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Neural specialization to English words in Chinese children: Joint contribution of age and English reading abilities

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A R T I C L E I N F O

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A B S T R A C T

N1 tuning to words, a neural marker of visual word recognition, develops by an interaction between age and ability. The development of N1 tuning to a second learnt print is unclear. The present study examined the joint contribution of age and English reading abilities to N1 amplitude and tuning to English print in Chinese children in Hong Kong. EEG signals were recorded from 179 children (six to nine years old) while they were performing a repetition detection task comprised of different print stimuli measuring three types of tuning, i.e., coarse tuning (real word versus false font), fine tuning (real versus nonword), and lexicality effect (real versus pseudo word). Children were assessed in English word reading accuracy (EWR) and English sub-lexical orthographic knowledge (EOK). Results indicated that coarse tuning decreased with age but increased with EWR and EOK. Fine tuning uniquely increased with EOK, and the lexicality effect increased with EWR. At last, higher EWR was linked to less right-lateralized coarse tuning in younger children. Taken together, the findings support the visual perceptual expertise account in the L2 context, in that N1 coarse tuning, fine tuning, and lexicality effect are driven by skill improvement.

1. Introduction

A large number of non-native-English-speaking children learn English as mandatory subject at school. Many studies have investigated how children's brains adapt to print in parallel to the development of reading abilities in their first language. However, the development of neural specialization for a second learnt script is less investigated. Such research is important, because children experience different developmental processes, although with overlap, becoming literate in English across different contexts (e.g. Geva and Yaghoub-zadeh, 2006; Mirza and Gottardo, 2023). The differences call for an investigation into the development of neural specialization to English print as a second learned script.

Successful reading is contingent on the process of rapidly and effortlessly conjoining groups of letters into integrated visual percepts (McCandliss et al., 2003). The neural substrates underlying fast and automatic visual word recognition involve brain regions such as the left ventral occipito-temporal cortex (vOT), also termed the visual word form area (VWFA) (Dehaene and Cohen, 2011). Specifically, this brain region generates enhanced negative activity at the early time window (150–220 ms) (N1) after a print word is presented. This neural specialization for print is observed for the contrast between the N1 component elicited by a word and the one elicited by non-print visual control stimuli; the difference is referred to as coarse tuning, which is pronounced at the posterior electrodes over the left hemisphere of adult readers (Brem et al., 2006, Nobre et al., 1994). Adult readers also exhibit

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fine tuning referring to the response difference between words and non-legal letter strings (e.g. consonants, non-words) (Coch and Meade, 2016; Wang et al., 2022), and lexicality effect (real words versus pseudo words) (Coch and Meade, 2016; Mahé et al., 2012).

The visual expertise (McCandliss et al., 2003) account posits that the neural specialization for print progresses with reading skill. The phonological mapping hypothesis posits that phoneme-grapheme decoding skill drives N1 print specialization (Maurer and McCandliss, 2007) in alphabetic languages. Evidence from individual differences studies have shown that children with higher phonological awareness and phonological decoding skill (measured by pseudo word reading) showed stronger N1 activity to words (Coch and Meade, 2016; Khalifian et al., 2016), more left lateralized N1 (Sacchi and Laszlo, 2016), stronger coarse tuning (Maurer et al., 2006) and stronger fine tuning (Zhao et al., 2014).

Furthermore, N1 specialization for print develops through an interaction between age and ability. Maurer et al. (2011) compared the development of coarse tuning between German-speaking children with dyslexia, determined by a cutoff point on word reading fluency, and age-matched typical developing children. The findings showed that typical children had stronger word N1 than dyslexic children in Grade 2, but the two groups were similar regarding false font N1. Both groups showed a reduction in false font N1 measured at Grade 5 in comparison to Grade 2. In addition, typical readers exhibited greater reduction in word N1 from across time, rendering the two groups comparable in word N1 and coarse tuning in Grade 5. In terms of lateralization, Maurer et al. (2011) found that typical readers showed larger activation to words in the left hemisphere and larger activation to false fonts in the right hemisphere, whereas dyslexics showed no lateralization effect in neither condition. The difference between dyslexics and typical readers in lateralization was more pronounced in Grade 2 than Grade 5. On the whole, the findings suggest the association between word reading ability and coarse tuning strength pronounced in the beginning readers diminishes as they get older; this has been corroborated by the findings that, after age was considered, ability was not associated with N1 print tuning and amplitude in older children beyond the early elementary school levels (Brem et al., 2009; Coch and Meade, 2016).

It remains unclear, however, if the of N1 specialization for L2 print develops the same way in parallel to L2 reading abilities, especially in children whose L1 and L2 are in great linguistic contrast, i.e. Chinese and English. Behavioral studies have indicated the influence of language background on English word reading. Wang et al. (2003) demonstrated that Chinese English language learners made more errors in a semantic decision task when the foil and target had similar spellings than when they were different, which indicated orthographic processing, meanwhile their Korean counterparts made more errors when the pair were homophones, which indicated phonological processing. Developmental studies have shown Chinese and English orthographic awareness accounted for additional variance in English word reading above and beyond phonological skills (Tong and McBride-Chang, 2010). Chinese children who struggled with English word reading showed poorer performance in English sub-lexical orthographic knowledge even in adolescence (Tong and McBride, 2017). In sum, orthographic processing plays a prominent role in English word reading in Chinese learners, possibly reflecting the transfer of Chinese reading strategy.

Studies on the development of N1 print specialization in the L2 context are scarce. Only one study has been conducted with Chinese English biliterate children. Tong et al. (2016) found that young Chinese children after more than 2 years of classroom English instruction showed right-lateralized coarse tuning to English words, suggesting novelty processing of English print resulted from low visual expertise. Fine tuning and lexicality effect were not examined in that study.

The present study extends X. H. Tong et al. (2016) 's study and characterizes the development of N1 specialization to English print with a cross-sectional study of a larger sample of a broad age and ability range. Specifically, we examined the joint contribution of age and English reading abilities to N1 amplitude elicited by four types of stimuli. LMER (linear mixed effect regression) was adopted in previous studies predicting ERP amplitude at trial level with demographic variables and reading skills (Khalifian et al., 2016). Moreover, the stimulus condition was included in the LMER model to interact with between-subject variables (age and ability). This mixed-design affords analyzing the influence of subject factors on N1 and N1 tuning effects indexed by the modulation of condition contrasts (Yum et al., 2018). We were particularly interested in the condition contrast between real words and false fonts (coarse tuning), real words and nonwords (fine tuning), and real words and pseudo words (lexicality effect). Tuning effects reflect neural specialization for print, which is subject to influence of both age and ability (Eberhard-Moscicka et al., 2015; Maurer et al., 2011; Tong et al., 2016b). As shown in previous studies, the individual differences in neural print specialization mostly come from variance in the word N1 (Maurer et al., 2011). However, some studies also indicated that reading-related abilities also impact the N1 to false fonts, letter strings, and misspelled characters (Coch and Meade, 2016; Khalifian et al., 2016; Zhao et al., 2019). The embedded condition-level analysis on N1 amplitude allows us to address this inconsistency in the literature.

Regarding the context of Chinese-English bilingual children in Hong Kong, we focused on the role of orthographic processing as suggested in behavioral studies. The orthographic choice task was adopted to measure sub-lexical orthographic knowledge, i.e. the efficiency of reflecting on and retrieving sub-lexical orthographic patterns in the English writing system, such as allowable doublets, consonant clusters, bigrams etc. (Apel et al., 2018). Moreover, we included English word reading as a predictor to control for the influence of other reading-related processes.

We addressed three issues regarding the development of N1 specialization to a second learned script:

1) The unique effect of age on print tuning independent of ability. Age encompasses multiple factors other than English reading ability that could affect N1 print specialization for English print. For one, neurobiological changes occur in VWFA both in terms of structure and function across the early elementary school years (e.g. Turkeltaub et al., 2003; Olulade et al., 2013). The age-related change in VWFA may lead to differences in L2 N1 print specialization. Other than neuro-biological changes, age may be a proxy for English exposure. English is one of the official scripts in Hong Kong, and therefore English print and the other use of roman alphabet is ubiquitous. Older individuals are assumed to have had greater exposure to English print than younger individuals. Studies have found an age effect on N1 responses (Coch and Meade, 2016) and coarse tuning (Brem et al., 2009) controlling for reading ability. We hypothesized that N1 coarse tuning would decrease with age, driven by the age-related decrease in word N1.
2) The effect of ability on print tuning independent of age. Guided by the visual perceptual expertise hypothesis, EWR, as a reading skill, would be linked to stronger N1 to real words more than false fonts and non-words, leading to EWR enhanced coarse and fine tuning. The lexicality effect could also be present in more skilled readers (Coch and Meade, 2016; Mahé et al., 2012; Wang et al., 2022). To further examine the role of sub-lexical orthographic knowledge in driving visual word expertise differently from word decoding, we hypothesized that EOK would contribute to English word N1 and tuning effects above and beyond EWR. In terms of lateralization, we hypothesized that more skilled readers would show more left lateralization of the real word N1 (Araújo et al., 2012; Maurer et al., 2011).
3) The interaction between ability and age. We hypothesized that the modulating effect of reading skills on coarse tuning strength and lateralization would be larger in younger than older children, as suggested in studies with L1 alphabetic readers (Maurer et al., 2006, 2011).

2. Methods

2.1. Participants

One hundred pairs of native Cantonese speaking twins (92 boys) in Hong Kong were invited to participate in the study (Wong et al., 2017). They were from 59 schools in Hong Kong and were in Grades 1–4 at the date of assessment. Their parents were asked for information including language background and the use of English at home and school. The children had never been diagnosed with developmental dyslexia according to parents' report. Families of the children were mixed in terms of social economic status. Out of the 179 children (87 boys) whose EEG data met our quality criteria were included in the analysis, there were 83 twin pairs (44 monozygotic pairs) and 13 children whose co-twins were not included in the study. In terms of the English learning background, 133 were from Chinese-mediated schools, where English was taught as a school subject that accounted for around 20% of the total lesson time (Hong Kong Education Bureau, 2002). In addition, 38 were from Chinese-English bilingual schools where at least 1 non-English subjects were taught in English. There were eight children from international schools, where most subjects were taught in English. The background information (collected from 90% of the participants) and assessment results for English reading and language performance is shown in Table 1. Written consent and assent were obtained from the child participants and their guardians.

2.2. English word reading abilities

2.2.1. English word accuracy (EWR)

The English word-reading task was adopted from previous studies (X. L. Tong and McBride-Chang, 2010; Zhou and McBride, 2018) that tapped into English word-reading skills for Chinese-speaking children learning English as a second language. Fifty items selected from the Chinese children's English textbooks were presented on a piece of paper. Among the 50 items, 41 were regular words, meaning that the decoding could be achieved solely relying on grapheme-phoneme-corresponding rules as specified in Earle and Sayeski (2017). The items (supplementary material 1a) were arranged in the ascending order of difficulty determined in pilot tests previously conducted. The more difficult words were ones with multiple syllables and less frequent usage. Children were asked to read aloud the words one by one. The test stopped if a child made 5 consecutive errors. Each correctly pronounced word was scored as 1 point. The reliability of this test in the study, as indicated by Cronbach's alpha, was 0.91.

Table 1
Demographic and English reading assessment information of the sample.

Variable	*n*		%	
Mother's education				
Elementary school	84		47.5%	
Secondary degree or higher diploma	26		14.7%	
Bachelor's Degree	39		22.0%	
Graduate Degree	28		15.8%	
English use at home				
Never	23		13.3%	
1–3 times per week	77		44.5%	
4–5 times per week	26		15.0%	
Almost everyday	47		27.2%	
Number of non-English subjects taught in English at school				
0	137		80.1%	
1	12		7.0%	
> 1	22		12.8%	
	M	***SD***	r_{Age}	r_{EWR}
Age (mths)	95.87	9.55		
English word reading (max = 50)	21.49	15.63	.38 * *	
English orthographic knowledge (max =30)	9.14	4.49	.30 * *	.55 * *
English rapid digit naming (secs)	30.62	11.63	-.30 * *	-.57 * *
English vocabulary knowledge (max=48)	25.76	11.24	.24	.84 * *
English dictation (max =36)	8.72	7.19	.37 * *	.90 * **

2.2.2. English sub-lexical orthographic knowledge (EOK)

This was measured by the English orthographic choice task (Lo et al., 2018). Participants were required to identify the nonword from three similar stimuli, i.e. "I want you to cross out the word that looks the least like an English word". There are 30 items (supplementary material 1b). Each item comprised three stimuli matched on onset and the number of letters, including a real word (e.g., <folk>), a pseudoword (e.g., <falk>) and a nonword (e.g., <foek>). The nonwords violated English orthographic rules in one of the three ways including vowel omission, incorrect vowel combination, and incorrect consonant combination. Children were given one minute to complete the task. One point was awarded for each correctly judged item. The Cronbach's alpha of this test was 0.89.

2.3. Experimental procedure

We used a one-back repetition detection task (e.g., Maurer et al., 2005, 2006; Tong et al., 2016) (refer to Fig. 1A). There were four conditions, i.e., real words, pseudowords, nonwords and false font symbols. Real words were all English words of high frequency. Pseudowords are letter combinations that conform to phonetic and orthographic rules but have no meaning in English language. Nonwords are orthographically illegal, created by rearranging letters in the real word condition. The stimuli described above across the three conditions were all based on four letters. The false font symbols (Eberhard-Moscicka et al., 2015) were created by converting the stimuli in the real word condition into unrecognizable drawings using a special font (refer to Fig. 1A). Each condition comprises 58 unique words and eight repetitions, amounting to 66 trials overall. All stimuli were presented in black on a silver background at the center of computer screen. First, the fixation "+ " was presented for a random length (range of 600–800 ms) in the center of the computer screen. Then it was replaced by a stimulus which was presented for 500 ms. Participants were asked to immediately press the button of the serial response (SR) Box when they saw the stimulus repeated. All stimuli were presented in a font size of 56. The stimuli covered vertical visual angle varying from 1.32 ° to 2.28 °, and horizontal visual angle from 2.08 ° to 4.29 °. The 264 (66 trials*4 conditions) stimuli were presented in eight blocks in pseudo-random order. Each block contained 33 trials of two conditions (sub-block). Each sub-block had either 16 or 17 trials including two repetitions. There was a 30-second break between blocks. The order of the two sub-blocks in each block was counterbalanced within participants. We used E-Prime software to present the stimuli and record children's accuracy and reaction times.

We conducted individual tests on children in a sound-attenuated EEG lab. At the beginning of each session, a Cantonese-speaking assistant trained in EEG procedures introduced the experimental procedures in detail to each participant. Before the formal recording of the EEG, the participants were asked to observe the changes in the waveform caused by their movement or blinking. These demonstrations were used to help participants to understand and comply with our requirements that participants keep quiet and sit as still as possible; they were also asked to avoid making eye movements or blinking during the test. There was a practice session to help children become familiar with this experiment.

2.4. EEG Recordings and Preprocessing

The EEG was recorded using the HydroCel GSN EGI 128-channel system (EGI net station v5.3, Electrical Geodesics Inc., Eugene, Oregon). The sampling rate was 500 Hz, and the Cz electrode was used as an online reference. The electrode impedance was to be kept below 50 kΩ. The time delay (12 ms) between the start of the actual stimulus and the event trigger was corrected basing on a separate timing test.

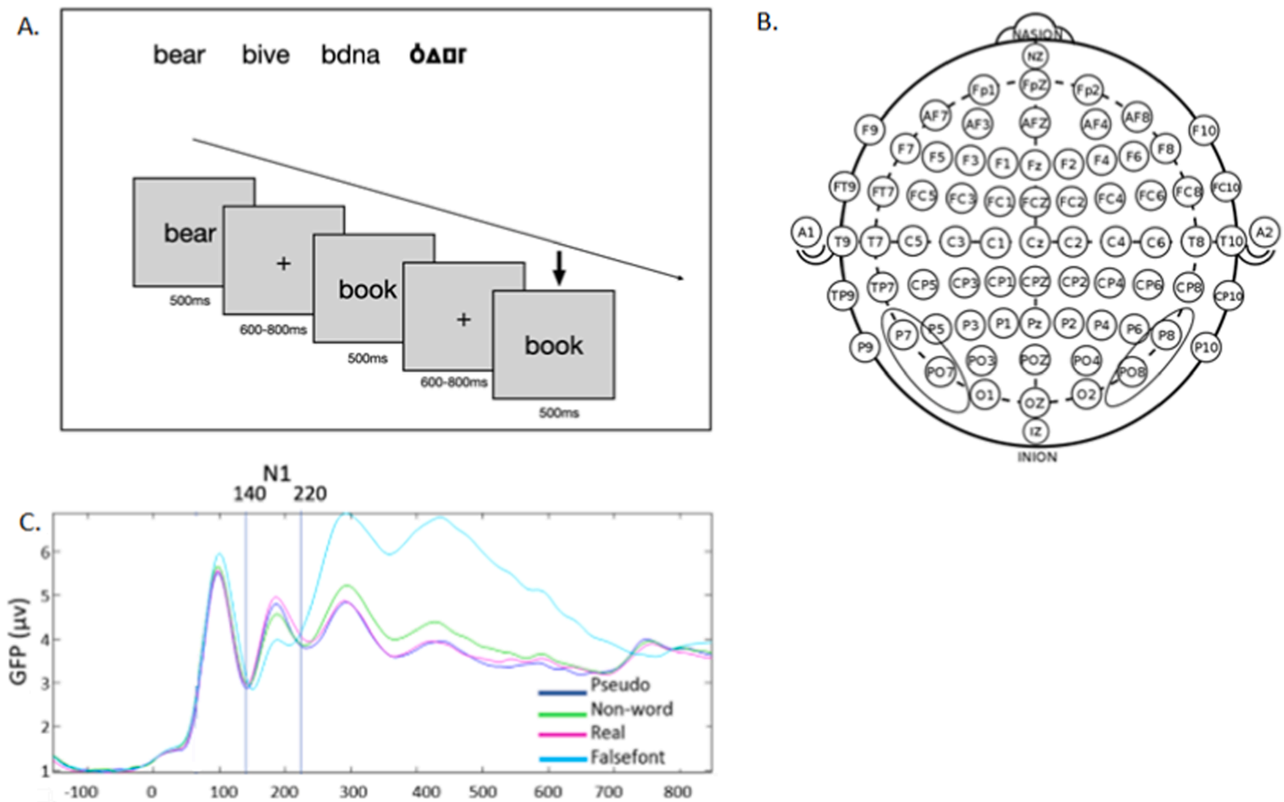

Fig. 1. A) Examples of stimuli from left to right: real words, pseudowords, nonwords, and false fonts and illustration of the repetition detection task, B) 10–10 system electrode positioning and sites of interest (oval shapes), C) global field power in four conditions.

The EEGLAB version 2021.0 was used to preprocess EEG data. The processing pipeline was adapted from Lo et al. (2019), who had examined ERPs of children performing similar tasks in Chinese. The preprocessing steps included (1) down-sampling to 250hz; (2) subdividing channels into 10–10 system montage (Fig. 1 B); (3) bandpass filtering at 0.3–30 Hz; (4) removing bad channels that have too much variance with PREPpipeline (for details please refer to Bigdely-Shamlo et al., 2015); (4) running independent component analysis using the infomax ICA algorithm of Bell and Sejnowski (1995), (5) automatically removing components of eye-movement-related artifacts using ADJUST (Mognon et al., 2011); (6) using the spherical spline method to interpolate removed channels in the 10–10 system montage; (7) referencing to average reference; (8) segmenting epoch at − 150–850 ms; (9) baseline correction; (10) removing trials that exceeded the − 80–80 μV thresholds. This pipeline was selected because it yielded the best signal-to-noise ratio (SNR) for the expected P1 and N1 ERP components. The mean (SD) SNR was 12.9 (5.11) for P1 and 9.5 (4.49) for N1. Among the 69 electrodes in the 10–10 system, on average 2.2 (SD = 2.23) electrodes were bad and later interpolated. The mean (SD) number of trials for the four conditions were Real: 40.1 (11.4), Pseudo: 39.8 (11.2), Non-words: 39.4 (11.8), False font symbols: 39.9 (11.4).

We selected participants for data analysis based on the following criteria: 1) had a SNR above 3 on the expected P1 or N1 ERP components; 2) scored above 70% on the repetition detection task; 3) had at least 10 trials for each of all four conditions. As a result, 10 participants were excluded because of due to SNR, two participants due to poor performance on the behavioral task, and nine due to a small number of trials.

Based on previous findings that N1 is predominantly detected in occipitotemporal sites (e.g., Maurer et al., 2008; Tong et al., 2016), the electrodes of P7, PO7, P8 and PO8 (see Fig. 1B), the representative electrodes of the occipitotemporal sites, were selected for statistical analyses. Among the four key sites, PO7 was rejected in 3 participants; PO8 was rejected in 1 participant; P7 was rejected in 1 participant; P8 was rejected in 1 participant, altogether yielding 1.6% of the data interpolated at the key sites. The mean amplitudes of P7 and PO7 were used to indicate N1 in the left hemisphere, and the mean amplitude of P8 and PO8 for the right hemisphere. The time windows were determined based on the global field power (see Fig. 1C), which was from 140 to 220 ms for N1.

2.5. Data Analysis

N1 amplitude and lateralization (amplitude difference between left and right sites) were analyzed separately. For each dependent variable, two models were compared to address whether orthographic knowledge played a unique role in N1 and tuning effects beyond word reading accuracy. The first one included EWR as the sole index of reading ability. The second one included both EWR and EOK. EOK would be considered to play an independent role from EWR if the second model fit the data significantly better than the first one. The first model included the following fixed effects: the three-way interaction between age, EWR, and condition together with embedded two-way and one-way contrasts. The second model was created by adding the three-way interaction between age, EOK, and condition and the embedded contrasts. Age (in months) and the raw EWR and EOK scores were transformed into z scores. Regarding the condition effect, real word was set as reference prespecifying three tuning effects. The interaction between age and contrasts of condition, and the interaction between ability (EWR/EOK) and condition contrast indicated the independent contribution of age and ability to the strength of tuning effects. The interaction between age and ability was also considered, indicating how one variable modulated the effects of the other. The three-way interaction between age, ability, and condition contrasts indicated a modulation of age on the influence of ability on tuning effects. The two-way interaction between age and ability indicated how age modulates the influence of ability on N1 strength. Trial order (centered) was entered as a fixed effect because previous findings showed a repetition effect with later trials eliciting stronger negativity (Yum et al., 2018).

The random effects were determined by the complex model with both EWR and EOK using an iterative approach, following the practice recommended by (Baayen, 2008). Random slope was only added if the model's goodness of fit significantly improved. Family ID was entered as a random intercept to account for the issue of data dependence within twin pairs. Participant ID and item were entered as random intercepts to account for the crossed design. The slope of hemisphere on participant was added as it significantly improved the model's goodness of fit ($\Delta\chi^2 = 1332.1$, $\Delta df = 2$, $p < .001$). For N1 strength, the complex LMER model was fully represented in the R code below.

Amplitude~ intercept+Order + Condition*Age*EOK +Condition*Age*EWR+(1|Item) +(1+Hemisphere| Participant ID)+(1| FamilyId)

For N1 lateralization, the fixed effects were identical to the model of strength. The random effects selected for both models included random intercepts of item, participant, and family. More complex random structure yielded nonconvergence when fitting the data. The complex LMER model was fully represented in R code as below. An additional LMER analysis including the twin structure was conducted on strength and lateralization to ensure the twin structure did not bias the results (See supplementary material 2).

Lateralization~ intercept+Order+ Condition*Age*EOK+Condition*Age*EWR+(1|Item) +(1 | Participant ID)+(1| FamilyId)

For behavioral data, LMER was employed to analyze fixed and random effects on response time in the repetition detection task at trial level. For accuracy, general linear mixed effect regression (GLMER) with Bernoulli distribution for residuals was adopted to predict the probability of giving a correct response to each trial. Like ERP data, a model comparison investigating the independent role of orthographic knowledge was also performed. The random effects for the LMER model for accuracy and response time included item, participant ID, and family ID as random intercepts.

The analysis was conducted with the lmertest package (Kuznetsova et al., 2017) in the R computing environment (R Development Core Team, 2013). The LMER model was estimated using the restricted maximum likelihood (REML) method. For a priori contrasts (three types of print tuning), the multivariate t (MVT) method (Genz and Bretz, 1999) computed the adjusted p value for each contrast while keeping the overall alpha level at 0.05. Subsequently, the post hoc analyses were motivated by the significant contrasts. The LMER model using age, ability, and the interaction term as predictors for each condition was reported in the supplementary material (Table S2-S4). The p values were adjusted using the Bonferroni approach to 0.025 (0.05/2). Variable Inflation Factors (VIF) for the subject-level variables were 1.10 (age), 1.20 (EWR), 1.19 (EOK), 1.23 (interaction between age and EWR) and 1.25 (interaction between age and EOK). The values were all smaller than the conservative threshold of 2.5 (Johnston et al., 2018), suggesting there was no issue of multicollinearity.

To further corroborate the effect of ability and age on tuning effects revealed in the LMER analysis, we calculated the t values for the three tuning effects for each participant, consistent with the previous practice (Eberhard-Moscicka et al., 2015). The regression of t values on age and ability was conducted to supplement the significant tuning contrasts revealed in LMER model.

3. Results

3.1. Behavioral data

Table 2 shows the means and standard deviations of accuracy rate and reaction time for all conditions, together with their correlations with age and word reading abilities. The results of the model comparison indicated that EOK did not play a role in accuracy rate independently of EWR ($\Delta\chi^2$ =3.64, Δdf= 8, $p > .05$). For this reason, the simple model with only EWR was selected. The model with EWR showed that, on average, the probability of responding correctly in the real word condition was significantly higher than in the pseudo word condition (*B = 0.68,* 95% *CI, 0.53 – 0.88, p < .01*), non-word condition (*B = 0.70*, 95% *CI, 0.55 – 0.89, p < .003*) and false font condition (*B = 0.36*, 95% *CI, 0.28 – 0.46, p < .001*). Results revealed a significant interaction between the contrast of coarse tuning (false font$_{\text{odds ratio}}$-real word $_{\text{odds ratio}}$) and EWR (*B = 0.67,* 95% *CI, 0.58 – 0.78*, $p < .001$), and also between the contrast of fine tuning (non-word $_{\text{odds ratio}}$-real word $_{\text{odds ratio}}$) and EWR (*B = 0.71,* 95% *CI, 0.60 – 0.83, p < .001*), indicating the word effect relative to non-words and false fonts was more pronounced in children with higher word reading ability. Post hoc analysis revealed that children with higher EWR a showed higher probability answering correctly in real word (*B = 2.05,* 95% *CI, 1.71 – 2.46*, $p < .025$), non-word condition (*B = 1.45,* 95% *CI, 1.22 – 1.73*, $p < .025$), and false font condition (*B = 1.39,* 95% *CI, 1.20 – 1.61*, $p < .025$), with the association between EWR and response accuracy being stronger in the real word condition than the non-word and false font conditions. In addition, the interaction between the contrast of lexicality effect and EWR was not significant (*B = 0.29,* 95% *CI*, 0.01 – 0.56, $p > .05$), indicating the facilitation of higher EWR was comparable between real and pseudo word conditions. Our results showed that there was no significant effect of age ($B = 1.12$, 95% *CI*, 0.95 – 1.34, $p > .05$) or significant interaction between age and contrast (all $p > .05$). Furthermore, no significant three-way interaction between age, condition and English word reading was found (all $p > .05$).

For reaction time, model comparison also also indicated that EOK did not play a role independently of EWR ($\Delta\chi^2$=2.92, Δdf= 8, $p > .05$). Therefore, the simple model with only EWR was selected. Reaction time for the real word condition was significantly shorter than for the pseudo word condition ($B = 31.34$, 95% *CI*, 10.41 – 52.27, $p < .01$), non-word condition ($B = 36.65$, 95% *CI*, 15.71 – 57.59, $p < .001$) and false font condition ($B = 70.16$, 95% *CI*, 49.24 – 91.09, $p < .001$). Results revealed that age had a significant effect. Older children showed significantly shorter reaction time across conditions ($B = -51.65$, 95% *CI*, 25.54 – 77.58, $p < .001$). There was no significant interaction between age and condition (all $p > .05$). The effect of EWR, the interaction between EWR and three tuning effects, and the three-way interaction between age, ability, and three tuning effects were all non-significant (all $p > .05$).

3.2. N1 strength

The model comparison results showed that the complex model fitted the data significantly better than the simple model ($\Delta\chi^2$ =27.60, Δdf= 8, $p < .001$), indicating that EOK played an independent role in N1 strength beyond EWR. The full parameters for the estimated LMER model with EWR and EOK on N1 strength are included in the supplementary material (Table S1). None of the three-way contrasts was significant (all $p > .05$), indicating age did not modulate the influence of either EWR or EOK on any type of tuning.

In the analysis of overall three tuning effects, the contrast for coarse tuning was significant, $B = 3.97$, 95% *CI*, 3.47 – 4.46, $p < .001$, and so was the contrast for fine tuning, $B = 0.88$, 95% *CI*, 0.38 – 1.27, $p < .001$, but the contrast for lexicality effect was non-significant, $p > .05$. The topographic maps for print tuning and N1 in four conditions, together with the ERP waves at the left and right sites are shown in Fig. 2. In addition, the main effect of order was significant, $B = -0.04$, 95% *CI*,

Table 2
Descriptive statistics of the behavioral performance in the repetition detection task and correlations with age and English word reading.

Condition	Accuracy				Response time			
	M	*SD*	r_{Age}	r_{EWR}	*M*	*SD*	r_{Age}	r_{EWR}
Pseudo words	0.95	0.05	.29 * *	.52 * *	797.35	138.60	-.45 * *	-.18
Nonwords	0.96	0.04	.18	.30 * *	798.21	134.04	-.39 * *	-.17
Real words	0.96	0.04	.25 * *	.54 * *	766.72	143.87	-.39 * *	-.22 * *
False fonts	0.93	0.05	.21 * *	.35 * *	834.36	150.64	-.39 * *	-.20 * *

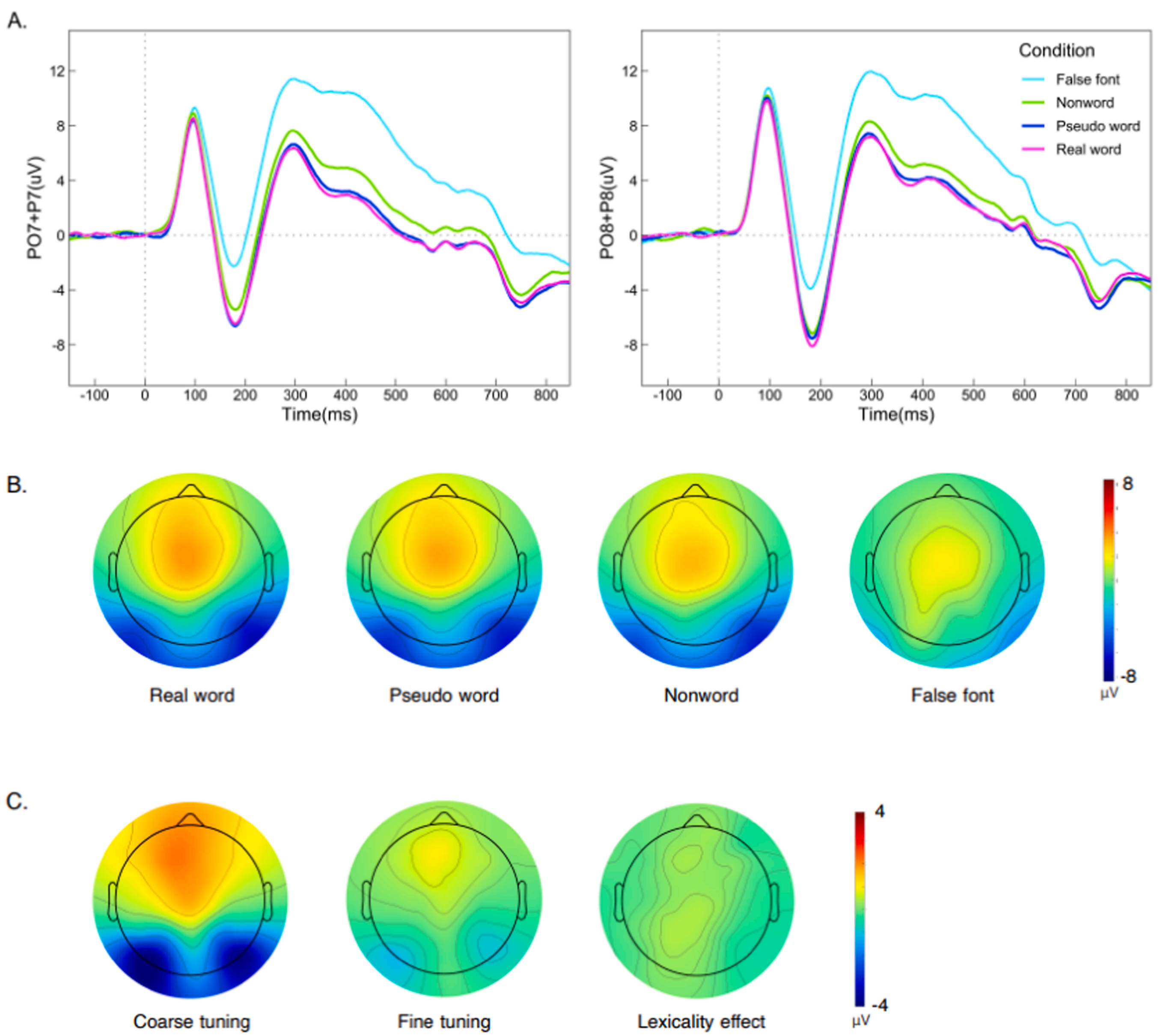

Fig. 2. A) ERP waves at four conditions at left and right sites, Topographic maps for B) N1 at four conditions and c) three tuning effects.

− 0.05 – − 0.03, $p < .001$. The negative effect indicated latter trials showing stronger negativity.

In the analysis focused on how age modulated three tuning effects, the interaction between age and condition was significant for coarse tuning, $B = -0.76$, 95% *CI*, − 1.03 – − 0.48, $p < .001$ (Refer to Fig. 3E right), and lexicality effect, $B = -0.32$, 95% *CI*, − 0.57 – − 0.03, $p < .05$ (Refer to Fig. 3F right), but nonsignificant for fine tuning, $p > .05$. The results of the post hoc analysis indicated that the N1 significantly decreased with age in real words ($B = 1.47$, 95% *CI*, 0.67 – 2.26, $p < .001$), whereas the decreasing trend of N1 to false fonts with age was not significant ($p > .025$) (Refer to Fig. 3E left). Furthermore, N1 to pseudo word also significantly decreased with age ($p < .025$), and the coefficient of age effect in the real word condition was larger than the pseudo word condition, yielding the significant interaction (Refer to Fig. 3F left).

Regarding the modulation of EWR on the three types of tuning, the interaction between EWR and condition was significant on the contrast of coarse tuning, $B = 0.46$, 95% *CI*, 0.15 – 0.77, $p < .001$ (Refer to

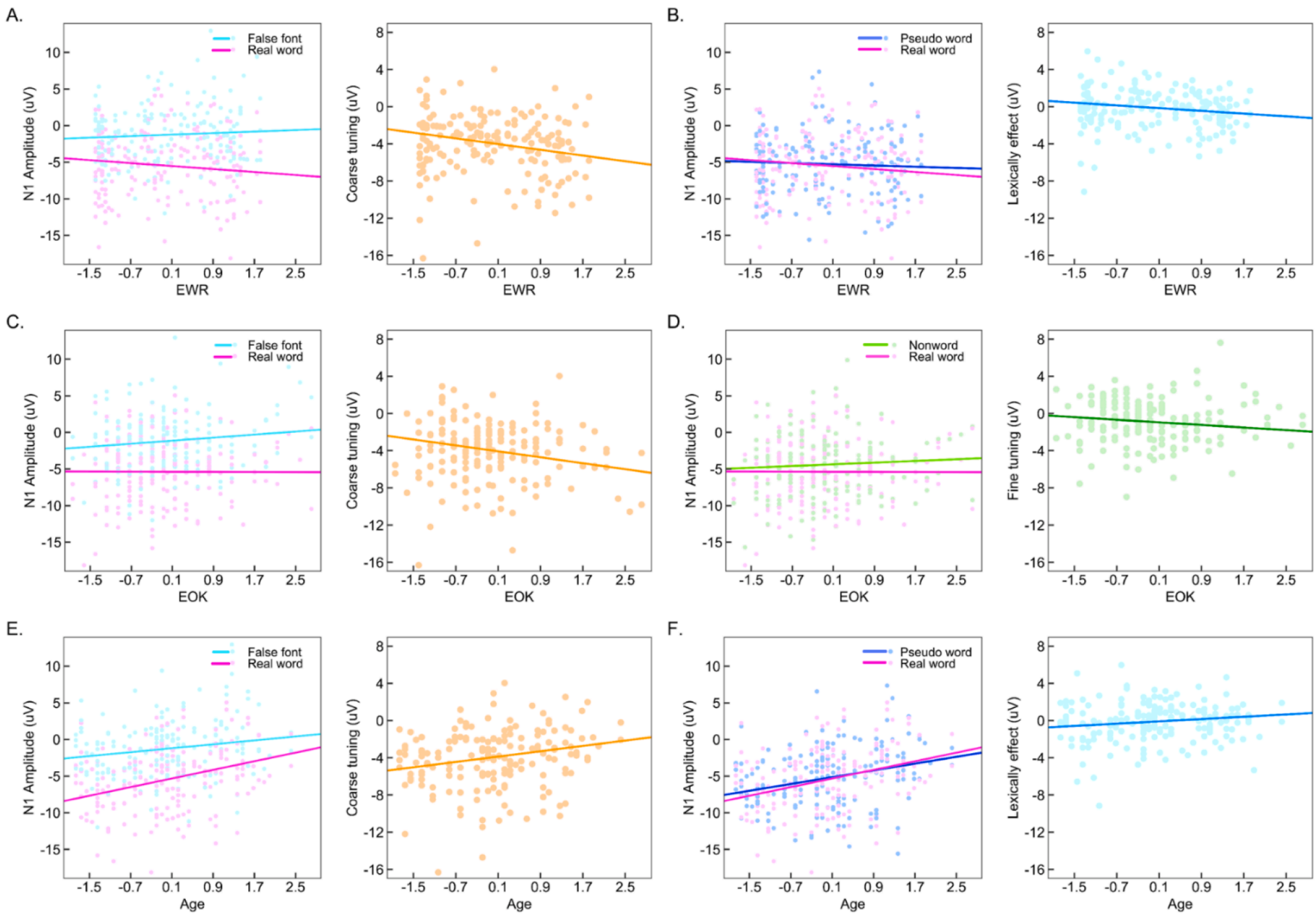

Fig. 3. Scatter plots and estimated effects of age/ability on tuning effects (right) and N1 amplitude in relevant conditions, i.e., simple effects (left). A) English word reading ability and coarse tuning, B) English word reading ability and lexicality effects, C) English orthographic knowledge and coarse tuning, D) English orthographic knowledge and fine tuning, E), age and coarse tuning, F) age and lexicality effects.

Fig. 3A right). However, the post hoc analysis indicated that the EWR-related change in N1 was not significant in any condition. The estimated model parameters showed that the N1 increased with EWR in the real word condition ($p > .025$) but decreased with EWR in the false font condition ($p > .025$), resulting in the EWR-related increase in N1 coarse tuning. The results of the regression of coarse tuning (individual t values) showed that higher EWR was significantly linked to larger coarse tuning, $B = -0.47$, 95% *CI*, $-0.72 - -0.11$, $p < .001$, while age showed a significant prediction of the reversed direction, $B = 0.37$, 95% *CI*, 0.10 – 0.62, $p < .01$. The results are consistent with that in the LMER model. Inspection of individual t values revealed that of 96% the children showed coarse tuning (with words more negative than false font strings). The interaction between fine tuning and EWR was not significant, $p > .05$.

For lexicality effect, the modulation of EWR was significant, $B = 0.34$, 95% *CI*, 0.03 – 0.65, $p < .05$ (Refer to Fig. 3B right). However, the post hoc analysis of the EWR effect on the N1 to pseudo words was not significant ($p > .025$). As shown in Fig. 3B left, children with lower EWR showed slightly stronger negativity in the pseudo than real word, while children with higher EWR showed slightly stronger negativity in the real than pseudo word. The result of the regression of lexicality effect showed that EWR significantly positively predicted the size of lexicality effect, $B = -0.24$, 95% *CI*, $-0.43 - -0.04$, $p < .05$, while age showed a negative prediction, although at the level of marginal significance, $B = 0.17$, 95% *CI*, $-0.01 - 0.37$, $p = .07$. Inspection of individual t values revealed that of 34% the children yielded lexicality effect (with words more negative than pseudo words). Children who displayed lexicality effect showed higher EWR as a trend, $F(1,177) = 2.70$, $p = .10$.

Regarding the modulation of EOK on the tuning effects, the interaction between EOK and condition was significant for the contrast of coarse tuning (refer to Fig. 3C right), $B = 0.58$, 95% *CI*, 0.27 – 0.89, $p < .001$, and fine tuning (refer to Fig. 3D right), $B = 0.32$, 95% *CI*, 0.00 – 0.63, $p < .05$. However, the post hoc analysis indicated the effect of EOK was not significant on any condition. The significant interaction effects were driven by the different directions of the EOK effects across conditions (Refer to Fig. 3C left and 3D left). The regression of coarse tuning t values on EOK showed a significant effect, $B = -0.46$, 95% *CI*, $-0.20 - -0.72$, $p < .05$. The regression of fine-tuning t-values indicated that the prediction from EOK showed a trend, $B = -0.17$, 95% *CI*, $-0.38 - 0.03$, $p = .09$. Inspection of individual t values revealed that of 39% the children had fine tuning (with words more negative than nonwords). Children who displayed fine tuning showed higher EOK, $F(1,177) = 4.40$, $p < .05$. At last, the interaction between lexicality effect and EOK was not significant, $p > .05$. To illustrate the effects of age and ability independent from each other in topographic maps and ERP waves, figures with groups differing on one while matched on the other were created (Fig. S1).

3.3. N1 Lateralization

The model comparison results showed that the complex model did not fit the data better than the simple model ($\Delta\chi^2 = 3.78$, $\Delta df = 8$, $p > .05$), indicating that EOK did not make a significant contribution to lateralization independently of EWR. The intercept was significantly larger than 0 ($B = 1.40$, 95% *CI*, 0.67 – 2.13, $p < .001$), indicating stronger activity in the right hemisphere. None of the condition contrasts were significant, indicating, on average, the bilateral distribution of coarse tuning ($p > .05$), fine tuning ($p > .05$), and lexicality effect ($p > .05$).

In the analysis of how age modulated the influence of EWR on tuning effects, a significant three-way interaction was found between the age, EWR, and the contrast of coarse tuning ($B = -0.62$, 95% *CI*, −1.05 to −0.20, $p < .01$). The other two three-way contrasts on fine tuning and lexicality effect were not significant (both $p > .05$). The post hoc analysis showed that there was significant interaction between age and EWR in the false font condition ($B = -1.30$, 95% *CI*, −1.95 to −0.66, $p < .001$), whereas the interaction between age and ability was not significant in the real word condition ($p > .025$). The simple effects are shown in Fig. 4. Younger children (age z score = −0.5) were estimated to show increase in right-lateralization with EWR in false font condition, resulting in an enhancement of left-lateralization of coarse tuning with the increase of reading ability. In contrast, older children (age z score = 0.5) showed slightly less right-lateralized N1 in real word than false font and did not show much change with EWR. The ERP waves and topographic maps of four groups are created to illustrate the interaction effect (Fig. S2).

4. Discussion

Our study investigated the development of N1 print specialization to English script in Chinese-speaking children in Hong Kong across the early elementary school years. On the group level, we found a bilaterally distributed coarse tuning and fine tuning. The presence of fine tuning indicates the processing of orthographic patterns, which resembles the N1 effect in skilled readers (e.g. Coch and Meade, 2016). The reading expertise account is supported by the subject-level findings, in that children with higher reading-related abilities showed stronger coarse and fine tuning, as well as lexicality effect. Furthermore, the unique role of sub-lexical orthographic knowledge in N1 coarse and fine tuning for English script in Chinese children was confirmed, suggesting than skills other than decoding are involved in driving visual expertise of English words in learners whose L1 is non-alphabetic. Finally, despite the ability-related enhancement, coarse tuning decreased with age. Taken together, the findings suggest that age, word decoding, and sub-lexical orthographic knowledge work differently in terms of driving the N1 print specialization for a second learned script, which are further discussed in detail.

4.1. *The Unique Effect of Age on Print Tuning Independent of Ability*

Regarding the independent effect of age, a descending trajectory of N1 coarse tuning confirmed the hypothesis and was consistent with a previous study with elementary school children in the alphabetic context (Maurer et al., 2011). The developmental decrease in coarse tuning cannot be attributed to the biological change with age such as skull thickness or widespread pruning because the overall age effect was not found on N1 amplitude to false fonts. In contrast, the age effect was more general on behavioral data. The age effect on response time was comparable across conditions, suggesting EEG was more sensitive than response time measuring the development of visual word processing.

The considerable reduction found in real word N1 may reflect functional efficiency in the occipital-temporal area (Brem et al., 2009; Price, 2010). In the L1 context, the functional efficiency of this reading-related network may be largely due to reading experience, i.e., the automated reading process as a result of repeated practice (Brem et al., 2009). The developmental decrease was more pronounced in real than pseudo words. It is possible that children practice reading real words more than pseudo words, leading to a more attenuated N1 response to real words. The age effects remained after English reading abilities were statistically controlled. Reading abilities are related to and might serve as a proxy for repeated practice. Therefore, the enhanced functional efficiency of reading related brain regions that comes with age could not be entirely attributed to the repeated practice of English reading. Other maturation mechanisms might be at work.

The decreasing trend of the N1 to English words was found in Chinese children aged from 6 to 9 years old, which is younger than ever reported in alphabetic-L1 studies (8.5–11.5 years old in Maurer et al., 2011). Yet, the early onset of diminution in coarse tuning echoes findings on N1 tuning to Chinese print in Chinese children (Cao et al., 2011; Tong et al., 2016b). Both studies showed that N1 amplitudes to Chinese characters has declined at the age nine in comparison to age seven. In addition, the age effect was marginally significant on fine tuning ($p = 0.077$), consistent with the previous finding on Chinese fine tuning (X. H. Tong et al., 2016b). Therefore, we speculate that age effects partly represent the maturation of reading network, which could be tuned by children's Chinese learning experience. However, there are many factors

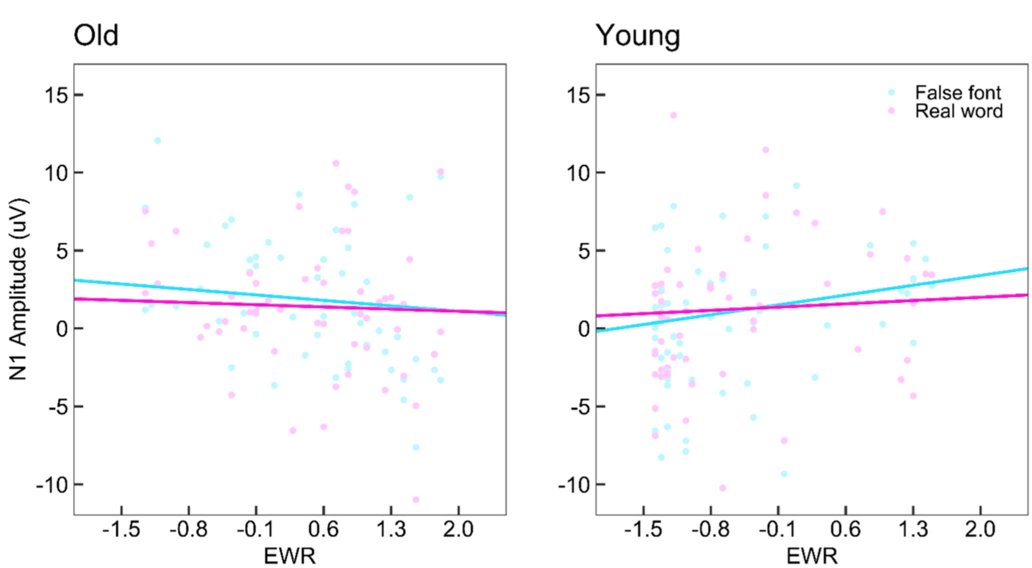

Fig. 4. Simple effects of English word reading ability on lateralization in real and false font conditions in older and younger children. The post hoc analysis showed that three-way interaction was driven by the significant two-way interaction between age and EWR in the false font condition ($p < .001$). Specifically, in younger group, the better word readers showed stronger right-lateralized N1 to false fonts, and better word readers showed bilateralized N1 to false fonts in the older group.

confounded with age that we did not tease apart in this study, such as biological change in the reading network, English exposure, and Chinese literacy experience. We cannot verify or reject this speculation.

4.2. The unique effect of ability on print tuning independent of age

We found the significant effects of EWR and EOK modulating the coarse tuning contrast independently of each other, which was consistent with our hypothesis. The EWR-related increase in coarse tuning is consistent with the N1 studies in L1 children (Eberhard-Moscicka et al., 2015). Furthermore, we found that a larger lexicality effect (real word N1 more negative than pseudo word N1) was linked to higher word reading skill, consistent with some of the literature (Coch and Meade, 2016; Mahé et al., 2012; Wang et al., 2022). This finding suggests that the lexicality effect could mean access to semantics in fast visual word processing in skilled readers, rather than lack of generalization of visual perceptual expertise (Maurer et al., 2006). The finding demonstrated for the first time the lexicality effect, although absent at the group level, was associated with better word decoding in children in the L2 context. Altogether, the findings support the visual expertise account of N1 print specialization, in that it is driven by skill and knowledge about English words.

One important finding of the present study is the unique effect of sub-lexical orthographic knowledge on English coarse and fine tuning. Fine tuning reflects the processing of orthography. A previous study with German-speaking children showed that fine tuning originated from good phonological decoding (Zhao et al., 2014). The present finding with Chinese English readers was somewhat different in that sub-lexical orthographic knowledge is the significant driver. There could be several explanations for this. The orthography of English is opaque in comparison to German. Applying phoneme-grapheme-correspondence rules cannot guarantee word identification, and retrieving orthographic knowledge is more important in the process of word recognition in English than German (Landerl et al., 2013). Alternatively, the reliance on orthographic processing in the recognition of English words may be more pronounced in Chinese children, since reading in the Chinese writing system requests dominantly orthographic processing (Perfetti et al., 2013). The current study cannot tease apart these two accounts. Cross-cultural studies comparing Chinese English L2 and English monolingual readers are needed to reach a conclusion. Of note, some of the target stimuli in the orthographic choice task are also unpronounceable. Therefore, it is possible that the participants judged the correct answer by pronounceability, rendering the task not purely measuring orthographic processing. We acknowledge this as a limitation. Thus, the effects of EOK should not be interpreted as effects of purely visual orthographic processing.

In contrast, word reading accuracy was not associated with fine tuning, possibly due to the specificity of fine tuning which largely reflects the automatic processing of well-formed letter patterns. Word decoding does not tap into this process as directly as the orthographic choice task does. Altogether, the present findings suggest that coarse tuning, fine tuning, and lexicality effect were modulated by different cognitive processes, which echo the recent finding that different cortical sources underly the three types of tuning (Wang et al., 2022).

Our hypothesis that word reading abilities are associated with N1 to English words was not confirmed. The non-significant effect of EWR or EOK on N1 to real words stands in contrast to the findings from training studies showing that short-term intensive training only has an effect on the N1 amplitude to real words (Brem et al., 2010, 2018), and also against the finding that N1 to real words significantly increases one year after formal literacy starts in the L1 setting (Maurer et al., 2006). The inconsistency could be explained by the different study design. Training and longitudinal studies have a within-subject design where the individual variance in N1 responses does not compete with the effect of interest, i.e. training and time. The present study is a mixed design containing both between-subject (ability, age) and within-subject (condition) factors. The individual variance in EEG N1 is influenced by many factors such as attention and expectation (F. Wang and Maurer, 2020) which could compete and interact with the between-subject factors, rendering a nonlinear relationship (as found between creativity and resting-state EEG [Jausovec and Jausovec, 2000]) between ability and raw N1, the modelling of which is beyond the scope of current study. The condition contrasts, however, measure N1 sensitivity to different aspects of print and exclude the individual variance on raw N1. Therefore, the linear increase and decrease with age and ability has shown to have a more pronounced effect on condition contrasts than raw N1.

The effects of ability were also evident in behavioral data for the repetition detection task. Children with higher word reading accuracy showed higher response accuracy in the real and pseudo word conditions. The repetition detection task, also known as a 1-back task, measures working memory at a lower load (Jaeggi et al., 2010). Better word level knowledge may facilitate the encoding of the visual words, and subsequently manipulation and retention of them. Moreover, this facilitating effect was more pronounced for real and pseudo words than for non-words and false fonts, which are difficult to verbally encode. EOK did not contribute to this facilitation effect independently of EWR. It is likely that the N1 print tuning is more sensitive than the word effect in behavioral accuracy as a measure of visual word processing.

4.3. The interaction between ability and age on print tuning

Studies in the L1 context indicate a developmental change in terms of the association between word reading ability and N1 coarse tuning. Specifically, in the beginning stage of learning to read (Grade 2), word reading (phonological decoding) is positively associated with N1 tuning strength, whereas the association diminishes beyond the beginning stage (Grade 5) (Maurer et al., 2011). This developmental change was not observed in the L2 context of the present study. The association between reading skills, i.e., EWR and EOK and N1 coarse tuning was long-lasting. There are several explanations for the inconsistency. The first is the difference in the measurement of word reading. Studies with older children in the L1 context used standardized measures (Brem et al., 2009; Coch and Meade, 2016), which is the percentile rank against the normative sample of the same age. This operation removes the variability of word reading caused by age, leaving less to be associated with N1 amplitude or print tuning. The present study used the z score across the entire sample, preserving the age-related variance in the ability measures.

The second explanation is the extended development of N1 print specialization in L2 versus L1. In the alphabetic L1 context, better readers initiate the decline of real word N1 after several years of literacy experience (Maurer et al., 2011), rendering earlier observed ability-tuning association disappeared in the later stage of reading development. In contrast, reading practice is relatively limited in the current L2 context, as most children only spent 20% instructional time in English. It might take children more exposure and practice to reach the level that the decoding process is largely integrated and automatic. However, we have no evidence to verify this speculation as we did not measure decoding fluency or conduct a longitudinal study.

The present study has also focused on the lateralization of N1 print specialization. The lateralization of coarse tuning can be explained as a joint contribution of age and word reading. For younger children, the lateralization difference between word and false font N1 enlarged with English word reading. Better word readers tended to show a more left-lateralized coarse tuning. For older children, the coarse tuning was bilateralized, and the lateralization of N1 coarse tuning did not change with English word reading ability. This interaction was consistent with previous findings comparing children with dyslexia and typical readers (Maurer et al., 2011), suggesting the lateralization of coarse tuning was more sensitive to reading ability in younger children. Despite the similar interaction effect, the N1 lateralization by condition was different from Maurer et al. (2011)'s finding. The present left lateralization of coarse tuning in younger and better readers was driven by a right-lateralized false font N1, not left-lateralized real word N1 as hypothesized. The word reading-related change in processing false fonts was demonstrated in previous studies in English L1 children (Maurer et al., 2006), which showed that second graders' N1 to false fonts decreased in the left hemisphere compared to kindergarteners, indicating a suppression effect of non-print stimuli. Studying Chinese preschool children, Li et al. (2013) found that young children good at sight word reading showed less right lateralization of face-related activities, the effect although in the opposite hemisphere to the present one, suggesting the impact of literacy experience on neural processing of other objects. The suppression of non-print N1 at the left hemisphere found in the current study was no longer linked to better word reading skill in older age, suggesting that the suppression of the non-print stimuli might be a short-lived mechanism in L2 word reading acquisition.

Previous studies with a sub-sample of the participants showed age-related change in the lateralization of Chinese print tuning (X. H. Tong et al., 2016b); younger children showed bilateralized coarse and fine tuning, whereas older children showed left-lateralized coarse and fine tuning. Most of the Chinese children in the sample were receiving more Chinese literacy instruction than English literacy instruction at school. It is possible that the amount of literacy experience contributes to the left-lateralization of Chinese print tuning, and that it would take more English literacy experience for children in this sample to show left-lateralized English print tuning.

5. Conclusions

Our findings, based on results from a large sample of a relatively broad range of age and ability, shed light on the developmental process of Chinese children's neural specialization to the English writing system as a second learned script. It shares similarities with the development of print tuning in the alphabetic L1 context, such as being driven by skill improvement as posited in the visual expertise hypothesis. It is also unique, which is reflected by the prominent role of sub-lexical orthographic knowledge in driving coarse and fine tuning, as well as by the protractive development manifesting as the long-lasting influence of skill and the absence of left-lateralization.

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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.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dcn.2023.101292.

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