989) but continues to improve during early childhood (Gordon, 1979). Sensorimotor rhythm ability appears to emerge later; it has been shown that 2-and-a-half-year-old children are able to tap to an auditory metronome (Provasi & Bobin-Bègue, 2003). Children's ability to synchronize their taps consistently with a metronome (i.e., exhibiting less variability) increases throughout childhood, approaching a plateau around adolescence (Drewing et al., 2006; McAuley et al., 2006). Much like tapping consistency, working memory performance gradually improves from early childhood to adolescence (Conklin et al., 2007; Gathercole et al., 2004). Overall, many studies have implicated that working memory, sensorimotor synchronization, and rhythm perception develop in similar ways during childhood.

Given the role of sensorimotor and working memory systems in supporting rhythm perception, these components may continue to interact with rhythm processing while children develop the cognitive and rhythm skills. Nevertheless, there are few studies investigating the relation among these components within the same children. Previous studies have shown that auditory working memory is associated with perceptual rhythm ability in preschoolers (Anvari et al., 2002; Politimou et al., 2019) as well as school-age children (Swaminathan & Schellenberg, 2019) but without measuring sensorimotor rhythm ability. Only a handful of studies have examined sensorimotor synchronization in predicting rhythmic pattern processing in children (Bonacina et al., 2019, 2020). Their results were mixed: in children of 5 to 8 years of age, the ability to remember and reproduce rhythmic patterns was correlated with the ability to clap to a metronome with visual feedback, but not with the ability to drum to a metronome without feedback. Thus, it remains to be further elucidated how sensorimotor rhythm ability, in concert with auditory working memory, relates to perceptual rhythm ability in children.

In the present study, we recruited a large cohort of children aged 7;1 to 12;10 years who participated in a variety of speech, language, and cognitive experiments. Among various measures, the current article focused on data concerning children's rhythm skills (both perception and production) and auditory working memory (AWM). In the rhythm discrimination (RD) task, children listened to a pair of musical rhythms successively played in each trial and judged whether the second rhythm was the same or different from the first rhythm (Figure 1). In the sensorimotor synchronization (SMS) task, children tapped their index and/or middle fingers in synchrony with isochronous metronome beats at 60, 100, 120, and 180 beat-per-minute (BPM), covering a wider range of beat rates (1-3 Hz) compared to previous studies (Bonacina et al., 2019, 2020; Tierney & Kraus, 2015). For AWM, we administered the digit span subtest of the Wechsler Intelligence Scale for Children (K-WISC-IV; Hwang & Oh, 2017), in which children heard a series of digits and repeated them back in either forward or reverse order.

Importantly, we sought to investigate how the relations of AWM, SMS, and RD abilities evolve during child development through cross-sectional comparisons across ages. Of note, the sensorimotor behavior affecting or affected by rhythm perception appears to emerge earlier than working memory in development (Fujii et al., 2014; Phillips-Silver & Trainor, 2005; Zentner & Eerola, 2010). For example, infants tend to spontaneously move in response to music (Fujii et al., 2014; Zentner & Eerola, 2010), and the engagement in rhythmic movements affects infants' preference for rhythmic patterns (Phillips-Silver & Trainor, 2005). During early childhood, humans tend to capitalize on the motor system when estimating temporal duration (Droit-Volet & Rattat, 1999). For example, when 3-year-old children were trained to produce a temporal duration with a particular motor behavior (e.g., pressing a squeezer and holding it for 5 s), they failed to reproduce the same duration using a different action (e.g., pressing a button and holding it for 5 s), suggesting that children as early as 3 years of age could not dissociate the representation of a temporal duration from motor processes. Five-year-old children, on the other hand, were able to reproduce a temporal duration regardless of association with a particular action, suggesting that motor-independent temporal representation has emerged by this age. Interestingly, higher-order cognitive resources seem to account for individual differences in temporal representation of children around and after this age (Droit-Volet, 2016). For example, 5-year-old children's temporal sensitivity in a duration reproduction task was poorer than that of 8-year-old children, and the difference in temporal performance was mainly due to age-related differences in attention and working memory (Droit-Volet et al., 2015). Notably, among the various cognitive measures, working memory capacity was predictive of the degree of temporal sensitivity in 5- and 9-year-old children (Zélanti & Droit-Volet, 2011). This finding reveals the critical role of working memory in perceptual rhythm processing as children begin to dissociate temporal information from motor processes at around 5 years of age (Droit-Volet & Rattat, 1999).

We hypothesized that both SMS and AWM would jointly but also independently account for RD performance even after controlling for other demographic variables including age, sex, socioeconomic status (SES), and music training background in school-age children. We also explored whether their relationships with RD vary as a function of age in school-age children. Given the role of motor processes in temporal representation early in development (Droit-Volet & Rattat, 1999) and the role of working memory during later childhood (Droit-Volet et al., 2015; Zélanti & Droit-Volet, 2011), we expect SMS may account more for RD in a younger cohort of children, while AWM would predict RD more strongly in an older cohort.

Methods

Participants

One hundred nineteen children aged from 7;1 to 12;10 years (M = 9;9 years, SD = 1.7 years, 62 females; Table 1), took part in the study. We conducted an a priori power analysis using G*Power version 3.1 (Faul et al., 2009), indicating that at least 109 participants were required to detect a medium effect size (f^2 = 0.15, α error = 0.05, Power = 0.8) with 8 predictors in a multiple regression analysis. We aimed to recruit participants evenly across ages from a local elementary school, which was confirmed by one sample Kolmogorov-Smirnov (K-S) test satisfying a uniform distribution of age (p=.149). All parents of children gave informed consent approved by the Institutional Review Board of Korea Advanced Institute of Science and Technology prior to the experiment. Parents filled out a demographic form about their children while the experiment was being conducted. Children's musical experience was determined based on the number of years of additional musical training outside of school (M = 2;4 years, SD = 1;12 years). If children had played multiple instruments in overlapping periods, only one of the instruments was counted. Parents' socioeconomic status (SES) was measured by their household income level. For one participant whose SES data was missing, we imputed the average value from the dataset.

Stimuli and Procedures

Children participated in the rhythm discrimination task, the sensorimotor synchronization task, and the digit span test in a counterbalanced order. The rhythm discrimination and sensorimotor synchronization tasks were conducted using a laptop computer (Samsung NT900X5Y-XD5S). Auditory stimuli were presented through the built-in computer speaker. For the digit span task, the subtest of the Korean version of the Wechsler Intelligence Scale for Children (K-WISC-IV; Hwang & Oh, 2017) was administered by the experimenter.

For the rhythm discrimination task, 10 metrically simple rhythms and their respective simple variants were chosen from the set of rhythm sequences used in Lee et al. (2020). Half of the rhythm stimuli contained 7 woodblock sounds and the other half contained 8 woodblock sounds, with intervals of 250, 500, 750, or 1,000 ms between the sounds. All rhythm stimuli lasted 4 s and induced perception of a beat at 120 BPM. A variant of each rhythm sequence was made by switching the order of two adjacent intervals in the rhythm (Figure 1). The RMS (root-mean-square) power of all rhythm stimuli were normalized. There were a total of 20 trials, in which each of the 10 rhythm sequences was paired with itself for 'same' trials or its corresponding variant for 'different' trials. The first 'standard' rhythm stimulus was presented along with a picture of a cartoon character. After 1.5 s delay, the second 'comparison' rhythm stimulus was accompanied by side-by-side cartoon characters, one being identical to the preceding character, and the other being a different cartoon character. Children were asked to indicate 'same/different' by choosing either of the two characters via a keyboard press. Five practice trials were given with feedback to ensure that children were familiarized with the task. There was no time constraint during practice. For the main experiment, children were encouraged to make a response within 3 s and no feedback was given. The order of trials was randomized for each participant.

The sensorimotor synchronization task consisted of four sessions differing in tempo (60, 100, 120, and 180 BPM, i.e., 1000, 600, 500, and 333.33 ms in inter-stimulus onset interval; IOI). In each session, children listened to isochronous woodblock sounds (200 ms in duration) and pressed the space bar with their right index and/or middle fingers in synchrony with the sounds. Each button press generated a snare drum sound. Children were instructed to start tapping after the first five woodblock sounds, accompanied by a visual countdown timer on the screen. Each trial lasted 24 s from the onset of sixth woodblock sound. The order of four trials was randomized across participants.

The digit span subtest of K-WISC-IV consisted of Digit Span Forward (DSF) and Digit Span Backward (DSB). In each trial beginning with aural presentation of digits, children were instructed to recall numbers in forward or reverse order. Both DSF and DSB started from two numbers that

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increased until children failed to recall. The score was obtained from the number of trials that children correctly recalled. The maximum list length was 9 digits.

Data Analyses

For the rhythm discrimination data, accuracy of each participant was converted to a d-prime (*d'*) score (Table 1). A *d'* score is calculated as the difference between the z-transformed hit rate (i.e., the rate of 'different' responses to different rhythms) and false alarm rate (i.e., the rate of 'different' responses to the same rhythms). Since the *d'* score was similar for 7- and 8-sound rhythms (paired t-test: $p = .892$), data from two conditions were combined for *d'* calculation. Hit and false-alarm rates of 1 or 0 were adjusted by replacing the rates of 0 with 0.05 and the rates of 1 with 0.95 to avoid an indefinite *d'* score (Macmillan & Kaplan, 1985).

For the synchronization tapping data, we opted to use a circular over a linear measure (e.g., Kirschner & Tomasello, 2009; Provasi et al., 2014). In particular, we calculated Shannon entropy (*SE*; Shannon, 1948) that indicates uncertainty of a probability distribution on the relative phase between tap onsets and nearest metronome beat.

$$SE = -\sum_{i=1}^{M} p(i) \ln p(i)$$

Above is the formula of *SE* wherein *M* is the number of bins, ranging from –180º to +180º, and $p(i)$ is the probability of tapping responses (i.e., relative phase angles) occurring within i_{th} bin (Figure 2). The *SE* reflects the degree of spreading of a data distribution, i.e., in the current study, the distribution of tapping responses around the beat timings. We have exhaustively searched for the optimal bin size by gradually increasing the angle from 10 to 60 degree. We have chosen 24º in that the bin size resulted in maximal individual differences in *SE* (see the Supplementary Figure 1). As was done in Fujii and Schlaug (2013), we calculated index of synchronization consistency (*SI*) using *SE*:

$$SI = 1 - \frac{SE}{\ln N}$$

where N is the total number of tap responses. The SI ranges from 0 to 1, where 1 is assigned when all responses occurred in a single bin and 0 is assigned when all responses occurred in different bins: the more consistent, the larger SI. The SI is thought to have advantage over other circular variance measures such as length of vector, for two reasons (Fujii & Schlaug, 2013). First, SI has been shown to be less skewed than mean vector length. In our data, SI satisfied the normality assumption for every BPM condition whereas vector length did not, specifically for the 60 and 100 BPM conditions. Second, SI is effective in disambiguating the behavioral data between random responses and multi-peak responses including mixture of in-phase and anti-phase responses (see Figure 2 for examples).

With all finalized metrics (e.g., *d'*, SI, etc.), the following statistical analyses were performed:

- A multiple linear regression analysis, in which the average of tapping consistency (SI) across four BPM conditions, digit span score, and demographic variables including gender, age, SES (ordinal scale from 1 to 5), and years of musical training were entered into the model to predict rhythm discrimination accuracy (*d'*). We also included two interaction terms (i.e., age × tapping consistency and age × digit span score) in the model to explore the moderating effects of age on the associations of sensorimotor synchronization and working memory with rhythm discrimination.

- Pearson's partial correlation coefficients between rhythm discrimination (*d'*), digit span score, and each of four tapping measures (SI) across all BPMs, while controlling for gender, age, SES, and years of music training. Two more partial correlation analyses were performed one between age and the three task measures above and the other between musical training years and those measures while the other demographic variables are controlled. One sample K-S test confirmed that the residuals of age, music training, and the behavioral measures against demographic variables satisfied the assumption of normal distribution for partial correlation analyses (all $ps > .082$).

- One-way repeated measures ANOVA to determine if consistency of sensorimotor synchronization differed across various tempos covering slow to fast range. The Greenhouse-Geisser correction was used to adjust degrees of freedom due to violation of sphericity assumption.

- Independent samples t-tests by gender were conducted to evaluate gender differences in behavioral performance.

Results

Descriptive statistics of demographic and behavioral variables are listed in Table 1. Prior to the main analyses (i.e., multiple linear regression), we first compared behavioral performance between boys and girls via independent sample t-test. We found that girls performed better than boys on RD task, but they did not differ in AWM and SMS tasks (Table 2).

Next, we performed two partial correlation analyses (see method above for more details). We found that age showed significant positive correlations with all task measures, except for tapping consistency (*SI*) at 100 and 180 BPMs, indicating overall improvement of behavioral performance as children develop (Table 2). In contrast, musical training was only correlated with a subset of SMS at 120 and 180 BPMs, but not with RD and AWM.

The multiple regression analysis was then performed, which showed that RD performance was significantly predicted by both SMS and AWM independent of other demographic variables (Table 3). That is, both greater tapping consistency and higher digit span score were associated with better rhythm accuracy. In addition, the interaction effect of tapping consistency × age was significant, indicating that the relationship between SMS and RD depends on age. In contrast, the digit span × age interaction effect did not reach significance.

As the average *SI* across tempos significantly predicted RD performance in the multiple regression model, we further explored the main effect of tapping consistency at each of four different tempos via partial correlation analyses (Table 4). Significant positive correlations between SMS and RD emerged at 60 BPM (r = .305, p = .001) and at 100 BPM (r = .194, p = .038). After further controlling for digit span, beat tapping at 60 BPM only remained significant (r = .261, p = .005), but not at 100 BPM (r = .170, p = .070). Tapping performance at four BPMs tended to be positively related to each other, although significant pairs were only found for 100 BPM (Table 4).

Next, to further explore the tapping consistency × age interaction effect, we performed the regression analysis separately in both younger and older cohorts of children after the data were divided relative to the median age (=9;6 years). Descriptive statistics of demographic and behavioral variables for each group are listed in Table 5. As can be seen in Table 6, higher tapping consistency significantly predicted higher rhythm accuracy in the younger children group, but not in the older children group. On the contrary, despite the non-significant interaction effect between age-by-AWM, digit span score was significantly associated with RD performance in the older children group while the association was marginal but not significant in the younger children group. We also found that female children performed significantly better than male children on the RD task among younger children.

Lastly, a one-way repeated measures ANOVA revealed a significant main effect of the beat tempo on tapping consistency (F(2.77, 326.63) = 10.288, p < .001). Post-hoc comparisons indicated that synchronization tapping was more consistent at 60 BPM than at other BPMs (vs 100 BPM: p < .05, vs 120 BPM: p < .001, vs 180 BPM, p < .001, Bonferroni corrected; see Table 1).

Discussion

The present study demonstrated that the ability to discriminate musical rhythms was independently predicted by both SMS (i.e., beat tapping consistency) and AWM (i.e., digit span score) performance in children aged between 7 and 12 years old. Notably, there was an age-related transition in the degree of relationship among these, wherein SMS, not AWM, was associated with RD in younger children (i.e., 7;1-9;6 years old), while it was AWM, not SMS, that accounted for the perceptual rhythm task in older children (i.e., 9;6-12;10 years old). Together, this is the first study reporting dynamic shift from sensorimotor to working memory in support of perceptual rhythm processing in a large cohort of the middle-to-late childhood population.

Relationship between sensorimotor synchronization and rhythm discrimination

In the present study, we found that children's beat-tapping ability predicted their perceptual rhythm discrimination performance. This finding is in line with extant literature showing a positive association between rhythm perception and production skills in adults (Dalla Bella et al., 2017; Fujii & Schlaug, 2013; Iversen & Patel, 2008). For example, the consistency of tapping to the underlying beat of a musical excerpt was correlated with perceptual thresholds of meter discrimination and finding beat or tempo changes (Fujii & Schlaug, 2013). The tapping-to-metronome consistency also predicted the ability to identify beat alignment with superimposed musical excerpts (Dalla Bella et al., 2017). Neuroimaging studies have also reported involvement of motoric circuitries in perceptual rhythm and beat processing without explicit action engagement (Bengtsson et al., 2009; Chen et al., 2008; Grahn & Brett, 2007; Grahn & Rowe, 2009). As postulated by the ASAP (Action simulation for Auditory Prediction) hypothesis (Cannon & Patel, 2021; Patel & Iversen, 2014), the motor system may tap into rhythm perception via generating temporal predictions by means of covert movements to the temporal regularity of rhythms.

There are, however, some studies that have contradicted our results and those described above (Tierney et al., 2017; Tierney & Kraus, 2015). For example, Tierney and Kraus (2015) showed that the ability to remember and reproduce rhythmic patterns was not correlated with auditory beat synchronization performance in adults. This was recently replicated by Bonacina et al. (2019; 2020) in children of 5-8 years old, leading them to conclude that there are multiple rhythm skills that are distinct and do not influence each other. There is, however, an important difference between these studies and ours; whereas they used intermediate-to-fast range tempos (i.e., 100 and 150 BPMs), we used a wider range of beat intervals (i.e., 60, 100, 120, and 180 BPMs) covering slow-to-middle-to-fast ranges. Indeed, our exploratory analysis revealed that the association between RD and SMS was much stronger at the slower (60 and 100 BPMs) than faster range (120 and 180 BPMs). Because tapping consistency at 60 BPM was correlated with digit span score, we questioned whether or not the connection between SMS and RD would disappear if AWM were included as a covariate in another partial correlation analysis. However, the association between SMS at 60 BPM and RD still remained significant, ruling out a possibility that the link between sensorimotor and perceptual rhythm skills is a mere epiphenomenon confounded by cognitive processes. Alternatively, beat tapping at faster and slower tempos may capture different aspects of individual differences in SMS. According to Wing and Kristofferson (1973)'s SMS model, tapping variability (i.e., consistency in our study) depends on two independent sources of variability: internal timekeeping variability and effector-specific motor variability. It has been shown that the variability of internal sensorimotor timing is increased as the metronome interval lengthens while motor variability remains constant (Ivry & Hazeltine, 1995; Krampe et al., 2002). Thus, the slower-tempo tapping ability might better reflect the internal timing ability related to rhythm perception than does the faster-tempo tapping, which in turn may reveal the stronger relationship between sensorimotor and perceptual rhythm skills. Further research is warranted to confirm the current finding made by adding slower ranges of SMS when relating it to perceptual rhythm skills.

Relationship between auditory working memory and rhythm discrimination

In addition to SMS, AWM independently predicted RD. There are ample behavioral studies demonstrating positive association between AWM and RD (Anvari et al., 2002; Hansen et al., 2013;

Politimou et al., 2019; Strait et al., 2011; Swaminathan & Schellenberg, 2019). AWM is also related to a variety of other rhythm tasks including perceptual timing judgment (Zélanti & Droit-Volet, 2011), synchronization with musical rhythm (Bailey & Penhune, 2010; Colley et al., 2018), as well as rhythm reproduction (Saito, 2001; Tierney & Kraus, 2015). Importantly, AWM can be impacted by rhythmic context embedded in the encoding items. To illustrate few examples, working memory of single interval timing information is better when the target interval is inserted within a temporally regular compared to an irregular interval sequence (Teki & Griffiths, 2014). Also, working memory performance can be improved by intermittent pauses in between verbal items (Henson et al., 2003; Hitch et al., 1996). Lastly, a concurrent presentation of regular rhythm (i.e., isochronous tones) during the maintenance phase improved subsequent recall of the same items (Plancher et al., 2018). Together, this line of evidence suggests that AWM not only contributes to the efficiency of processing auditory temporal information, but its performance can be also affected by rhythmic contexts. Such a reciprocal influence between rhythm processing and AWM suggests common neural resources may be at play, which deserves active future investigations.

Previous research has shown that music training enhances working memory in children (Chen et al., 2021; Lee et al., 2007; Roden et al., 2014). Given the mutual connection between rhythm processing and working memory, one may surmise that music training benefits working memory by honing rhythmic skills. In line with this idea, Hansen et al. (2013) reported that musicians outperformed non-musicians in forward digit span as well as rhythm discrimination tasks, and the performance of the two tasks were correlated. Nevertheless, in the present study, the number of years of musical training was predictive of neither AWM nor RD (Table 2). Similarly, some recent studies failed to support the association between musical training and digit span in children (Kragness et al., 2021) as well as adults (Vanden Bosch der Nederlanden et al., 2020). Future studies are in need of resolving the discrepancy across extant literature by utilizing standardize and consistent measures of musical training.

Distinct contribution of sensorimotor and working memory systems in supporting development of rhythm discrimination in middle-to-late childhood

Perhaps the most notable finding of the present study lies in the change of relationship between SMS, AWM, and RD over the course of middle childhood. That is, SMS tended to predict RD at younger age (7-to-9 years), while AWM took a stronger position in predicting RD at older age (10-to-12 years). In consistent with our finding, a recent study observed that SMS facilitated subsequent RD task in children aged 5-to-8 years, but not in adults (Monier et al., 2019). There is also evidence that 6-to-7-year-old children with motor coordination deficits have poorer rhythm perception compared to typically developing controls (Chang et al., 2021). Thus, children may benefit from better sensorimotor skills in perceptual rhythm task at younger ages. By contrast, in the older children cohort, the association between RD and SMS was no longer significant; instead RD was more reliably predicted by AWM. This finding is consistent with a recent longitudinal study where the correlation between AWM and musical ability became stronger in 13 years of age compared to 8 years of age (Kragness et al., 2021).

To the best of our knowledge, this is the first to show a dynamic shift of the relationship between the sensorimotor and working memory systems in support of perceptual rhythm processing prior to the pre-adolescence period. Our findings suggest that, as children develop, children may be more able to dissociate temporal information from motor processes (Droit-Volet & Rattat, 1999) while they rely more on working memory processes to maintain the temporal structure of rhythms (Droit-Volet et al., 2015). The present data demonstrates that this shift of neural strategy occurs during middle-to-late childhood. This transition can be explained in light of differential developmental trajectories between the sensorimotor and working memory systems to support rhythm perception. That is, the development of sensorimotor system may reach a level at which sensorimotor skills add no further benefit to rhythm processing around pre-adolescence. By contrast, AWM may continue to exert a substantial influence on perceptual rhythm skill throughout development of the higher-order cognitive processes well beyond adolescence (Fuster, 2002; Roberts et al., 2018).

Although quite conceivable, we note that this conjecture is not yet fully supported by existing data indicating similar developmental trajectories of SMS (Drewing et al., 2006; McAuley et al., 2006) and AWM (Conklin et al., 2007; Gathercole et al., 2004) during childhood. Certainly, follow-up research is warranted to corroborate the current finding to elucidate the neurodevelopmental trajectory underpinning rhythm processes.

Other findings

Two other minor, though interesting, findings are worthy of a brief discussion. First, we found that beat tapping at 60 BPM was more consistent than tapping at other faster tempos. There are mixed reports in children's performance on the slow-range beat tapping. Some studies have shown that children's tapping performance at the slow range was not different from that at faster ranges (Kirschner & Tomasello, 2009; Monier & Droit-Volet, 2019; Provasi & Bobin-Bègue, 2003). For example, in children aged from 5 to 7 years, the variability of inter-tap intervals was comparable between slow and intermediate range tempos (i.e., 67, 85, and 120 BPMs) (Monier & Droit-Volet, 2019). However, other study reported that the tapping variability was smaller in longer inter-onset-interval (Drewing et al., 2006). Secondly, we found a gender difference in which RD was better in girls than in boys, especially in younger children. There is scarce evidence regarding gender differences in auditory and cognitive abilities (Ardila et al., 2011; Yathiraj & Vanaja, 2015). One study reported that 5-6-year-old girls outperformed age-matched boys in beat tapping, but not in RD ability (Pollatou et al., 2005). These findings deserve further investigation to more clearly understand the effect of tempo on SMS as well as gender difference in perceptual rhythm processing.

Conclusion

In summary, the current study used multiple measures of rhythm processing and working memory to examine how these skills are inter-related over the course of the elementary school period. Specifically, we showed that the sensorimotor and working memory systems are independently at play during musical rhythm discrimination processing. Furthermore, we found a dynamic shift from sensorimotor to auditory working memory in terms of degree of association with perceptual rhythm processing before entering pre-adolescence. Lastly, our data suggest the importance of covering a wide range of temporal ranges in beat tapping when exploring the functional role of the sensorimotor system in cognitive processes.

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Table 1. Mean raw scores (*M*) and standard deviation (*SD*) of demographic and behavioral variables.

Variable	*N*	*M*	Min	Max	*SD*
Gender (% female)	119	52.1%	–	–	–
Age (years; months)	119	9;9	7;1	12;10	1;7
Parental income (5 levels)	118	4.24	3	5	.71
Years of musical training	119	2.28	0	9	1.85
Rhythm discrimination (*d'*)	119	1.46	–.59	3.29	.77
Working memory (Digit span)	119	19.92	11	32	4.75
Tapping consistency (*SI*)	119	.472	.319	.638	.065
BPM 60	119	.515	.171	.755	.122
BPM 100	119	.475	.275	.705	.100
BPM 120	119	.450	.295	.719	.086
BPM 180	119	.448	.346	.665	.072

Table 2. Student's t values from independent sample t-tests of behavioral measures by gender, with positive values indicating better performance in male (left). Pearson's partial correlation r values between age and behavioral measures (left) and between years of musical training and behavioral measures (middle), controlling for the other demographic variables.

Variable	t-test by gender (*t*)	Correlation with age (*r*)	Correlation with years of musical training (*r*)
Rhythm discrimination (*d*')	**–2.07***	**.255****	.015
Working memory (Digit span)	–.86	**.265****	.055
Tapping consistency (*SI*)	.87	**.238***	**.228***
BPM 60	.40	**.195***	.137
BPM 100	.70	.176	.061
BPM 120	–.24	**.218***	**.194***
BPM 180	1.80	–.010	**.243****

Significant values are in bold; **p*<.05, ***p*<.01, ****p* <.001

Table 3. Standardized regression coefficients in predicting rhythm discrimination accuracy as a function of demographic and behavioral variables.

Predictors	b	t-test	p
Gender	.164	1.900	.060
Age	.154	1.603	.112
Parental income	.041	.490	.625
Years of musical training	–.066	–.677	.500
Working memory (Digit span)	**.288**	**3.287****	**.001**
Tapping consistency (*SI*)	**.259**	**2.893****	**.005**
Age × Working memory	.129	1.517	.132
Age × Tapping consistency	**–.178**	**–2.087***	**.039**

Significant values are in bold; **p*<.05, ***p*<.01

Table 4. Pearson's partial correlation r values between behavioral measures controlling for age, gender, years of musical training, and parental income.

Variable	Digit span	60 BPM	100 BPM	120 BPM	180 BPM
Rhythm discrimination (*d'*)	**.349*** **	**.305** **	**.194***	–.014	.141
Working memory (Digit span)	–	**.186***	.101	–.081	.043
Tapping consistency (*SI*)					
60 BPM		–	**.271** **	.125	.175
100 BPM			–	**.272** **	**.318** **
120 BPM				–	.149
180 BPM					–

Significant values are in bold; *p<.05, **p<.01, ***p<.001

Table 5. Mean raw scores (*M*) and standard deviation (*SD*) of demographic and behavioral variables for the younger and older children.

Variable	Younger children			Older children		
	N	*M*	*SD*	*N*	*M*	*SD*
Gender (% female)	59	52.5%	–	60	51.7%	–
Age (years; months)	59	8;5	0;8	60	11;0	0;11
Parental income (5 levels)	59	4.31	.75	59	4.18	.68
Years of musical training	59	1.47	1.13	60	3.07	2.07
Rhythm discrimination (*d*’)	59	1.30	.80	60	1.62	.72
Working memory (Digit span)	59	18.73	4.16	60	21.08	5.03
Tapping consistency (*SI*)	59	.451	.057	60	.493	.065
BPM 60	59	.489	.122	60	.542	.116
BPM 100	59	.454	.095	60	.495	.100
BPM 120	59	.423	.077	60	.477	.087
BPM 180	59	.437	.071	60	.459	.072

Table 6. Standardized regression coefficients in predicting rhythm discrimination accuracy as a function of demographic and behavioral variables.

Predictors	Younger children			Older children		
	b	t-test	p	b	t-test	p
Gender	**.265**	**2.023***	**.048**	–.077	–.578	.566
Age	.075	.611	.544	.213	1.725	.090
Parental income	–.030	–.243	.809	.191	1.515	.136
Years of musical training	.053	.391	.697	–.073	–.560	.578
Working memory (Digit span)	.228	1.879	.066	**.403**	**3.333***	**.002**
Tapping consistency (*SI*)	**–.304**	**–2.507***	**.015**	–.022	–.169	.867

Significant values are in bold; *p<.05

Figure 1.

Examples of 7-sound and 8-sound rhythms and their respective variants in rhythm discrimination task. For each rhythm, a variant was made by swapping two adjacent intervals, as indicated by the dashed-line boxes.

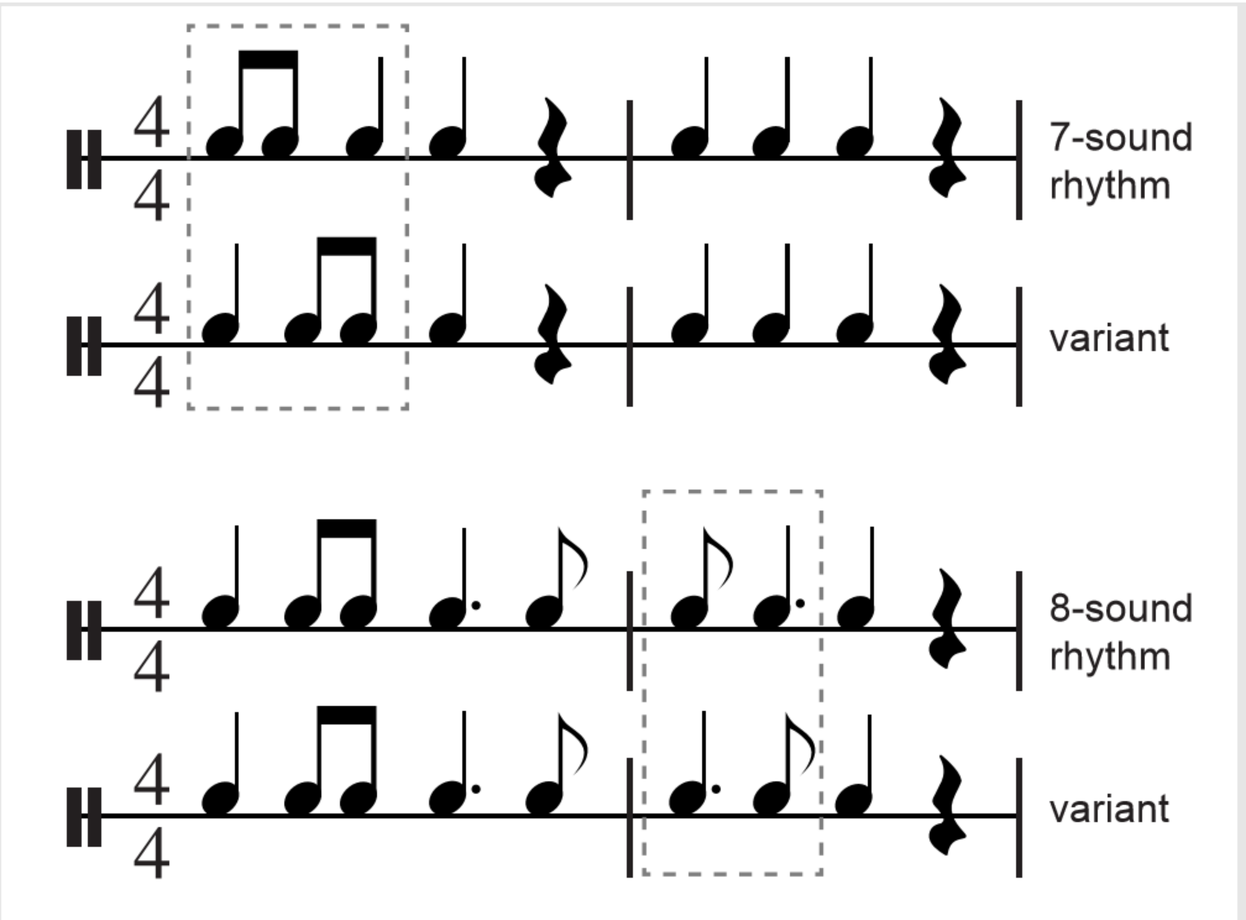

Figure 2.

Relative phase probability distributions and the corresponding *SI* values from three representative participants (P33, P63, and P36). The bin size was set to 24º, resulting in a total of 15 bins. The phase value of 0º is indicative of a tapping response in perfect synchrony with a current sound. The value of ±180º is indicative of a response that occurred at mid-point between the current and preceding (–) or succeeding sound (+). Each bar length indicates the probability with which tapping responses occurred within the phase bin. The numbers below the dotted lines indicate probability values. The *SI* is sensitive to capture the difference between random responses (P36) and multi-peak responses (P63).