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Musical pitch processing predicts reading development in Chinese school-age children

Shiting Yang [a], Lirong Tang [a], Li Liu [a], Qi Dong [a], George K. Georgiou [b], Yun Nan [a,*]

[a] State Key Laboratory of Cognitive Neuroscience and Learning & IDG/McGovern Institute for Brain Research, Beijing Normal University, Beijing, 100875, China

[b] Department of Educational Psychology, University of Alberta, Edmonton, Alberta, T6G 2G5, Canada

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ABSTRACT

Musical pitch perception is closely related to phonological awareness and reading development in alphabetic languages. However, whether such a relation also exists in tonal languages such as Chinese remains unclear. Here, we examined the musical pitch—reading relations and the possible mediating effects of phonological awareness in a sample of typically-developing Chinese children followed from Grade 3 (age 9) to Grade 5 (age 11). Phonological awareness and reading (accuracy and fluency) were assessed at both time points. Musical pitch perception was examined with a passive oddball EEG paradigm and an active identification task at age 9. Results showed that neural musical pitch sensitivity (indexed by P3a latency) predicted reading accuracy at age 11 and its two-year development. Behavioral musical pitch sensitivity predicted reading fluency at both ages through the effects of phonological awareness. Together, our results reveal the effects of musical pitch processing on reading development at both behavioral and neural levels in Chinese.

1. Introduction

It is widely accepted that music and speech share many different neurocognitive levels of sound processing (i.e., the overlapping neural auditory networks across domains; Besson et al., 2011; Patel, 2011). At the most fundamental level, pitches are the predominant sound units in music, and rhythms refer to their temporal structure. Phonemes, on the other hand, constitute the distinct sound units in speech. Phonological awareness refers to an individual's ability to identify and manipulate the sound structure of language at different levels (e.g., syllable, onset and rime, and phoneme; Wagner & Torgesen, 1987). Accumulating studies in both alphabetic (Goswami et al., 2011, 2013; Huss et al., 2011; Overy et al., 2003; Tierney & Kraus, 2013a; van Zuijen et al., 2012) and non-alphabetic (Chiang et al., 2020; Lee et al., 2015; Sun et al., 2022) languages have shown that rhythm skills are closely related to phonological awareness and reading development in preschoolers (van Zuijen et al., 2012), school-age children (Chiang et al., 2020; Lee et al., 2015; Sun et al., 2022; Tierney & Kraus, 2013a), and children with reading difficulties (Goswami et al., 2013; Huss et al., 2011; Overy et al., 2003). Although musical pitch perception is also closely associated with phonological awareness and early reading development in preschool (Anvari et al., 2002; Lamb & Gregory, 1993) and school-age (Moreno et al., 2009; Putkinen et al., 2019) children in alphabetic languages, whether such an association also exists in non-alphabetic languages such as Chinese remains unclear. Chinese offers a unique opportunity to understand the possible connection between musical pitch processing and reading because it is a tonal language and

* Corresponding author.
E-mail address: nany@bnu.edu.cn (Y. Nan).

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musical pitch plays an important role in reading (e.g., Nan et al., 2018). Thus, the current study aimed to examine whether musical pitch processing is related to reading development in typically-developing Chinese children and whether phonological awareness mediates their relation.

1.1. The relation between musical pitch processing and reading

Studies in alphabetic languages (e.g., English: Anvari et al., 2002; Lamb & Gregory, 1993; Portuguese: Moreno et al., 2009; Tsang & Conrad, 2011) have shown that musical pitch processing is related to reading. In preschool children, pitch discrimination was found to correlate significantly with reading skills, even after controlling for the effects of age and nonverbal IQ (Lamb & Gregory, 1993). Anvari et al. (2002) also found that musical pitch perception correlated with early reading skills in preschool children. In school-age children, musical pitch processing correlated significantly with word identification (Tsang & Conrad, 2011). In addition, training studies have shown a close relation between musical pitch processing and reading. For example, Moreno et al. (2009) showed that relative to painting training and a control group, children who underwent music training showed improved reading as well as enhanced neural and behavioral sensitivities to pitch variations for both music and speech.

Similar to typically-developing children, the musical pitch–reading relation has been found among children with developmental disorders (e.g., dyslexia). Children with dyslexia scored significantly lower than their chronological-age controls in a musical pitch discrimination task (Couvignou & Kolinsky, 2021; Forgeard et al., 2008). About 34% of the dyslexic children were musically impaired and pitch processing was a significant predictor of their literacy skills, even after controlling for the effects of age, phonological awareness, and rapid automatized naming (Couvignou & Kolinsky, 2021).

Most of the studies examining the association between musical pitch processing and reading development have been conducted in alphabetic languages. It remains unclear whether similar findings can be found in Chinese, a non-alphabetic language. Recent evidence showed that preschoolers' pitch discrimination predicted word reading in first grade above and beyond the effects of age (Chung & Bidelman, 2021). However, one might argue that at the transition from preschool to elementary school, the effects of formal reading instruction are yet to unfold. It is thus crucial to examine the same relations among school-age children.

Previous studies in Chinese have shown that school-age children with dyslexia were impaired in musical pitch processing (Wang et al., 2012, 2019), and pitch perception predicted nonsense syllable reading across dyslexics and controls (Wang et al., 2012). Wang et al. (2019) also found that after controlling for the effects of age and IQ, pitch perception predicted Chinese character recognition among school-age dyslexic children and controls. These results need to be replicated with typically-developing children. Additionally, most of the previous studies were cross-sectional, and measures of musical pitch and reading skills were tested only once. Longitudinal studies are needed to examine whether the effects of musical pitch perception on reading persist over time, particularly after controlling for the effects of autoregressor (i.e., reading performance at an earlier point in time).

1.2. Possible mediator of the relation between musical pitch processing and reading

A possible mediator in the relation between musical pitch processing and reading is phonological awareness. Studies have shown that musical pitch processing is closely related to phonological awareness (e.g., Anvari et al., 2002; Degé et al., 2015). Music training has also been found to improve preschool children's phonological skills. Degé and Schwarzer (2011), for example, found that after a 20-week training, the music training group and the phonological-skill training group showed a significant improvement in phonological awareness compared to the control group. Music training's positive effects on phonological awareness may be due to improved musical pitch processing (Patscheke et al., 2019). Six-month piano training resulted in enhanced neural musical pitch processing, which was correlated with improvements in consonant-based word discrimination (Nan et al., 2018). Given that phonological awareness is a significant predictor of reading (e.g., Caravolas et al., 2005; Li et al., 2012; Liu et al., 2017; Scarborough, 1998) and musical pitch processing is related to phonological awareness (e.g., Anvari et al., 2002; Loui et al., 2011; Patscheke et al., 2019), phonological awareness may mediate (at least partly) the relation between musical pitch processing and reading. Studies in alphabetical languages and Chinese-English bilinguals have provided some support for this hypothesis. Anvari et al. (2002) revealed that phonological awareness partly mediated the relations between musical pitch processing and early reading skills in 4–5 years old children. Zhang et al. (2017) found that musical perception, based on pitch and rhythm tasks, was linked to English reading in school-age Chinese bilingual children through the effects of English phonological awareness. For the purpose of this study, we examined the possible mediating role of phonological awareness in the relation between musical pitch and reading in a sample of typically-developing Chinese children.

1.3. The present study

The current study aimed to examine (a) whether there is an association between musical pitch processing and reading skills in typically-developing Chinese school-age children, and (b) whether phonological awareness mediates their relationship. First, on the basis of previous findings (e.g., Wang et al., 2012, 2019), we hypothesized that musical pitch processing would be related to reading accuracy and fluency in typically-developing school-age Chinese children. Second, we hypothesized that phonological awareness would mediate, at least partially, the musical pitch—reading relation.

An important contribution of this study is that we measured musical pitch processing using both behavioral and neural measures. Using a passive auditory oddball paradigm, we were specifically interested in two ERP responses to deviant pitch changes, i.e., MMN and P3a. MMN indexes automatic auditory change detection (Näätänen et al., 2007), and P3a indexes involuntary attention allocation to deviant sound (Kujala et al., 2007). This passive task is also less influenced by attention and motivational factors compared to an active task (Wronka et al., 2008). Neural musical pitch processing might shed unique light on the musical pitch—reading relation, as early findings suggest that the electrophysiological measures might be more sensitive to developmental differences than behavioral measures (e.g., Nan et al., 2018). We anticipated that latencies and/or amplitudes of musical pitch MMN and P3a may be associated with reading and its development.

The present study will make three additional important contributions to the literature. First, we examined the relation between musical pitch processing and reading skills using a longitudinal design. Note that with one exception (Chung & Bidelman, 2021), most previous studies on this topic were cross-sectional. Longitudinal studies enable us to examine whether the effects of musical pitch perception on reading persist over time. In order to minimize possible practice effects resulting from repeated measurements, we tested and retested our participants over a two-year span. This duration has been shown to be an optimal follow-up period in earlier research (Braw et al., 2013), as practice effects during multiple testing could peak at approximately three months (Bartels et al., 2010) and decline significantly after four months (Kexel et al., 2021). Second, our results will extend those of previous studies conducted in alphabetic languages to typically-developing Chinese school-age children. Finally, because previous studies have demonstrated that music experience is an important factor for musical pitch processing and reading-related skills (Degé & Schwarzer, 2011; Putkinen et al., 2015; Sofologi et al., 2022; Tierney & Kraus, 2013b), we controlled for the effects of music experience before examining the relationship between musical pitch processing and reading in our study.

2. Method

2.1. Participants

Sixty-five Grade 3 Mandarin-speaking children (37 boys and 28 girls, $M_{age} = 9.4$ years, $SD = 0.3$) were recruited on a voluntary basis from two public elementary schools in Beijing to participate in our study. Based on parents' reports, none of the children were experiencing any intellectual, sensory or behavioral difficulties. Their audiometric thresholds were lower than 20 dB hearing level from 250 Hz to 8000 Hz. In addition, their music experience ranged from 0 to 66 months (mean $\pm$ SD = 19.4 $\pm$ 21.0 months). The median and mode of both mother's and father's educational level was "completed university", and the average monthly family income was between 20,000 and 30,000 RMB. These two indicators of socioeconomic status (SES) suggested that our participants were coming mostly from upper-middle class families (Beijing Municipal Bureau of Statistics, 2021). Fifty-nine of these children were retested in Grade 5 (32 boys and 27 girls, $M_{age} = 11.4$ years, $SD = 0.3$). Six children moved to a different city and could not be tested. This study was approved by the Institutional Review Board of Beijing Normal University. Adhering to the Declaration of Helsinki principles, we obtained written informed consents from children and their parents at each measurement point.

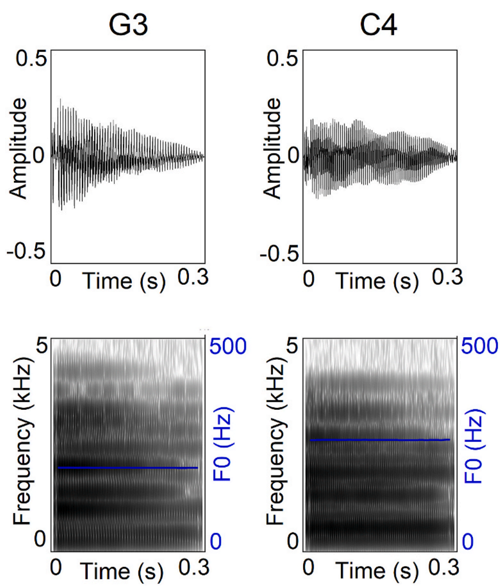

Fig. 1. The acoustic waveforms (upper panel) and spectrograms (lower panel) of the stimuli used in musical pitch perception task (EEG and behavioral).
The blue line of each spectrogram indicates the pitch contour of F0. Pitch interval between the two notes (mean F0 of G3 is 196.6 Hz, and mean F0 of C4 is 261.8 Hz) is approximately 5 semitones.

2.2. EEG and behavioral measures of musical pitch perception

2.2.1. Stimuli

Musical pitch perception was measured using a passive oddball paradigm with electroencephalogram (EEG) and an active behavioral identification task.

Two musical notes (G3 and C4) were presented in both EEG and behavioral measurements (Fig. 1). G3 and C4 were computer-synthesized with a piano-like timbre. Praat (Boersma & Van Heuven, 2001) was then applied to standardize these stimuli to 300 ms (with rise and fall times of 10 ms each) in duration and 70 dB in intensity. The interval between G3 (F0 = 196.6 Hz) and C4 (F0 = 261.8 Hz) was approximately five semitones, which was within the range of pitch changes normally occurring in Chinese Mandarin (e.g., Nan et al., 2010).

The two blocks of musical pitch stimuli were presented in a counterbalanced order using a Latin square design across participants during both the EEG and the behavioral testing. The two stimuli (G3 and C4) served as the standard and the deviant interchangeably in the two blocks. For the EEG testing, one block contained 720 trials with 120 deviants (deviant probability = 17%) and 600 standards. Trials in each block were presented in a pseudorandom order, ensuring at least two standards between deviants. The inter-trial interval differed randomly between 600 ms and 800 ms at a step of 1 ms. For the behavioral identification task, each block had 120 trials with 90 standards and 30 deviants. The sequence of trials in each block was pseudorandom, with at least one standard between deviants. We chose an identification task over a discrimination task because the former not only requires comparing stimuli but also associating them with specific categories or labels, making it relatively more complex than the latter.

2.2.2. Procedure

During the EEG testing, children were required to ignore the sounds while watching self-selected silent cartoons with subtitles. They were told to minimize their eye blinks and head motions. A short break was given between blocks. The whole EEG section lasted about half an hour.

After the EEG experiment, children were asked to finish the 5-min behavioral identification task. For each block, they first learned the standards and deviants during a short practice. During testing, they were instructed to respond to the standard and deviant stimuli by pressing two corresponding buttons on the keyboard as accurately and quickly as possible without any feedback after each item. Stimuli in both the EEG and behavioral testing were presented via E-prime (Psychology Software Tools, Pittsburgh, PA, USA) through headphones at a consistent and comfortable volume level.

2.2.3. EEG recording

The EEGs were recorded using a SynAmps EEG amplifier with a 32-channel (Ag/AgCl) Neuroscan system, with a sampling rate of 1000 Hz and a bandpass filter of 0.1–100 Hz. The 32 electrodes were arranged according to the international 10–20 system. The ground electrode was located at the midpoint between FP1 and FP2, and the reference electrode was placed on the tip of the nose. Horizontal electrooculograms (HEOGs) were recorded from two electrodes placed next to the outer canthi of each eye, and vertical electrooculograms (VEOGs) were recorded from two electrodes above and below the left eye. The impedance of each channel was kept below 5 kΩ.

2.2.4. Data processing

Offline EEG data preprocessing was performed using EEGLAB toolbox (Delorme & Makeig, 2004) in Matlab (The MathWorks, Inc, Natick, Massachusetts, USA). The signals were band-pass filtered (1–30 Hz) and segmented into 900-ms epochs with a 100-ms pre-stimulus baseline and an 800-ms interval after the onset of stimuli. After baseline correction, epochs with voltage changes exceeding ±100 μV were rejected. Independent Component Analysis (ICA) was applied to remove eye blinks. The average accepted number of epochs for deviant stimuli was above 67. Standard waveforms and deviant waveforms were separately averaged across two blocks in order to minimize the effects of acoustic properties of different sounds. Difference waveforms for each participant were obtained by subtracting the standard waveforms from the respective deviant waveforms.

For the neural sensitivities to the musical pitch changes, the mismatch responses including MMN and P3a at nine electrodes (F3, Fz, F4, FC3, FCz, FC4, C3, Cz, and C4) were computed based on the difference waveforms. The peak latencies of MMN were measured at the negative maximum between 130 and 270 ms post-stimulus onset. The peak latencies of P3a were measured at the positive maximum between 250 and 400 ms post-stimulus onset. In order to avoid the maximum voltage falls at the border of the window, local peak latency measure was applied (Luck, 2014). The amplitudes of MMN and P3a were computed from 60-ms time windows centered on the peaks across all participants (134–194 ms for MMN, and 282–342 ms for P3a).

The behavioral sensitivities were indexed by *d*-prime. According to signal detection theory (SDT), the calculation of *d*-prime was based on hit rates and false alarm rates: hits were the correct answers to the deviants and misses were the false answers to the deviants. False alarms were the wrong answers to the standards, and correct rejections were the right answers to the standards. The formula for *d*-prime is: $d^{'} = Z(hit\ rate) - Z(false\ alarm\ rate)$, where $hit\ rate = \frac{hits}{hits+misses}$, and $false\ alarm\ rate = \frac{false\ alarms}{false\ alarms+correct\ rejections}$. Following the suggestions of Stanislaw and Todorov (1999), the extreme values 0 and 1 were replaced with 0.5/N and (N-0.5)/N (N was the number of signal or noise trials).

2.3. General cognitive and reading-related measures

Nonverbal IQ. Raven's Standard Progressively Matrices (Raven & Court, 1998) was administered to assess children's nonverbal IQ. The task had five subtests and each subtest contained 12 items. Children were presented with a visual configuration of different designs with a missing piece and were asked to choose among six to eight options the one that would accurately complete the pattern. One point was given for each correct answer (max = 60). Cronbach's alpha in our sample was 0.83.

Verbal IQ. The vocabulary subtest of the Wechsler Intelligence Scale for Children-China Revised (Lin & Zhang, 1986) was used to measure children's verbal IQ. Children were asked to provide a definition of a given word. Each child's score was calculated based on the number of important semantic features s/he provided. For each word, one point was given for each semantic feature and the maximum score was 2. There were 32 words and the highest score was 64. Cronbach's alpha reliability in our sample was 0.87.

Principal component analysis was applied for verbal and nonverbal IQ to create a composite factor (IQ), which was subsequently used in the following analysis.

Phonological awareness. A phoneme deletion task adopted from Xue et al. (2013) was used to measure children's phonological awareness. Children were required to say what was left in a single-syllable word after deleting one of its phonemes. The deleted phoneme was at either the initial (8 items), medial (8 items), or final (10 items) position within the syllable. One point was given for each correct answer (max = 26). Cronbach's alpha reliability in our sample was 0.84.

Reading accuracy. Children were required to read a list of 150 Chinese characters that were ordered in increasing difficulty based on the grade level in which these words are taught in the primary school (Pan et al., 2011). The task was discontinued after 15 consecutive errors. One point was given for each correct answer. Cronbach's alpha in our sample was 0.96.

Reading fluency. A sentence verification task was used to measure reading fluency. Children were asked to silently read as many sentences as possible and judge if the meaning of each sentence was true or false by circling Yes or No at the end of each sentence within a 3-min time limit (Pan et al., 2011). There were 100 sentences arranged in order of increasing length. The score was the total number of correct sentences minus the total number of incorrect sentences. Reading fluency correlated 0.96 with reading accuracy in our sample.

2.4. Procedure

The EEG and behavioral tests of musical pitch perception as well as verbal and nonverbal IQ tests were administered at age 9. All the other behavioral tasks were completed at ages 9 and 11. At each measurement point, children finished all the tasks with a counterbalanced order within a day. For musical pitch perception, the behavioral task was completed after the EEG task. Before each task, detailed instructions and a warm-up training were given to ensure that children understood the task requirements. A small present (e.g., stickers) was given after the completion of each task to maintain children's motivation. Three experienced experimenters administered the cognitive and reading-related tests, all of which were based on objective questions with predefined correct answers.

2.5. General statistical analysis

Linear Mixed-effects Models (LMM) with restricted maximum likelihood estimation were performed in R (R Core Team, 2023) for neural musical pitch perception and behavioral reading-related skills (phonological awareness, reading accuracy, and reading fluency). To illustrate the neural responses to musical pitch changes, area (frontal: F3, Fz, and F4; fronto-central: FC3, FCz, and FC4; and central: C3, Cz, and C4), hemisphere (left: F3, FC3, and C3; middle: Fz, FCz, and Cz; and right: F4, FC4, and C4), and their interactions were specified as fixed factors. For the behavioral reading-related skills, testing time (at ages 9 and 11) was treated as a fixed factor. In each model, participants were defined as a random factor (random intercept) to account for individual variability. Covariates

Table 1
Performance on behavioral and neural measures at ages 9 and 11.

	Age 9	Age 11	F	Estimate	AIC
Nonverbal IQ (SD)	44.6 (5.9)	–	–	–	–
Verbal IQ (SD)	45.8 (8.6)	–	–	–	–
*d'*_pitch (SD)	1.5 (1.2)[a]	–	–	–	–
MMN_L (SD)	188.0 (29.1)	–	–	–	–
MMN_A (SD)	−0.6 (2.3)	–	–	–	–
P3a_L (SD)	320.6 (30.9)	–	–	–	–
P3a_A (SD)	1.3 (2.9)	–	–	–	–
Phoneme deletion (SD)	17.9 (4.9)	22.6 (3.0)[b]	49.56***	4.30***	646.81
Reading accuracy (SD)	101.8 (17.7)	124.9 (12.5)[b]	373.25***	22.60***	860.96
Reading fluency (SD)	49.1 (13.2)	65.5 (12.6)[c]	157.20***	16.70***	847.97

Note: SD indicates standard deviation. IQ = Intelligence Quotient; *d'* = *d*-prime; MMN_L = mean peak latencies of musical pitch MMN; MMN_A = mean amplitudes of musical pitch MMN; P3a_L = mean peak latencies of musical pitch P3a; P3a_A = mean amplitudes of musical pitch P3a. Values are in microvolts (μV) for amplitudes and in milliseconds (ms) for latencies. ***$p < 0.001$.

[a] Three children missed behavioral musical pitch perception task.

[b] Two children missed phoneme deletion and reading accuracy tasks.

[c] Three children missed reading fluency task. AIC = Akaike Information Criterion.

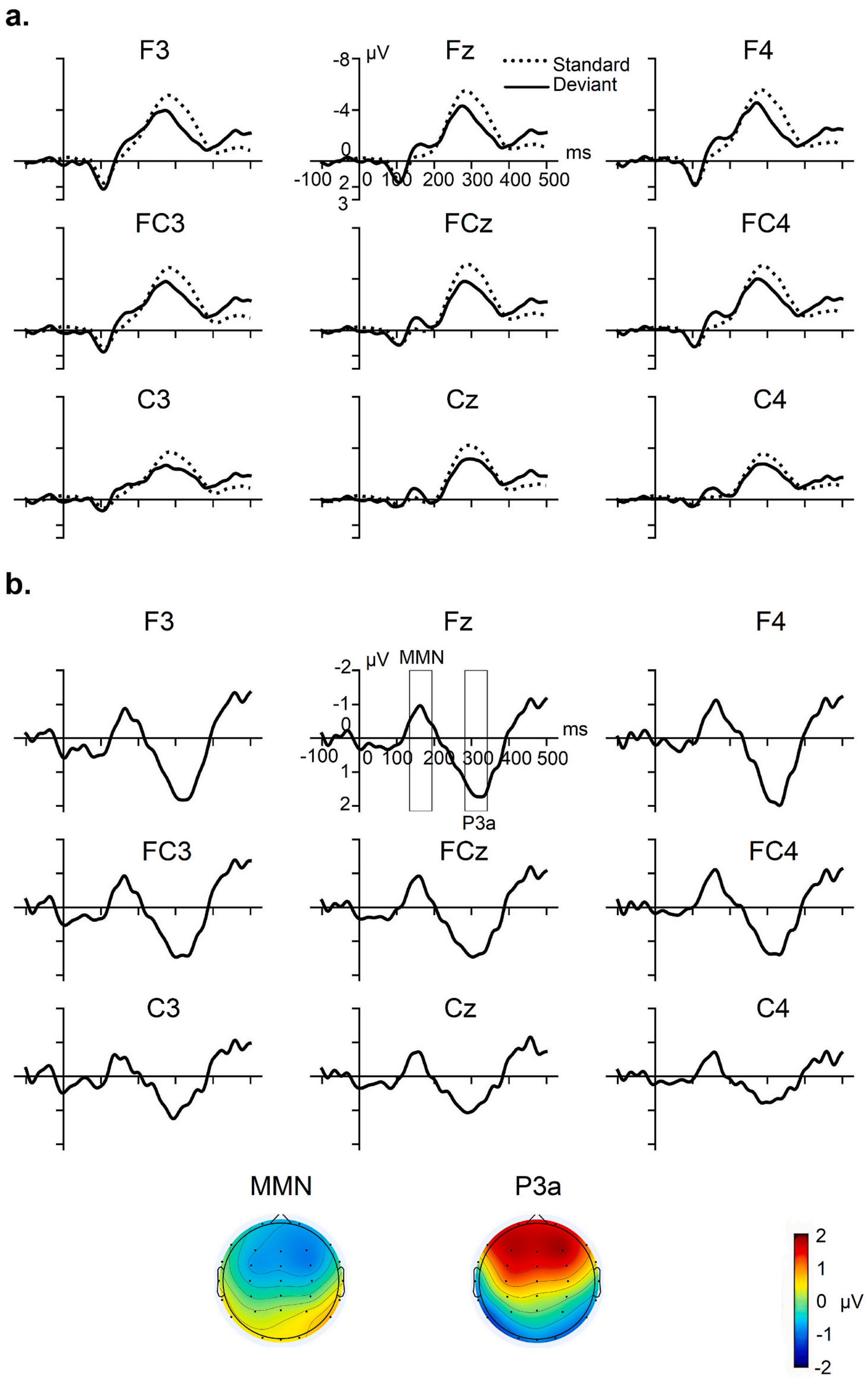

Fig. 2. The grand-averaged waveforms (a) as well as the difference waveforms (b) at nine electrodes, and the topographic maps of MMNs and P3as for musical pitch changes.

The grand-averaged waveforms (**a**) and the difference waveforms (**b**) elicited by deviant and standard stimuli of musical pitch at nine electrodes. The time windows for MMN (134–194 ms) and P3a (282–342 ms) amplitudes analyses are marked by rectangles. The topographic maps exhibit the scalp distributions of the MMN and P3a components. The time window is 60 ms. As shown by the key in the figure, darker red areas indicate greater positivity, and darker blue areas indicate greater negativity.

including individual differences (age, music experience, and SES) and IQ were also included in the model as fixed effects to account for confounding effects. Bonferroni corrections were applied for post hoc comparisons (Howell, 2012). The amplitudes and the peak latencies of MMN and P3a were averaged across the nine electrodes for further correlational and regression analyses.

In order to detect the transfer effects of musical pitch processing (behavioral measure: *d'*_pitch; neural measures including amplitudes and latencies of MMN and P3a) to reading-related skills at ages 9 and 11, we first conducted correlational analyses, controlling for the effects of age, music experience, SES, and IQ. Hierarchical regressions with autoregressors (reading skills measured at age 9) were conducted to further explore the observed significant correlations between musical pitch processing and reading skills over the two-year span. Additionally, mediation analyses with Mplus 7.4 were conducted to examine for possible mediating effects of phonological awareness between musical pitch processing and reading skills, controlling at the same time for the effects of age, music experience, SES, and IQ. The structural models in the mediation analyses were fitted using the bootstrap (bias-corrected) method (Mackinnon et al., 2004), with 5000 repeated samples and 95% confidence interval (CI).

3. Results

3.1. Musical pitch perception

The descriptive statistics on behavioral and neural musical pitch processing are presented in Table 1. For the neural responses to musical pitch changes (Fig. 2), the linear mixed-effects model on the MMN amplitudes yielded a significant main effect of area (AIC = 1893.77, $F(2, 512) = 5.28$, $p = 0.005$), *df* was estimated by Satterthwaite approximation. MMNs were significantly larger in the frontal region than in the central region (Estimate = −0.28, $p = 0.013$) and in the fronto-central than in the central regions (Estimate = −0.27, $p = 0.017$), while no significant difference was observed between the frontal and fronto-central regions (Estimate = −0.01, $p = 1$). As for the P3a amplitudes, there was a significant main effect of area (AIC = 2028.01, $F(2, 512) = 28.95$, $p < 0.001$). P3as were significantly larger in the frontal region than in the central region (Estimate = 0.81, $p < 0.001$), in the fronto-central than in the central regions (Estimate = 0.48, $p < 0.001$), and in the frontal than in the fronto-central regions (Estimate = 0.32, $p = 0.008$). No significant effects were observed for the MMN latencies and P3a latencies. As for the relations between the MMNs and P3as, correlational analyses revealed that MMN amplitudes correlated significantly with P3a amplitudes ($r = 0.45$, $p < 0.001$). There was no significant correlation between MMN latencies and P3a latencies ($r = 0.19$, $p = 0.134$).

3.2. The relations between musical pitch processing and reading development

As shown in Table 1, the linear mixed-effects models revealed that children's performance in phoneme deletion as well as the two reading tasks (reading accuracy and fluency) improved significantly from age 9 to age 11. Table 2 shows the partial correlations between musical pitch measures and reading-related measures at ages 9 and 11. After controlling for the effects of age, music experience, SES, and IQ, musical pitch P3a latency correlated with reading accuracy at age 11. Behavioral musical pitch sensitivities, as indexed by *d'*_ pitch, correlated with phoneme deletion at age 9. Table 3 shows the partial correlations between the possible mediator (i.e., phoneme awareness) and reading skills at ages 9 and 11. Phoneme deletion at age 9 correlated with reading accuracy at ages 9 and 11 and reading fluency at age 9.

3.3. Hierarchical regression analysis

Hierarchical regression analysis with the autoregressor was conducted to further examine the observed relation between the musical pitch measure (i.e., P3a latency) and reading accuracy over the two-year span (Table 4). The results showed that, after controlling for the effects of the autoregressor, musical pitch P3a latency explained 3.3% of unique variance in reading accuracy at age 11.

3.4. Mediation analysis

We further examined the tentative mediation mechanism from behavioral musical pitch processing via phonological awareness

Table 2
Partial correlations (controlling for the effects of age, music experience, SES, and IQ) between musical pitch measures and reading-related skills at ages 9 and 11.

	Phoneme deletion_9	Reading accuracy_9	Reading fluency_9	Phoneme deletion_11	Reading accuracy_11	Reading fluency_11
*d'*_pitch	**0.38****	0.03	−0.17	0.24	0.13	−0.08
MMN_L	0.12	0.03	0.15	0.10	−0.08	0.10
MMN_A	−0.02	0.03	0.07	−0.08	0.14	0.04
P3a_L	0.04	−0.17	−0.23	0.22	**−0.34***	−0.05
P3a_A	−0.18	0.17	0.08	−0.06	0.20	0.08

Note: SES = socioeconomic status; IQ = Intelligence Quotient; *d'* = *d*-prime; MMN_L = mean peak latencies of musical pitch MMN; MMN_A = mean amplitudes of musical pitch MMN; P3a_L = mean peak latencies of musical pitch P3a; P3a_A = mean amplitudes of musical pitch P3a. Suffix number indicates the data collection age. *$p < 0.05$; **$p < 0.01$.

Table 3
Partial correlations (controlling for the effects of age, music experience, SES, and IQ) between the mediator (phonological awareness) and reading skills at ages 9 and 11.

	Reading accuracy_9	Reading fluency_9	Reading accuracy_11	Reading fluency_11
Phoneme deletion_9	**0.27***	**0.27***	**0.28***	0.20
Phoneme deletion_11	–	–	−0.04	0.01

Note: SES = socioeconomic status; IQ = Intelligence Quotient. Suffix number indicates the data collection age. *$p < 0.05$.

Table 4
Hierarchical regression predicting reading accuracy at age 11.

		Reading accuracy at age 11	
step		ß	ΔR^2
1	Autoregressor	**0.849***	**0.721***
2	P3a_L	**−0.182***	**0.033***

Note: P3a_L = mean peak latencies of musical pitch P3a. *$p < 0.05$; ***$p < 0.001$.

(phoneme deletion) to reading skills based on the observed significant correlations 1) between behavioral musical pitch perception and phonological awareness (i.e., between the independent variable and the mediator) and 2) between phonological awareness and reading skills (i.e., between the mediator and the dependent variables) (Kenny et al., 1998).

Fig. 3 shows the mediator of the relation between *d'*_pitch and reading fluency at ages 9 (Model 1) and 11 (Model 2), after controlling for age, music experience, SES, and IQ. Model 1 fitted the data well, χ^2 (15) = 61.94, $p < 0.001$, RMSEA <0.001, CFI = 1.0, TLI = 1.0. In line with our hypothesis, there were significant indirect effects of *d'*_pitch via phoneme deletion at age 9 on reading fluency at age 9 (ab = 0.133, CI [0.016, 0.345]). There was also a significant direct effect between *d'*_pitch and reading fluency at age 9 (CI = [−0.529, −0.044]). Model 2 also fitted the data very well, χ^2 (15) = 54.81, $p < 0.001$, RMSEA <0.001, CFI = 1.0, TLI = 1.0. Results revealed significant indirect effects of *d'*_pitch through phoneme deletion at age 9 on reading fluency at age 11 (ab = 0.107, CI [0.005, 0.290]). The models with reading accuracy at ages 9 (χ^2 (15) = 68.85, $p < 0.001$, RMSEA <0.001, CFI = 1.0, TLI = 1.0) and 11 (χ^2 (15) = 58.47, $p < 0.001$, RMSEA <0.001, CFI = 1.0, TLI = 1.0) also fitted the data well. However, there were no significant indirect effects between *d'*_pitch and reading accuracy at age 9 (ab = 0.096, CI = [−0.002, 0.274]) or age 11 (ab = 0.085, CI = [−0.010, 0.267]) through phoneme deletion at age 9.

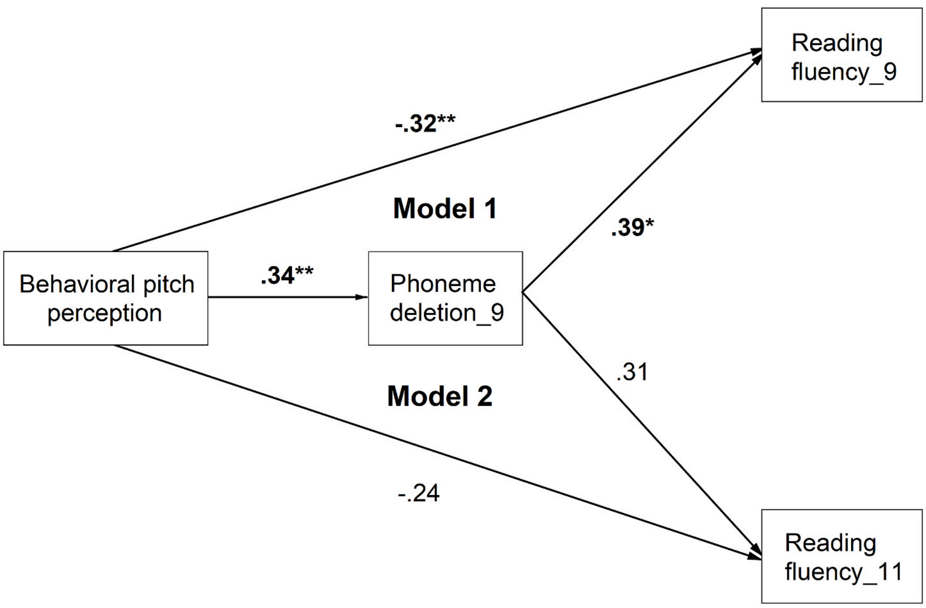

Fig. 3. The mediating effects of phonological awareness at age 9 on the relations between behavioral musical pitch perception and reading fluency at ages 9 (Model 1) and 11 (Model 2), controlling for age, music experience, SES, and IQ.
Note: SES = socioeconomic status; IQ = Intelligence Quotient. Suffix number indicates the data collection age. *$p < 0.05$; **$p < 0.01$.

4. Discussion

The current study aimed to examine the relations between musical pitch processing and reading skills and the possible mediating role of phonological awareness in a sample of typically-developing Chinese children followed from Grade 3 (age 9) to Grade 5 (age 11). First, we found that neural musical pitch sensitivity (indexed by P3a latency) significantly predicted reading accuracy at age 11 and its development from age 9 to age 11. Second, behavioral musical pitch sensitivity at age 9 predicted reading fluency at ages 9 and 11 through the effects of phonological awareness at age 9.

The present findings revealed that a relation between musical pitch processing and reading skills in Chinese does exist. To our knowledge, this is the first study to document the relation between musical pitch and reading in typically-developing Chinese children, extending the findings of previous studies with Chinese children with dyslexia (Wang et al., 2012, 2019) and preschoolers (Chung & Bidelman, 2021), as well as the findings of previous studies in alphabetic languages (Anvari et al., 2002; Couvignou & Kolinsky, 2021; Putkinen et al., 2019).

Neural musical pitch P3a latency at age 9 significantly predicted reading accuracy at age 11, after controlling for the effects of individual differences (age, music experience, and SES) and IQ. Moreover, musical P3a latency at age 9 uniquely predicted the two-year growth of reading accuracy (growth that is not explained by the same reading skill at an earlier point in time; see Parrila et al., 2004, for a discussion on autoregressors). However, behavioral pitch perception was related to reading through the effects of phonological awareness. These results add to those of previous studies (e.g., Nan et al., 2018) by suggesting that neural measures might be more sensitive to developmental differences than behavioral measures. Indeed, the behavioral performance in musical pitch identification was not at all related to neural responses to pitch changes (see, Gu et al., 2019; Nan et al., 2018; Shestopalova et al., 2018; Tang et al., 2016, for similar findings). This dissociation between behavioral pitch identification and neural MMN and P3a responses to pitch changes might indicate different pitch processes involved in behavioral and neural measures, possibly due to a neural mechanism of lateral inhibition (Gu et al., 2019). Moreover, the neural pitch measures were obtained through a passive task, which is less influenced by attention and motivational factors compared to the active task used in the behavioral session. This difference in task design might also explain why phonological awareness only mediated the relationship between the behavioral pitch measure and reading fluency.

Our results demonstrated that shortened P3a latencies predicted higher levels of reading development from age 9 to age 11. P3a is mainly generated in the anterior cingulate cortex and frontal lobe, reflecting heightened attentional sensitivities to deviant changes with decreased latencies (Polich, 2007). In adults, shorter P3a latencies were associated with successful L2 learners (Jakoby et al., 2011) and higher IQ scores among individuals with intellectual disabilities (Ikeda et al., 2009). A recent study has shown delayed P3a latency for rhythm changes in children aged 6–7 years at risk for developmental coordination disorder, together with delayed MMN latency for duration changes (Chang et al., 2021). P3a latency, together with its mean amplitude, decreased significantly across adolescence, whereas there were no such reliable changes in the MMN (Mahajan & McArthur, 2015). Taken together, our results suggest that more advanced attentional sensitivities to pitch deviants, as reflected by the decreased P3a latencies, confer benefits to reading development in typically-developing Chinese school-age children.

Furthermore, the current results showed that behavioral musical pitch sensitivity was related to reading in Chinese through the mediating effects of phonological awareness. The present study is the first to report the mediating effects of phonological awareness on the association between musical pitch and reading in Chinese. Note that earlier studies revealed only lexical tone awareness as a possible mediator underlying the musical pitch and reading association in Chinese (Wang et al., 2019), although phonological awareness has often been found to mediate the relation between musical pitch and reading in alphabetic languages (Anvari et al., 2002; Zhang et al., 2017). Specifically, a significant negative association emerged between behavioral musical pitch sensitivity and reading fluency at age 9 after introducing phonological awareness into the model (Fig. 3, model 1). This suppression effect might reflect an unbalanced development (e.g., Pillai & Yathiraj, 2015) or even a tradeoff (e.g., Zhang et al., 2021) between auditory and visual processing, as represented by behavioral musical pitch sensitivity and reading fluency, once their mediated relationship through phonological awareness has been taken into account. Future studies are needed to examine these possibilities.

Additionally, using a longitudinal design, we showed that phonological awareness mediated the association between behavioral musical pitch processing and reading development at age 9 rather than age 11. Specifically, its contribution to reading declined with age: at age 9 (Grade 3), it mediated the relation between behavioral musical pitch processing and reading fluency at ages 9 and 11 (Fig. 3), but at age 11 (Grade 5), it was not related to any reading skill (Table 3). These results are in line with earlier findings, suggesting that phonological awareness' role in reading development might be limited to the early school years (e.g., Badian, 1994; McBride-Chang et al., 2011; Parrila et al., 2004; Vaessen et al., 2010). As shown in previous studies (e.g., Wang et al., 2019), lexical tone awareness is likely another mediator. In comparison to phonological awareness, lexical tone awareness appears to have a unique relationship with reading. A study with Cantonese children aged 5–6 years revealed associations between lexical tone awareness and vocabulary and word recognition, even after controlling for the effects of phonological awareness (Tong et al., 2015). Indeed, lexical tone awareness and phonological awareness may be two independent processes that are both crucial to reading development in Chinese. Research conducted on Chinese students demonstrated that lexical tone awareness and phonological awareness independently explained variance in Chinese character recognition (Shu et al., 2008). Future research is needed to understand whether lexical tone awareness and phonological awareness both mediate the relation between musical pitch and reading in typically-developing Chinese children.

There are some limitations in the current study worth mentioning. First, this study was correlational and any significant associations between musical pitch processing and reading development do not imply causation. Second, our sample was relatively small and a future study should replicate our findings using a larger sample size. Furthermore, given that the P3a latency decreased significantly from late childhood to adolescence (Mahajan & McArthur, 2015), it would be interesting to further explore how musical pitch sensitivities progress from age 9 to age 11 and how the relationship between musical pitch and reading varies across ages. Finally, the complex nature of the relationship between music and literacy is still an area of ongoing investigation (for reviews, see Gordon et al., 2015; Witton et al., 2020). Given that rhythm has also been found to be a significant predictor of reading (e.g., Ahokas et al., 2023; Goswami et al., 2013; Sun et al., 2022), future studies involving both musical pitch and rhythm are needed to determine their common and unique contribution to reading development.

5. Conclusion

The present study examined the relations between musical pitch processing and reading skills in typically-developing Chinese school-age children. Neural musical pitch processing as reflected by P3a latency served as a unique predictor of reading accuracy and its development in school-age children. Behavioral musical pitch processing predicted reading through the effects of phonological awareness. Together, our current results shed light on the effects of musical pitch processing on reading development at both behavioral and neural levels.

CRediT authorship contribution statement

Shiting Yang: Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation. **Lirong Tang:** Methodology, Investigation. **Li Liu:** Resources, Methodology, Conceptualization. **Qi Dong:** Resources, Funding acquisition. **George K. Georgiou:** Writing – review & editing, Formal analysis. **Yun Nan:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jneuroling.2024.101199.

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