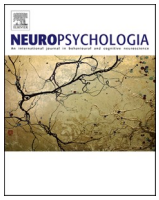
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Minimal evidence of adaptation deficits in children with dyslexia: An EEG study with controlled expectations

Brian W.L. Wong [a,b], Lucas Yiu Hei Chan [a], Shuting Huo [a], Urs Maurer [a,c,*]

[a] Department of Psychology, The Chinese University of Hong Kong, Hong Kong, China
[b] BCBL, Basque Center on Cognition, Brain and Language, Donostia-San Sebastián, Spain
[c] Brain and Mind Institute, The Chinese University of Hong Kong, Hong Kong, China

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ABSTRACT

Some recent research has implicated the implicit learning of statistical regularities as a potential factor contributing to reading deficits in individuals with dyslexia. These deficits are characterized by weaker neural adaptation compared to typically developing readers, suggesting impaired general processing in forming short-term representations of stimulus consistency. In addition, inconsistent findings have been observed regarding amplitude differences in mismatch negativity (MMN) between individuals with and without dyslexia. To address these inconsistencies, the present study examines neural adaptation and MMN responses in children with and without dyslexia, with the aim of clarifying their potential relationship. Forty-two children with Chinese dyslexia and 26 children without dyslexia participated in an EEG roving paradigm experiment with continuous pure-tone stimuli. Importantly, the stimuli were carefully arranged to minimize expectations and isolate pure adaptation effects. Initial and subsequent adaptation effects were quantified as changes in amplitude in early ERP components (P1a, P1b, and N250), defined respectively as the difference between the deviants and the 2nd tones, and between the 2nd and final tones. In addition, the MMN and late MMN, computed as the amplitude difference between the deviants and the final tones, were extracted. We found that both groups exhibited similar adaptation effects, as well as comparable MMN and late MMN responses, supported by minimal evidence for group differences in Bayesian analyses across most measures. These findings suggest that dyslexia is not characterized by a neural adaptation deficit per se, but that group differences in adaptation and MMN may depend on experimental context and language background.

1. Introduction

Dyslexia is a persistent difficulty in reading skill development that cannot be accounted for by mental age, visual problems, or inadequate education (World Health Organization, 2016), with a prevalence of 3-10% (Snowling, 2000). Although extensive research has investigated the deficits of dyslexia, it remains unclear whether dyslexia is mainly attributed to a phonological or a more general deficit. While many studies have linked dyslexia to phonological deficits (e.g., Landerl et al., 1997), individuals with dyslexia may also have difficulty performing simple perceptual tasks, such as pure tone frequency discrimination (Mcanally and Stein, 1996). This suggests that dyslexia may involve deficits in early auditory processing that are not inherently phonological, but may nonetheless contribute to later phonological difficulties. Some evidence further suggests that these deficits may be more general and span both auditory and visual modalities (e.g., Perrachione et al., 2016). While many behavioural studies have explored dyslexia-related deficits, electroencephalography (EEG) has recently been used to investigate these issues (Kujala and Näätänen, 2001). In the present study, two relevant EEG measures are neural adaptation and mismatch negativity (MMN).

1.1. Neural adaptation and dyslexia

Deficits in tone discrimination among individuals with dyslexia have been attributed to impaired implicit learning of statistical regularities. This is supported by findings showing that individuals with dyslexia rely less on global contextual information (Gertsovski and Ahissar, 2021;

* Corresponding author. Rm 325, Sino Building, The Chinese University of Hong Kong, Hong Kong, China.
E-mail addresses: b.wong@bcbl.eu (B.W.L. Wong), lucaschan@link.cuhk.edu.hk (L.Y.H. Chan), shutinghuo@cuhk.edu.hk (S. Huo), umaurer@cuhk.edu.hk (U. Maurer).

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Jaffe-Dax et al., 2015; Lieder et al., 2019; but see Ozernov-Palchik et al., 2022) or struggle to accumulate and use stimulus statistics to form perceptual anchors (anchoring deficit hypothesis; Ahissar et al., 2006). Specifically, when judging whether two tones with different frequencies are the same, individuals with dyslexia are less influenced by the global mean of preceding tones than typically developing readers, while being similarly influenced by local context (i.e., the first tone of the previous trial). Differences in perceptual anchoring have also been proposed to reflect underlying differences in adaptation between individuals with dyslexia and controls. Consistent with this account, behavioural evidence indicates that children and adults with dyslexia show reduced adaptation to repeated information in speech sound stimuli (Ozernov-Palchik et al., 2022). Neural measures of adaptation, such as those provided by EEG, may provide a more sensitive means of clarifying the mechanisms underlying these behavioural effects.

Repeated exposure to the same stimulus typically results in reduced neural activity, a phenomenon known as neural adaptation (Grill-Spector et al., 2006). In EEG research, adaptation is often quantified as a reduction in the amplitude of auditory evoked potentials (AEPs), that is, event-related potential (ERP) components elicited by auditory stimuli. In adult studies, neural adaptation is commonly indexed using the N1 and P2 components: the N1 typically manifests as a negative-going deflection occurring approximately 60–160 ms after stimulus onset (Woods, 1995), whereas the P2 is a positive-going deflection peaking around 150–250 ms (Crowley and Colrain, 2004). In contrast, the auditory components observed in children differ from those observed in adults (Ponton et al., 2002; A. Sharma et al., 1997; Sussman et al., 2008). Typically, when children perceive auditory stimuli with relatively short inter-stimulus interval (ISI), they exhibit a P1 component around 100 ms after stimulus onset, which can be divided into P1a and P1b, followed by an N250 component, which is a broad negativity around 250 ms after stimulus onset (Ponton et al., 2002; A. Sharma et al., 1997). The P1 complex (including P1a and P1b) is a prominent auditory evoked response in children and is widely used as an index of early auditory cortical development and maturation. In contrast, the N250 is a developmentally specific component that is robust in childhood and gradually diminishes with age, and has been interpreted as reflecting immature auditory cortical processing and prolonged sensory integration.

Weaker neural adaptation has been reported in some EEG studies using sensory gating paradigms in children and adults with dyslexia (Panahi et al., 2023; Peter et al., 2019). Peter et al. (2019) found that, when participants listened to pairs of identical tones, the decrease in N1 amplitude from the first to the second tone was significantly smaller in adults with dyslexia than in controls, indicating reduced neural adaptation in the dyslexia group. In contrast, no group differences in adaptation were observed for the P2 component. Based on a significant positive correlation between the N1 amplitude decrease and performance on a word comparison task, in which participants judged whether a pair of words presented simultaneously on a screen were the same or different, Peter et al. (2019) concluded that diminished neural adaptation might interfere with implicit learning and the formation of stable word representations.

Following this work, Panahi et al. (2023) applied a similar sensory-gating paradigm to children in a Persian-speaking context, focusing on the P1, N1, and P2 components. Notably, the ERP components examined differ from those typically reported in children, as discussed above, which may be attributable to the longer inter-trial interval used in this paradigm (approximately 8 s; Sussman et al., 2008). Similar to Peter et al. (2019), Panahi et al. (2023) reported that children with dyslexia showed weaker neural adaptation, quantified as a smaller amplitude reduction between the first and second tones across all three components, with no clear adaptation effect observed for the N1 component in the dyslexia group. Based on these findings, Panahi et al. (2023) concluded that reduced adaptation effects in children with dyslexia reflect atypical auditory sensory processing, potentially related to attentional mechanisms and sound discrimination.

Importantly, neural adaptation in this study was assessed using isolated pairs of identical tones rather than continuous tone sequences, which may limit the ability to capture adaptation dynamics as they unfold over repeated stimulation. Therefore, more studies are needed to validate weaker neural adaptation in dyslexia, particularly using precise temporal measurements and continuous tone sequences, as adopted in the present study.

While the above discussion has focused on studies using pure tone stimuli, some work has also examined perceptual anchoring and adaptation effects using speech sound stimuli in children (e.g., Männel et al., 2024; Ozernov-Palchik et al., 2022). For example, Männel et al. (2024) reported group differences between children with and without dyslexia in early auditory ERP components (P1 and N1, but not P2) during speech perception, suggesting altered use of contextual information. These studies provide important insights into the relationship between reading ability and speech perception. However, for the purposes of the present study, pure tones offer a more controlled means of isolating neural adaptation processes, without the additional linguistic and lexical influences inherent in speech.

In addition to evidence for weaker neural adaptation, other EEG studies have reported shorter neural adaptation timescales in dyslexia. For example, Jaffe-Dax et al. (2017) showed that individuals with dyslexia exhibited a faster decay of implicit auditory memory, manifested as more rapid recovery from neural adaptation. In this study, dyslexic and typically developing readers were exposed to continuous streams of pure tones, either passively while watching a silent movie or actively while performing a two-tone frequency discrimination task, with inter-stimulus intervals (ISIs) manipulated to probe adaptation dynamics. The results showed that, in both conditions, N1 and P2 responses in individuals with dyslexia recovered to their unadapted (i.e., baseline) magnitude at shorter ISIs than in controls, indicating a shorter temporal window over which past stimuli influenced neural responses. Jaffe-Dax et al. (2017) proposed that such shorter adaptation timescales reflect reduced integration of past sensory information, leading to less reliable predictions of upcoming stimuli, which may in turn contribute to reading difficulties. These findings support the view that neural adaptation plays a key role in statistical learning, a process that is critical for acquiring regularities in written language. Sensitivity to statistical regularities is crucial for reading across writing systems, including letter combinations in alphabetic languages and character structure and radicals in Chinese (Yeung et al., 2011).

In addition to EEG studies, several MRI studies have also reported weaker or shorter neural adaptation in dyslexia. An fMRI study showed that individuals with dyslexia exhibited weaker neural adaptation compared to controls, with this difference observed in overlapping brain regions when adult participants listened to spoken words or viewed written words, objects, and faces, as well as when child participants listened to spoken words (Perrachione et al., 2016). Given the wide range of stimuli and modalities, these results support the presence of a general deficit in dyslexia. Moreover, higher levels of neural adaptation were associated with better word-reading performance, suggesting that impaired processing involved in forming short-term representations of stimulus consistency may contribute to poorer reading abilities in dyslexia (Perrachione et al., 2016). In another study, fMRI data revealed that faster decay of adaptation in dyslexia was broadly distributed across the brain, with the strongest effects observed in the left superior temporal lobe, including the auditory cortex, suggesting that this deficit may reflect a general neural dysfunction (Jaffe-Dax et al., 2018). More recently, an fMRI study found that typically developing adults exhibited adaptation to repeated pure tones in the primary auditory cortex and higher-level regions, paralleling category learning, whereas no such adaptation was observed in adults with dyslexia (Gertsovski and Ahissar, 2021).

While these fMRI studies provide important insights into the spatial distribution of adaptation-related effects, they are limited in their ability

to capture the rapid temporal dynamics through which neural adaptation unfolds. EEG, with its high temporal resolution, allows adaptation to be tracked across successive stimuli and enables the dissociation of early sensory adaptation effects from later mismatch responses (discussed below). The present study therefore uses EEG to clarify how neural adaptation unfolds over time and how it relates to later mismatch responses in the context of dyslexia.

Taken together, most studies reporting weaker or shorter neural adaptation in dyslexia have focused on adults, whereas evidence from children remains limited. Given that dyslexia is a neurodevelopmental disorder, examining the development of neural adaptation and its temporal dynamics in children is crucial for understanding how early auditory processing relates to reading development. Moreover, existing child work has primarily relied on paradigms such as sensory gating or speech-based perceptual anchoring. These approaches do not isolate adaptation dynamics as they unfold over repeated stimulation, particularly in continuous tone sequences. As a result, it remains unclear how neural adaptation operates at early sensory stages in children with dyslexia, an issue of clear theoretical importance given the unresolved relationship between neural adaptation and reading ability in childhood.

1.2. MMN, late MMN, and dyslexia

Another key focus of the present study, alongside adaptation, is mismatch negativity (MMN). Originally described by Näätänen et al. (1978), MMN typically occurs when a deviant stimulus (hereafter "deviant") differing in properties such as frequency, intensity, or duration is introduced within a sequence of repeated standard stimuli (hereafter "standards"). Extensively studied in the auditory domain, MMN is calculated by subtracting the ERP response to standards, which are usually presented near the end of a stimulus sequence, from the response to deviants (Garrido et al., 2009). MMN typically peaks 100–250 ms after the point of deviation, with its strongest amplitudes observed in fronto-central areas and a polarity reversal at the mastoids (Kujala and Näätänen, 2001). Its neural sources are localized in the temporal and frontal regions (Alho, 1995). Notably, MMN is associated with pre-attentive auditory processing and does not require active attention to be elicited (Näätänen et al., 2001).

The mechanisms underlying MMN are primarily explained by two main hypotheses: the adaptation hypothesis (Jääskeläinen et al., 2004; May et al., 1999; May and Tiitinen, 2010) and the model-adjustment hypothesis (Näätänen and Alho, 1995; Näätänen et al., 2005; Näätänen and Winkler, 1999; Sussman and Winkler, 2001; Winkler et al., 1996). The adaptation hypothesis suggests that a reduced sensitivity to stimulus repetition may contribute to the abnormal mismatch responses observed in individuals with dyslexia (Gu and Bi, 2020; Schulte-Körne and Bruder, 2010). In contrast, the model-adjustment hypothesis proposes that individuals with dyslexia may have difficulty adjusting their internal models based on stimulus statistics (Gabay et al., 2015; Vandermosten et al., 2019). These hypotheses are further linked to the predictive coding model, which provides a unifying framework by reconciling the two hypotheses (Carbajal and Malmierca, 2018; Friston, 2005; Garrido et al., 2009; Winkler, 2007). The predictive coding model suggests that individuals with dyslexia may exhibit a reduced sensitivity to prediction errors (Beach et al., 2022a).

Previous findings regarding MMN in individuals with dyslexia have been inconsistent. In children, several studies have reported MMN amplitudes comparable to those of controls in dyslexia (Halliday et al., 2014; Meng et al., 2005; Schulte-Körne et al., 1998; M. Sharma et al., 2006), while others have reported an enhanced MMN in dyslexia (e.g., Hugdahl et al., 1998). Findings in adults are similarly mixed: some studies have reported reduced MMN amplitudes in adults with dyslexia (Baldeweg et al., 1999; Sebastian and Yasin, 2008), whereas others have found no group differences (e.g., Schulte-Körne et al., 2001). The differing findings from previous studies may be attributed to several factors, such as differences in statistical power, participant characteristics, stimulus characteristics, and presentation rates (Bishop, 2007). For example, Kujala et al. (2006) found that adults with dyslexia showed a reduced MMN to pitch deviants, but an enhanced MMN to spatial (location) deviants defined by interaural time differences between the ears, suggesting that auditory deficits in dyslexia may be more specific to pitch processing. In addition, in the study by Baldeweg et al. (1999), smaller and later MMNs were observed in individuals with dyslexia compared to controls in all conditions (tone differences: 15 Hz, 30 Hz, and 60 Hz), except for the largest tone difference condition (90 Hz). Thus, individuals with dyslexia may have more difficulty discriminating small stimulus differences than larger ones. Importantly, the heterogeneity of findings in adults does not resolve the question of whether and how MMN differences emerge in childhood, motivating the present investigation in children using a tightly controlled roving paradigm.

In addition, the late MMN, or late discriminative negativity, is a component that may be related to dyslexia. The late MMN is a prolonged negativity occurring around 300–550 ms post-stimulus onset (Cheour et al., 2001). It was first identified by Korpilahti et al. (1995) in children and adults in response to changes in linguistic stimuli, but not pure tones, representing the auditory processing of complex stimuli. However, later studies found that the late MMN could be elicited by changes in pure tones (e.g., Čeponiene et al., 1998). Moreover, an attenuation of the late MMN was found in children with a familial risk of dyslexia when presented with pure tone deviants (Maurer et al., 2003a). Recent research suggests that the late MMN, rather than the early MMN, may serve as a marker of auditory change detection deficits in children with dyslexia, indicating that dyslexia may involve impairments in later stages of auditory processing (Halliday et al., 2014). However, more studies are needed, as research on the late MMN and dyslexia is still relatively limited.

1.3. Present study

The present study compares neural adaptation effects between children with and without dyslexia during passive listening to pure tones. Neural adaptation is indexed by changes in ERP amplitudes across tones. Because neural adaptation is thought to provide a neural substrate supporting perceptual anchoring and statistical learning (e.g., Jaffe-Dax et al., 2017), examining neural adaptation allows us to test whether early sensory mechanisms required for learning from regularities are intact in children with dyslexia, independently of overt behavioural learning outcomes. We also compared MMN and late MMN responses between children with and without dyslexia. In cases where group differences in MMN and/or late MMN were observed, we assessed whether adaptation-related variability was associated with differences in MMN responses.

A roving paradigm was adopted in the present study. In this paradigm, a deviant becomes the subsequent standard to ensure that the properties of the deviants and standards are identical. Therefore, MMN must reflect inherent differences between standards and deviants, without being influenced by other physical properties. This paradigm has been used in previous studies (e.g., Baldeweg et al., 2004; Cowan et al., 1993; Garrido et al., 2008; Haenschel et al., 2005; Huotilainen et al., 2001; Wong et al., 2024). Importantly, stimuli were arranged in a way that controlled for expectation (see 2.2 Stimuli, materials, and procedure for details), as expectation can influence adaptation and MMN (Barbosa and Kouider, 2018; Chennu et al., 2013; Costa-Faidella et al., 2011; Hari et al., 1979; Herholz et al., 2009; Kuravi and Vogels, 2017; Lecaignard et al., 2021; Todorovic et al., 2011). This design choice allows the paradigm to primarily probe short-term, stimulus-driven neural adaptation under stable expectations, rather than longer-term learning or memory decay mechanisms. Here, short-term neural adaptation refers to rapid changes in neural responses across successive repetitions of the same stimulus within a single roving train, reflecting adaptation to repeated input under stable expectations and unfolding

over the duration of the train (a few seconds). In contrast, longer-term adaptation or statistical learning refers to the accumulation or updating of stimulus regularities across trials or trains, often over seconds to minutes. Accordingly, the roving paradigm allows us to test whether neural adaptation deficits per se are present in dyslexia.

In our previous work, we adopted the same paradigm in adults and distinguished initial adaptation, defined as the amplitude change from the 1st to the 2nd tone, and subsequent adaptation, defined as the amplitude change from the 2nd to the final tone within each train (Wong et al., 2024). Using this approach, we demonstrated distinct adaptation patterns in the N1 and P2 components, as well as their relationships to MMN, in adults. The same two adaptation measures, initial adaptation and subsequent adaptation, were adopted in the present study.

We compared ERPs across tones within each train to examine neural adaptation. Based on previous findings showing early adaptation differences in dyslexia (Männel et al., 2024; Panahi et al., 2023; Peter et al., 2019), we predicted that the decrease in amplitude across repetitions would be smaller in children with dyslexia for the early auditory components P1a and P1b. While no group difference was predicted for the N250 component, this component is a prominent auditory component in children and reflects later stages of auditory processing that are not captured by earlier components. Previous child studies have primarily focused on the N1 (Männel et al., 2024; Panahi et al., 2023), often using longer ISIs that yield more adult-like ERP morphology (Sussman et al., 2008), whereas adaptation effects in the N250 have not been systematically examined. Including the N250 therefore allowed us to test whether potential adaptation differences in dyslexia are confined to early sensory stages or extend to later integrative processing. In addition, based on prior work in children (e.g., Halliday et al., 2014; Maurer et al., 2003a), we expected that children with dyslexia would show a smaller late MMN, whereas the MMN would not differ between groups.

In addition to the EEG experiment, the present study included a behavioural measure of tone discrimination. Our participants were Cantonese speakers, whose first language is tonal. To our knowledge, neural adaptation in dyslexia has not previously been examined in a tonal-language context. Previous studies conducted in alphabetic-language contexts have reported tone discrimination deficits in adults and children with dyslexia (Baldeweg et al., 1999; Halliday and Bishop, 2006; Kujala et al., 2006). Given evidence that tone discrimination performance differs between speakers of tonal and non-tonal languages (Bao et al., 2013), it is possible that both behavioural sensitivity to pitch and neural adaptation dynamics differ in Cantonese-speaking individuals with dyslexia. This task therefore served two purposes: first, to assess whether children with dyslexia in a tonal-language context show behavioural deficits in tone discrimination; and second, to include tone discrimination as a covariate in the analyses, to account for potential individual differences in pitch sensitivity that may influence neural adaptation effects.

In addition to tone discrimination, auditory evoked potentials are known to show robust age-related changes across development (Sussman et al., 2008). Musical training has also been shown to enhance pitch discrimination abilities (Micheyl et al., 2006). Accordingly, age and musical training were considered as additional covariates in the analyses.

This study is theoretically significant because it investigates whether neural adaptation effects can help explain reading deficits in children with dyslexia whose first language is Cantonese, a tonal language. Whether MMN differences are present in this population also remains unknown. The study is also practically important, as EEG components related to adaptation, such as P1a, P1b, and N250, together with the MMN, may serve as potential markers for the early identification of dyslexia. Early identification is particularly valuable because earlier interventions are often more effective (Kujala and Näätänen, 2001).

2. Method

2.1. Participants

Forty-five children with dyslexia and 27 typically developing children participated in the experiment. Four participants were excluded due to an excessive number of bad electrodes (≥30) or a low total remaining segment percentage (<40%). Therefore, 42 children (fourth to sixth grade; 9–13 years old; 17 females) and 26 children (fourth to sixth grade; 10–12 years old; 17 females) remained in the dyslexia and control groups, respectively. All participants were part of a larger research project, approved by The Joint Chinese University of Hong Kong—New Territories East Cluster Clinical Research Ethics Committee (The Joint CUHK-NTEC CREC; reference no.: 2019.048). They were recruited from Hong Kong primary schools and education authorities. Children with dyslexia were formally diagnosed by either educational or clinical psychologists using The Hong Kong Test of Specific Learning Difficulties in Reading and Writing for Primary School Students—Third Edition [HKT-P(III)] (Ho et al., 2016). Criteria included adequate IQ (higher than 85), poor literacy (−1 SD or below), and at least one area of cognitive-linguistic deficit (−1 SD or below; Chung, 2017). In addition, the children had no history of neurological or psychiatric disorders, brain injury, birth complications, or significant sensory impairment. The typically developing children had no reported difficulty in reading or writing, based on parents' reports. Written consent was obtained from the children and their guardians.

2.2. Stimuli, materials, and procedure

2.2.1. Participants' background measures

Prior to the experiment, parents completed a questionnaire to provide demographic information about the participants. This included a question about whether the child was currently receiving or had previously received musical training, given that musical training may enhance pitch discrimination abilities (Micheyl et al., 2006), potentially influencing adaptation outcomes. If the response was affirmative, parents were also asked to report the duration of their child's musical training.

2.2.2. EEG experiment

The experiment was the same as the one previously conducted in our lab with adults (Wong et al., 2024). The experiment was programmed using E-Prime 3.0. All stimuli were pure sinusoidal tones with seven different frequencies (500 Hz, 550 Hz, 600 Hz, 650 Hz, 700 Hz, 750 Hz, and 800 Hz). Each tone lasted 70 ms (with 5 ms rise and fall times), and the stimulus-onset asynchrony (SOA) was fixed at 650 ms. The relatively long SOA allowed for investigation of the late MMN. All tones were presented at 70 dB.

EEG data were recorded using NetStation, with a Net Amps 300 amplifier and 128-channel Electrical Geodesics Incorporated (EGI) nets referenced to Cz. The sampling rate was 500 Hz, and the online filter was set at a 0.1 Hz high-pass. Impedance was kept below 50 kΩ for each electrode. Data recording took place in a sound-attenuated laboratory at the Department of Psychology, CUHK. Before the experiment, participants were instructed to watch a silent movie while listening to sounds, but to ignore the sounds. They were also asked to minimize body movements during the experiment to reduce muscle artifacts.

In each experimental session, the first tone was randomly selected from the seven different frequencies. After that, there was an 85% chance that the next tone would be the same as the first (2nd tone: standard) and a 15% chance that it would be different (2nd tone: deviant). To control for expectation, this criterion remained unchanged, with one exception: if 30 standards were played consecutively, the next tone had to be a deviant (occurring two to three times on average across approximately 300 sequences per participant). The experiment ended after 2000 tones were played. Participants watched a silent movie, "Tom

and Jerry" (as in our previous work: Jost et al., 2015; Maurer et al., 2003a, 2003b; Wong et al., 2024) on a laptop while listening to tones played by speakers placed 80 cm away. The experiment lasted approximately 20 min. Fig. 1 illustrates the experimental design of the roving paradigm.

2.2.3. Tone discrimination task

After the EEG experiment, a tone discrimination task was administered using E-Prime 3.0 to assess the children's ability to discriminate tones. In each trial, participants listened to a pair of tones. The task began with eight practice trials to familiarize the children with the procedure, followed by 104 experimental trials. Of these, 48 involved different tone pairs, while the remaining 56 featured identical pairs. Tone properties matched those used in the EEG experiment, and sequences were presented in a pseudorandomized order. In the experimental trials, all different tone pairs had a 50 Hz frequency difference, the smallest difference presented in the EEG task, though larger differences were included in the practice trials. Participants were instructed to press "f" if the tones were the same and "j" if they were different, emphasizing both accuracy and speed.

The procedure for each trial was as follows: a 1-s fixation cross was displayed, followed by the presentation of two tones (each lasting 70 ms) with a 280-ms gap between them. Afterward, a question mark appeared, prompting participants to indicate whether the tones were identical or different by pressing the corresponding key. The next trial began immediately after the response. Feedback on accuracy and reaction time was provided during practice trials but not during experimental trials. The task took approximately 5 min to complete.

The tone discrimination task was administered after the EEG session to avoid potential task-related learning or fatigue effects influencing neural adaptation during passive listening. Performance on this task was not used as an exclusion criterion. Instead, tone discrimination was included to examine whether children with and without dyslexia differ in this ability and to serve as a covariate controlling for individual differences in pitch sensitivity. This allowed us to better interpret the neural adaptation results in relation to behavioural sensitivity to pitch.

2.2.4. Reading task

Children's reading abilities were measured by a word reading task, which included 135 Chinese characters selected from a database by Lui et al. (2010). Each character was embedded as the second character in a two-character word. The list of 135 two-character words, arranged in increasing difficulty, was shown on a piece of paper, and the children were asked to read aloud the second character of each word. The task ended if they gave incorrect or no responses for 10 consecutive items, or if they finished reading all the items. The number of correct responses was recorded as the word reading score. The Cronbach's alpha of this task is 0.982.

The reading task was included to confirm group classification and to provide a continuous measure of reading ability. Although group differences in reading were expected, reading scores were also used to capture individual variability, as reading ability lies on a continuum rather than being strictly categorical. Treating reading ability as a continuous variable allows a more sensitive examination of its relationship with neural measures beyond group membership alone (Hemelstrand and Inoue, 2025). For completeness and transparency, we report both group-based and continuous analyses, ensuring that our conclusions are not dependent on a single analytic approach.

2.3. EEG preprocessing

Brain Vision Analyzer (version 2.2.2.8298; Brain Products, Gilching, Germany) was used for EEG preprocessing and waveform analysis. Data preprocessing was performed on continuous EEG recordings and included filtering (0.3 Hz high-pass with a slope of 24 dB/oct and 30 Hz low-pass with a slope of 48 dB/oct), bad channel identification, raw data inspection, and independent component analysis (ICA) using a restricted Infomax algorithm to correct for eye blinks and lateral eye movements. Bad channels were subsequently interpolated using spherical splines, and data were re-referenced to the average of all electrodes. ERP epochs were then segmented from −168 ms to 632 ms relative to stimulus onset, separately for standards and deviants, allowing both the MMN and late MMN components to be fully captured. A fixed delay of 18 ms was corrected to account for the anti-aliasing filter of the Net Amps 300 amplifier (EGI advisory notice, 26 November 2014). Artifact rejection was performed using an amplitude threshold of ±100 μV. Entire epochs were rejected if this threshold was exceeded at any point within the segmented trial. The data were then segmented by tone position and averaged. Baseline correction was applied using the pre-stimulus interval.

Overall, an average of 28.81% of trials were rejected. The average remaining trial numbers in the three conditions related to the adaptation effects, namely the deviants (1st tones), the 2nd tones, and the final tones in the 4th to 30th positions, were 208 (147–288), 177 (115–250),

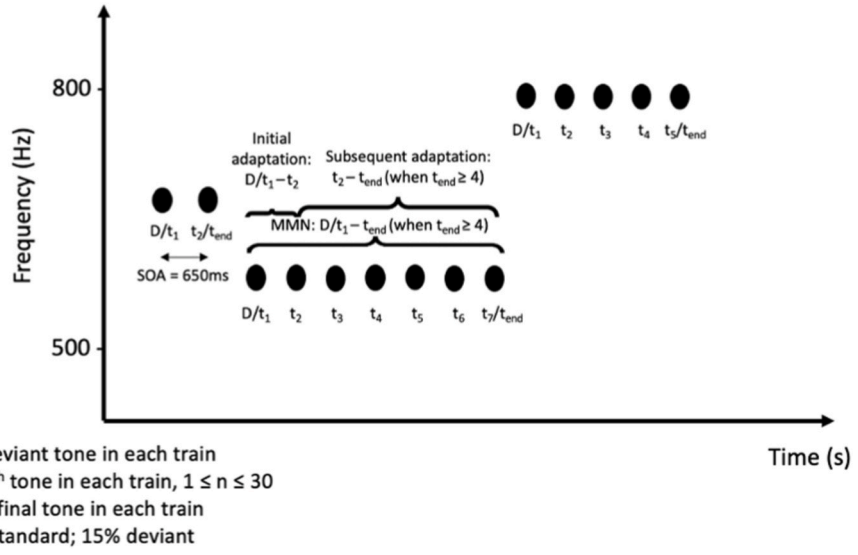


Fig. 1. Roving paradigm used in the present study, with calculation methods for initial adaptation, subsequent adaptation, and MMN amplitudes, as in Wong et al. (2024).

and 125 (88–186), respectively. Importantly, the number of remaining trials did not differ between groups in any of these three conditions, suggesting no systematic group differences in artifact rates. Bayesian independent-samples t-tests indicated inconclusive evidence for group differences in the deviant condition and weak evidence in favor of the null hypothesis for the 2nd- and final-tone conditions (deviants: Bayes factor [*BF*] = 1.15; 2nd tones: *BF* = 0.75; final tones: *BF* = 0.54; see 2.4 Data analyses for Bayes factor interpretation). Table S1 shows the average number of remaining trials for the two groups at each tone position.

2.4. Data analyses

Based on previous literature related to adaptation and MMN (e.g., Bühler et al., 2017; Jaffe-Dax et al., 2017; Jost et al., 2015), the following 25 frontocentral electrodes were pooled for analysis: E19, E11, E4, E20, E12, E5, E118, E13, E6, E112, E10, E16, E18, E30, E7, E106, E105, E37, E31, E129, E80, E87, E55, E36, E104.

Following previous work related to adaptation (e.g., Panahi et al., 2023; Peter et al., 2019; Wong et al., 2024), peak amplitudes of the P1a, P1b, and N250 components were extracted. We acknowledge that peak amplitude measures can be sensitive to signal-to-noise ratio and trial-count differences (Luck, 2014). As noted above, the number of remaining trials differed across conditions. While all available trials were retained in the primary analyses to maximize statistical power, we conducted an additional control analysis to ensure that trial-count differences did not bias the peak amplitude measures, in which trial numbers were equated across conditions by randomly subsampling trials to match the number of final-tone trials (the condition with the fewest trials) within each participant. All main findings remained unchanged. Details of these analyses are provided in the Supplementary Materials.

The time windows for detecting peak amplitudes of P1a, P1b, and N250 were defined using the global field power (GFP) of the grand average data, collapsed across both dyslexia and control groups. GFP is the root mean square (RMS) across average-referenced electrode values, or the standard deviation of all electrodes at a given time point (Murray et al., 2008). GFPs were generated using Brain Vision Analyzer. For each component, the window was centered on the corresponding GFP peak and extended to the surrounding local minima. The P1a time windows for deviants, 2nd tones, and final tones in the 4th to 30th positions were 38–102 ms, 32–100 ms, and 44–110 ms, respectively. The P1b time windows for the same stimuli were 102–148 ms, 100–154 ms, and 110–146 ms, respectively. The N250 time windows for these stimuli were 148–632 ms, 154–404 ms, and 146–518 ms, respectively.

The MMN waveform was formed by subtracting the amplitudes of the final tones in the 4th to 30th positions from that of the deviants in the same frontocentral electrodes (deviants–final tones). To define the time windows of MMN and late MMN, we conducted a non-parametric topographic analysis of variance (TANOVA) on RAGU using the area amplitude in the deviant and standard conditions across all participants (permutation test, $p < .05$). Only effects that were sustained across consecutive time points were considered. The resulting significant intervals were used to define the MMN and late MMN windows. Non-normalized (raw) maps were used for each time point (400 time points indexed into 2 ms steps with 500 Hz data recording; time window: −168 to 632 ms) for the analysis. The time windows for MMN and late MMN are 111–185 ms and 343–631 ms, respectively. Area amplitudes were used for the MMN and late MMN components, as these responses are typically broad and sustained rather than sharply peaked, and area measures are less affected by inter-individual variability in peak latency (Bishop, 2007; Picton et al., 2000a).

For the adaptation effects, the local peak amplitude at each tone position and time window were identified automatically using Brain Vision Analyzer. As in Wong et al. (2024), initial adaptation was defined as the difference in peak amplitude between the deviants and the tones in the 2nd position in the frontocentral electrodes (deviants–2nd tones). Subsequent adaptation was defined as the difference in peak amplitudes between the tones in the 2nd position and the final tones in the 4th to 30th positions in the same electrodes (2nd tones–final tones). Fig. 1 illustrates the calculation methods for initial adaptation, subsequent adaptation, and MMN.

Mixed ANOVAs were used to compare initial and subsequent adaptation between groups for each ERP component, with tone position (1st vs. 2nd tone for initial adaptation and 2nd vs. final tone for subsequent adaptation) as a within-subject factor and group (dyslexia vs. control) as a between-subject factor. Similarly, mixed ANOVAs were conducted to examine group differences in MMN and late MMN amplitude, with deviance (deviant = 1st tone vs. standard = final tone) as a within-subject factor and group as a between-subject factor. To further investigate potential differences in initial adaptation, subsequent adaptation, MMN, and late MMN, relationships between these neural measures and reading ability (a continuous variable) were examined using correlation analyses. Due to violations of the normality assumption, Spearman's rank-order correlations were used. In addition, hierarchical regression analyses were conducted to examine the contributions of group and reading ability to neural measures while controlling for other relevant factors.

For all Bayesian analyses, default priors were used, following the recommendations of Keysers et al. (2020). Bayes Factors (BFs) were calculated to evaluate the strength of evidence for our hypotheses. A BF represents the ratio comparing the predictive performance of two competing hypotheses: the null hypothesis (H_0) and the alternative hypothesis (H_1) (Keysers et al., 2020). A BF greater than 1 suggests that the data are more likely under H_1 than H_0. Specifically, a BF greater than 1 supports H_1, while a BF less than 1 favors H_0. For example, a BF of 10 indicates that the data are 10 times more likely under H_1, providing moderate-to-strong evidence for the alternative hypothesis. We interpreted the BFs using the guidelines proposed by Lee and Wagenmakers (2013), adapted from Jeffreys (1961). BF values between 1 and 3 indicate weak evidence for H_1, values between 3 and 10 indicate moderate evidence, 10 to 30 strong evidence, 30 to 100 very strong evidence, and values above 100 represent extreme evidence in favor of H_1. Conversely, BF values between 0.33 and 1 suggest weak evidence against H_1, 0.1 to 0.33 moderate evidence, 0.03 to 0.1 strong evidence, 0.01 to 0.03 very strong evidence, and values below 0.01 represent extreme evidence against H_1. BFs close to 1 were interpreted as inconclusive, indicating that the data were relatively insensitive with respect to the tested hypothesis. For the Bayesian repeated-measures ANOVAs, we report Bayes factors for inclusion (BF_{incl}), which quantify the evidence for including a given effect in the model by comparing models that include the effect to otherwise equivalent models that exclude it (Keysers et al., 2020). BF_{incl} values are interpreted using the same evidential scale and principles as BF. All statistical tests were conducted using both frequentist and Bayesian methods in JASP (Version 0.19.1; JASP Team, 2024).

In the present study, Bayesian analyses were used to complement frequentist statistics by quantifying the strength of evidence for or against effects of interest. In cases where frequentist and Bayesian results diverged, we report both and interpret such effects cautiously. We also refrained from follow-up t-tests or from drawing strong conclusions when Bayesian evidence was weak or inconclusive.

3. Results

Table 1 presents descriptive statistics for the main variables. All data are openly available at https://osf.io/uyekv/files/osfstorage.

3.1. Behavioural measures

D-prime (*d'*), a measure of sensitivity from signal detection theory, was used to quantify the performance of tone discrimination. It reflects the ability to distinguish between signal (correct detections) and noise (false alarms). *d'* is calculated based on the hit rate and false alarm rate,

Table 1
Descriptive statistics of main variables in dyslexia and control groups.

	Dyslexia ($N = 42$)		Control ($N = 26$)	
Variable	*Mean*	*SD*	*Mean*	*SD*
Age	11.07	0.81	11.19	0.75
Tone discrimination performance (in d')	1.56	0.92	2.01	1.21
Reading performance (out of 135)	83.95	33.27	116.62	11.31
Musical training duration (in year)[a]	0.96	2.08	2.15	2.79
MMN amplitude	−0.48	1.03	−0.62	0.91
Late MMN amplitude	−0.59	1.04	−0.91	0.88
P1a initial adaptation amplitude	0.27	0.67	0.15	0.69
P1a subsequent adaptation amplitude	−0.32	0.89	−0.08	0.73
P1b initial adaptation amplitude	0.49	0.87	0.004	0.80
P1b subsequent adaptation amplitude	−0.70	1.03	−0.39	1.11
N250 initial adaptation amplitude	0.28	0.92	−0.16	1.14
N250 subsequent adaptation amplitude	0.26	1.02	0.54	1.15

Note.
[a] $N = 24$ for control group and $N = 36$ for dyslexia group due to missing data.

by taking the difference between their corresponding z-scores. This quantifies the distance between the means of the signal and noise distributions in standard deviation units, reflecting the participant's sensitivity. Higher *d'* values indicate better discrimination between tones. A one-tailed independent *t*-test revealed a significant difference in *d'*, with children with dyslexia showing lower discrimination sensitivity than controls, $t(66) = 1.74$, $p = .043$, Cohen's d *(d)* = 0.43. Bayesian analysis, however, indicated only weak and largely inconclusive evidence for this group difference, Bayes Factor (*BF*) = 1.71, suggesting that the data were only slightly more likely under the alternative hypothesis than under the null.

Due to clear violations of normality and homogeneity of variance in the dyslexia group's reading scores, a nonparametric Mann–Whitney *U* test was used to compare reading ability between groups. As expected, based on the Mann-Whitney *U* test, children in the control group outperformed children in the dyslexia group in the Chinese reading task, $U = 963.50$, $p < .001$, rank-biserial correlation (r_b) = 0.77, with extreme evidence in favor of a group difference, $BF = 1657.05$.

Fig. 2 illustrates the initial and subsequent adaptation effects of the P1a, P1b, and N250 components in children with and without dyslexia. Detailed results are reported below. Fig. S1 shows the adaptation patterns based on the peak amplitudes of P1a, P1b, and N250 across the first ten tone positions. The ERPs corresponding to these ten tone positions for the dyslexia and control groups are shown in Fig. S2.

3.2. P1a adaptation

Based on Fig. 2a, visual inspection suggested minimal differences in the adaptation pattern between the two groups for the P1a component. This observation was supported by the statistical analyses.

To examine whether P1a initial adaptation differed between groups, we conducted a mixed ANOVA with Tone position (1st vs. 2nd tone) as a within-subject factor and Group (dyslexia vs. control) as a between-subject factor. The analysis revealed a significant main effect of Tone position, $F(1, 66) = 6.19$, $p = .015$, $\eta_p^2 = 0.086$, with Bayesian analysis indicating moderate evidence for the inclusion of Tone position, $BF_{incl} = 4.64$, reflecting a reliable reduction in amplitude from the 1st to the 2nd tone across participants. Critically, if children with and without dyslexia differed in P1a adaptation, a Tone position × Group interaction would be expected. However, this interaction was not significant, $F(1, 66) = 0.47$, $p = .497$, $\eta_p^2 = 0.007$, with Bayesian model comparison indicating weak evidence against the interaction, $BF_{incl} = 0.39$, suggesting that the magnitude of initial adaptation did not differ between the dyslexia and control groups. There was also no main effect of Group, $F(1, 66) = 0.33$, $p = .570$, $\eta_p^2 = 0.005$, with weak evidence against the inclusion of Group, $BF_{incl} = 0.38$, indicating comparable overall P1a amplitudes across groups.

To examine whether P1a subsequent adaptation differed between groups, we conducted a mixed ANOVA with Tone position (2nd vs. final tone) as a within-subject factor and Group (dyslexia vs. control) as a between-subject factor. The analysis revealed no significant main effect of Tone position, $F(1, 66) = 3.87$, $p = .053$, $\eta_p^2 = 0.055$, indicating that the increase in amplitude from the 2nd to the final tone was not reliable across participants. Bayesian analysis yielded a Bayes factor close to 1, $BF_{incl} = 1.37$, indicating weak and inconclusive evidence for the inclusion of Tone position. This suggests that the data were largely insensitive with respect to detecting a reliable subsequent adaptation effect. Critically, the Tone position × Group interaction was not significant, $F(1, 66) = 1.36$, $p = .249$, $\eta_p^2 = 0.020$. Bayesian analysis indicated moderate evidence against the inclusion of the interaction, $BF_{incl} = 0.25$, suggesting that the magnitude of subsequent adaptation did not differ between the dyslexia and control groups. There was also no main effect of Group, $F(1, 66) = 0.84$, $p = .362$, $\eta_p^2 = 0.013$, with Bayesian analysis showing moderate evidence against the inclusion of Group, $BF_{incl} = 0.21$, suggesting comparable overall P1a amplitudes across groups.

3.3. P1b adaptation

Similarly, the adaptation curve for the P1b component showed minimal differences between the two groups (Fig. 2b), consistent with the statistical results reported below. The same analytical approach used for P1a was applied to the P1b component. For initial adaptation (1st vs. 2nd tones), the mixed ANOVA revealed a significant main effect of Tone position, $F(1, 66) = 5.62$, $p = .021$, $\eta_p^2 = 0.078$, indicating a reliable reduction in P1b amplitude from the 1st to the 2nd tone across participants. Bayesian analysis showed moderate evidence for the inclusion of Tone position, $BF_{incl} = 8.09$, corroborating the presence of an initial adaptation effect. The Tone position × Group interaction was also significant, $F(1, 66) = 5.42$, $p = .023$, $\eta_p^2 = 0.076$, indicating that the reduction in P1b amplitude from the 1st to the 2nd tone was numerically larger in the dyslexia group than in the control group. However, Bayesian analysis revealed only weak evidence for the inclusion of the interaction, $BF_{incl} = 2.48$. This indicates that, although the interaction reached statistical significance, the overall evidence supporting a reliable group difference in initial P1b adaptation is limited and should be interpreted cautiously. There was no main effect of Group, $F(1, 66) = 0.05$, $p = .823$, $\eta_p^2 < 0.001$, with Bayesian analysis indicating weak evidence against the inclusion of Group, $BF_{incl} = 0.81$, suggesting comparable overall P1b amplitudes across groups.

For subsequent adaptation (2nd vs. final tones), the analysis revealed a robust main effect of Tone position, $F(1, 66) = 36.27$, $p < .001$, $\eta_p^2 = 0.355$, indicating a reliable increase in P1b amplitude from the 2nd to the final tone across participants. Bayesian analysis showed extreme evidence for the inclusion of Tone position, $BF_{incl} = 502.91$. Critically, the Tone position × Group interaction was not significant, $F(1, 66) = 2.60$, $p = .112$, $\eta_p^2 = 0.038$. Bayesian analysis indicated weak evidence against the inclusion of the interaction, $BF_{incl} = 0.46$, suggesting that the magnitude of the subsequent amplitude increase did not differ reliably between the dyslexia and control groups. There was also no main effect of Group, $F(1, 66) = 0.06$, $p = .812$, $\eta_p^2 < 0.001$, with moderate Bayesian evidence against the inclusion of Group, $BF_{incl} = 0.29$, suggesting comparable overall P1b amplitudes across groups.

3.4. N250 adaptation

Likewise, visual inspection of Fig. 2c suggested minimal differences between the dyslexia and control groups in N250 initial and subsequent adaptation. For initial adaptation, the analysis revealed no significant main effect of Tone position, $F(1, 66) = 0.23$, $p = .634$, $\eta_p^2 = 0.003$, indicating no reliable change in N250 amplitude from the 1st to the 2nd tone across participants. Bayesian analysis revealed moderate evidence against the inclusion of Tone position, $BF_{incl} = 0.26$. The Tone position × Group interaction was also not significant, $F(1, 66) = 3.09$, $p = .083$,

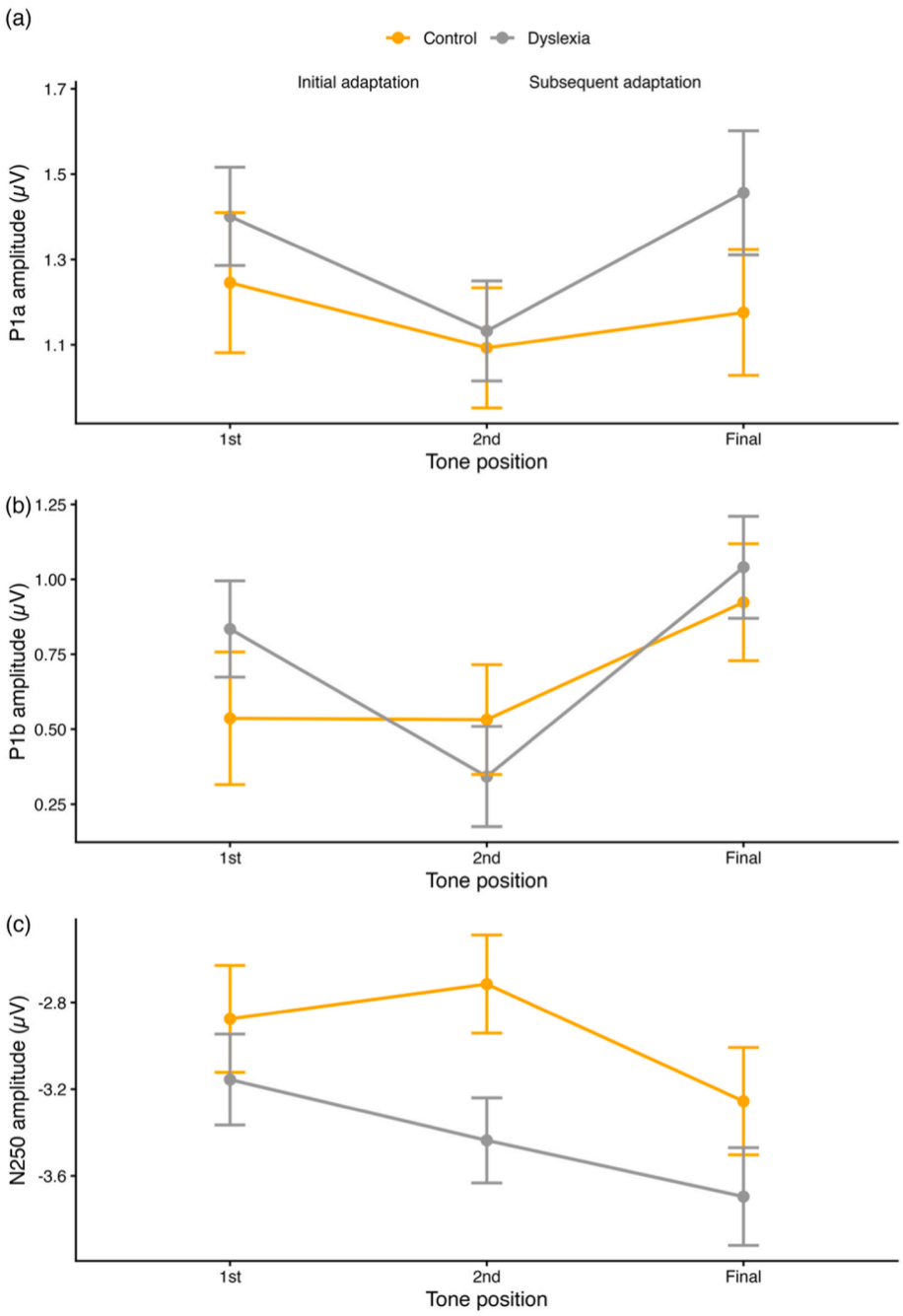


Fig. 2. Adaptation curves based on the peak amplitudes of (a) P1a, (b) P1b, and (c) N250 for the 1st, 2nd, and final tones in the control (N = 26) and dyslexia groups (N = 42).

Note. Points indicate group means, and error bars represent ±1 standard error of the mean (SEM). Initial adaptation is defined as the amplitude change from the 1st to the 2nd tone, and subsequent adaptation as the amplitude change from the 2nd to the final tone.

$\eta_p^2 = 0.045$, with weak Bayesian evidence against the inclusion of the interaction, $BF_{incl} = 0.42$. These results indicate no reliable evidence for group differences in N250 initial adaptation. There was no main effect of Group, $F(1, 66) = 2.93$, $p = .092$, $\eta_p^2 = 0.042$, with weak Bayesian evidence against the inclusion of Group, $BF_{incl} = 0.84$, suggesting comparable overall N250 amplitudes across groups.

Regarding N250 subsequent adaptation, the analysis revealed a significant main effect of Tone position, $F(1, 66) = 8.94$, $p = .004$, $\eta_p^2 = 0.119$, indicating a reliable increase (i.e., becoming more negative) in N250 amplitude from the 2nd to the final tone across participants. with moderate evidence for the inclusion of Tone position, $BF_{incl} = 4.77$, supporting the presence of a subsequent amplitude change. Critically, the Tone position × Group interaction was not significant, $F(1, 66) = 1.11$, $p = .297$, $\eta_p^2 = 0.016$. Bayesian analysis showed weak evidence against the inclusion of the interaction, $BF_{incl} = 0.77$, suggesting that the magnitude of the subsequent N250 amplitude increase did not differ reliably between the dyslexia and control groups. There was also no significant main effect of Group, $F(1, 66) = 3.78$, $p = .056$, $\eta_p^2 = 0.054$. Bayesian analysis revealed only weak and inconclusive evidence for the inclusion of Group, $BF_{incl} = 1.32$, indicating that the data do not provide clear support for a reliable difference in overall N250 amplitudes between groups.

Taken together, these results indicate that adaptation patterns in early AEP components did not differ reliably between children with

dyslexia and controls.

3.5. MMN

The waveforms of the deviant, standard (final tone), and the resulting MMN for each group are shown in Fig. 3 (see the top-left panel of Fig. 3a for electrode positions and the scalp topographies of MMN in Fig. S3a). As illustrated in Fig. 3, a clear MMN was elicited in both groups, and the waveforms appeared highly similar across children with dyslexia and controls. To statistically examine MMN mean amplitude, we conducted a mixed ANOVA with Deviance (standard vs. deviant) as a within-subject factor and Group (dyslexia vs. control) as a between-subject factor. The analysis revealed a significant main effect of Deviance, $F(1, 66) = 11.13$, $p = .001$, $\eta_p^2 = 0.144$, indicating that deviant

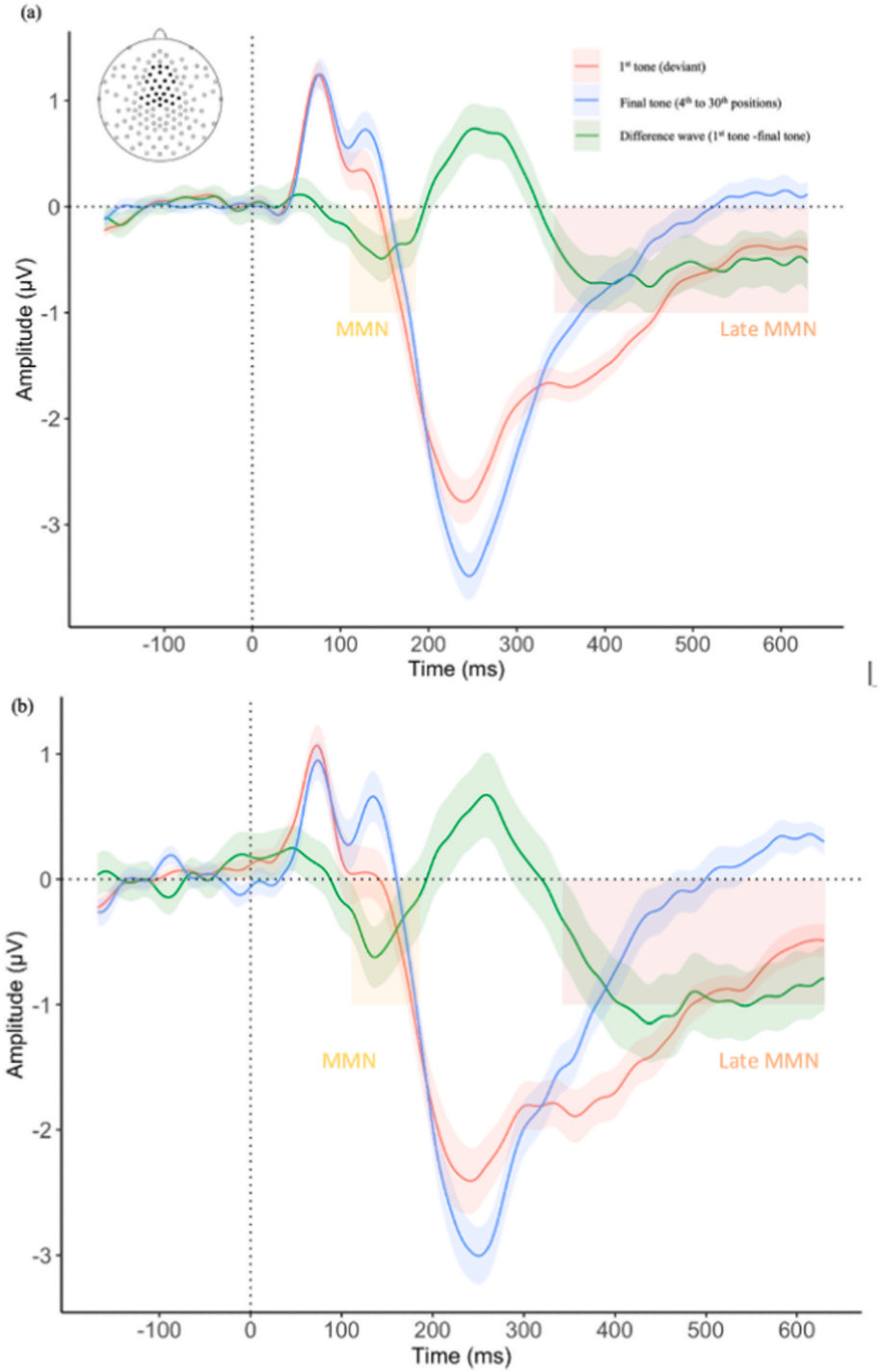


Fig. 3. Waveforms of deviants, standards from the 4th to the 30th tones and the difference wave associated with MMN in (a) the dyslexia group (N = 42) and (b) the control group (N = 26).

Note. Data were pooled from 25 fronto-central electrodes (marked by black dots at the top-left corner). The average difference wave (green) was computed by subtracting the amplitudes at the final position of each sequence of stimuli (4th–30th tone positions) from those of the deviants. Waveforms of deviants and the final tones are depicted in red and blue, respectively. Shaded ribbons indicate standard errors of the means (SEMs). The yellow-shaded region denotes the MMN time window (111–185 ms), while the pink-shaded region denotes the late MMN time window (343–631 ms).

tones elicited more negative responses than standards across participants. Bayesian analysis revealed strong evidence for the inclusion of Deviance, $BF_{incl} = 18.27$, corroborating the presence of a robust MMN effect. Critically, the Deviance × Group interaction was not significant, $F(1, 66) = 0.02$, $p = .878$, $\eta_p^2 < 0.001$, with moderate Bayesian evidence against the inclusion of the interaction, $BF_{incl} = 0.25$, suggesting no reliable evidence for group differences in MMN magnitude. There was also no significant main effect of Group, $F(1, 66) = 0.02$, $p = .886$, $\eta_p^2 < 0.001$, with moderate Bayesian evidence against the inclusion of Group, $BF_{incl} = 0.28$, suggesting comparable overall amplitudes across groups.

3.6. Late MMN

Fig. 3 shows the grand-average waveforms for the deviant, standard, and the resulting late MMN in the dyslexia and control groups. Corresponding scalp topographies are shown in Fig. S3b. Visual inspection of Fig. 3 indicated that late MMN responses were highly similar across groups, which was confirmed by the statistical analyses. The mixed ANOVA revealed a significant main effect of Deviance, $F(1, 66) = 37.76$, $p < .001$, $\eta_p^2 = 0.364$, indicating that deviant tones elicited more negative responses than standards across participants. Bayesian analysis showed extreme evidence for the inclusion of Deviance, $BF_{incl} = 481.91$, corroborating the presence of a robust late MMN effect. Notably, the Deviance × Group interaction was not significant, $F(1, 66) = 1.73$, $p = .193$, $\eta_p^2 = 0.026$, with moderate Bayesian evidence against the inclusion of the interaction, $BF_{incl} = 0.31$, suggesting that late MMN magnitude did not differ reliably between children with dyslexia and controls. There was also no main effect of Group, $F(1, 66) = 0.28$, $p = .601$, $\eta_p^2 = 0.004$, with weak-to-moderate Bayesian evidence against the inclusion of Group, $BF_{incl} = 0.33$, indicating comparable overall amplitudes across the dyslexia and control groups.

Taken together, these results indicate that MMN and late MMN responses were robustly elicited in both groups and did not differ reliably between groups.

3.7. Correlation analyses

Our main focus of the correlation analyses was on the relationship between reading ability and ERP measures, including initial and subsequent adaptation effects in the P1a, P1b, and N250 components, as well as MMN and late MMN measures. Reading ability was included as a continuous variable because continuous measures provide a more sensitive and accurate index of individual differences than categorical group classifications, as discussed above. The results of the Spearman correlations between all relevant variables across all children are presented in Table S2. Based on Holm–Bonferroni-corrected p-values (Holm, 1979), no significant correlations were found between reading ability and ERP measures, with Bayes factors again showing moderate evidence for the null to weak evidence for the alternative (*BF*s = 0.15–1.51).

3.8. Hierarchical regression analyses

Although the correlational analyses did not reveal significant associations between reading ability and ERP measures, we conducted hierarchical regression analyses to examine whether group or reading ability explained unique variance in ERP outcomes after controlling for theoretically relevant covariates, including age, musical training duration, and tone discrimination ability.

We conducted hierarchical regression analyses to examine whether group (dyslexia vs. control) predicts P1a initial adaptation, P1a subsequent adaptation, P1b initial adaptation, P1b subsequent adaptation, N250 initial adaptation, N250 subsequent adaptation, MMN, and late MMN amplitudes. These analyses were conducted in two steps. In the first step, we included age, musical training duration (in year), and tone discrimination ability (in *d'*) as predictors. In the second step, we added group, our main variable of interest. As shown in Table S3–S10, no significant effects of group were found (all $p > .066$). Bayesian linear regression revealed *BF* values ranging from 0.32 to 2.93, indicating that, in most cases, including P1a initial adaptation, P1a subsequent adaptation, P1b subsequent adaptation, N250 subsequent adaptation, and MMN, there was weak to moderate evidence in favor of the null hypothesis. No conclusive evidence was found for N250 initial adaptation and late MMN, while P1b initial adaptation was the only case showing weak evidence in favor of the alternative hypothesis.

The same analysis was conducted using reading ability instead of group, yielding largely similar results (see Table S11–S18). The only exception was an effect of reading ability on N250 initial adaptation amplitude (Fig. S4), which reached significance in the frequentist analysis, $p = .040$, but was associated with only weak evidence in the Bayesian linear regression, $BF = 2.07$. This pattern tentatively suggests that higher reading ability may be associated with a larger N250 initial adaptation effect, reflected in less negative amplitudes for the second tone relative to the deviant. However, given the weak Bayesian support, this finding should be interpreted cautiously. No other predictors were significant (all $p > .173$). Bayesian linear regression for the remaining ERP measures yielded BF values ranging from 0.26 to 1.31, indicating weak to moderate evidence in favor of the null hypothesis, while Bayesian evidence for P1b initial adaptation was inconclusive.

4. Discussion

Using a roving paradigm in which stimulus-driven expectations were tightly controlled, the present study aimed to examine (1) whether adaptation patterns differ between children with dyslexia and typically developing children, (2) whether MMN and late MMN responses differ between the two groups, and (3) whether potential group differences in neural adaptation contribute to differences in MMN responses. Overall, we observed minimal differences between children with dyslexia and controls in neural adaptation patterns, MMN, and late MMN responses. These conclusions were supported by both frequentist and Bayesian analyses. Specifically, Bayesian analyses provided weak to moderate evidence in favor of the null hypothesis for most adaptation and MMN measures, indicating limited support for reliable group differences. In a small number of cases, Bayes factors fell in the inconclusive range, and for P1b initial adaptation only weak evidence for a group difference was observed. Analyses using reading ability as a continuous predictor yielded a largely similar pattern, with Bayes factors indicating weak to moderate evidence for the null evidence across most neural adaptation and MMN measures. The largely comparable neural responses observed here contrast with previous studies reporting group differences in auditory adaptation or MMN in dyslexia (e.g., Baldeweg et al., 1999; Panahi et al., 2023; Peter et al., 2019). In the following sections, we discuss several potential explanations for these discrepancies.

4.1. Minimal differences in neural adaptation between groups

The minimal evidence for group differences in neural adaptation observed here contrasts with previous EEG studies that reported adaptation deficits in individuals with dyslexia using pure-tone paradigms (Panahi et al., 2023; Peter et al., 2019). These studies are particularly relevant, as they also examined neural adaptation strength using non-speech tones and electrophysiological measures. However, important methodological differences may contribute to the differing findings.

Both Peter et al. (2019) and Panahi et al. (2023) employed an auditory sensory-gating paradigm in which only a pair of tones was presented per trial, separated by long intertrial intervals (8 s in Panahi et al., 2023; two to 9 s in Peter et al., 2019). This design allows substantial recovery from neural adaptation. In contrast, the present study used a continuous roving-tone paradigm with relatively short intertrial intervals, which may limit full recovery from adaptation and instead emphasize short-term neural adaptation under stable temporal

conditions. As a result, although short-term adaptation is still present, this design may reduce overall adaptation magnitude and make group differences more difficult to detect. It therefore remains possible that longer recovery periods are required for adaptation differences between children with and without dyslexia to emerge, particularly in developmental populations.

Language background may also play an important role. Most previous studies on this topic have focused on alphabetic languages. For example, in an English-speaking context, Ozernov-Palchik et al. (2022) reported significant relationships between tone discrimination and phonological awareness in both adults and children, as well as between speech adaptation and phonological awareness in adults with dyslexia. Notably, adaptation deficits in dyslexia were observed for speech sound stimuli, but not for pure tone stimuli, and no reduced perceptual anchoring effect was found. More broadly, positive findings using the anchoring-tone paradigm have primarily been reported in Hebrew (Ahissar et al., 2006), whereas studies conducted in Dutch (Wijnen et al., 2012), French (Agus et al., 2014), and English (Gabay and Holt, 2018) have failed to replicate these effects. Consistent with this pattern, a systematic meta-analysis examining whether implicit learning deficits, including statistical learning, constitute a core cause of developmental dyslexia concluded that the evidence for domain-general implicit learning impairments is weak and inconclusive (West et al., 2021). Against this backdrop, the absence of group differences in neural adaptation, a proposed neural substrate for perceptual anchoring, is consistent with the predominance of null findings in the existing literature across languages.

Notably, this is the first related study conducted in Cantonese, a tonal language. Listeners, including those with dyslexia, may show relatively good tone discrimination due to extensive lifelong exposure to lexical tone. Consistent with this possibility, the present study did not provide clear evidence for group differences in tone discrimination. Moreover, reading in Chinese relies less on phonological awareness and more heavily on morphological awareness than reading in alphabetic languages (Shu et al., 2006). Together, these considerations raise the possibility that neural adaptation may be less sensitive to group differences in reading ability in tonal-language contexts, where alternative linguistic and cognitive mechanisms may play a more prominent role. Future studies directly comparing tonal and non-tonal language populations will be needed to evaluate this hypothesis.

4.2. Minimal differences in MMN and late MMN between groups

Our findings, which show minimal differences in MMN and late MMN between children with dyslexia and controls, diverge from previous studies using pure-tone stimuli in children (e.g., Hakvoort et al., 2015; Halliday et al., 2014; Lachmann et al., 2005; Shankarnarayan and Maruthy, 2007). However, our results align with findings from a subset of studies in children (e.g., Meng et al., 2005; Schulte-Körne et al., 1998; M. Sharma et al., 2006). A recent meta-analysis on MMN deficits in dyslexia found no significant MMN differences between children with and without dyslexia when non-speech stimuli were used (Gu and Bi, 2020; see also Hämäläinen et al., 2013; Schulte-Körne and Bruder, 2010 for reviews of active paradigms). This suggests that children with dyslexia do not exhibit impairments in non-speech auditory processing, including pure tones, although such deficits have been observed in adults with dyslexia. In contrast, speech-related auditory deficits were reported in both children and adults with dyslexia. These findings indicate that the underlying deficits in dyslexia in children are likely more closely related to speech processing. It is important to note that pure tones were the stimuli we used in the experiment. Therefore, we cannot exclude the possibility that MMN differences could be found with other stimuli or in other modalities. Future studies should include both pure tones and speech-based stimuli, such as consonant–vowel syllables, to better understand the relationship between MMN and reading ability.

It is worth noting that the meta-analysis by Gu and Bi (2020) mainly focused on studies employing oddball paradigms, whereas studies using a roving paradigm in children with dyslexia are scarce. Notably, a recent MEG study employing a roving paradigm with speech stimuli reported minimal differences in multivariate mismatch responses between adults with and without dyslexia, except for an observation that repetition progressively built a standard that diverged more significantly from a deviant in the control group (Beach et al., 2022b; see also Paul et al., 2006). Based on these results, Beach et al. (2022b) concluded that many neural mechanisms underlying adaptation and mismatch responses are preserved in dyslexia, although the predictive mechanism driving repetition effects on accuracy appears to function more efficiently in controls. Our findings, despite utilizing different methodologies (EEG with a univariate approach) and stimuli (pure tones), align with these results. Because our stimuli were specifically designed to reduce predictability by controlling expectation, children in both groups likely found it more challenging to form predictions about stimulus statistics. Moreover, unlike oddball paradigms in which standards remain constant, the roving paradigm continuously updates the standard, which may further increase unpredictability and reduce longer-term adaptation. This lack of predictability may explain why children with dyslexia and controls showed minimal differences in MMN and late MMN, as well as adaptation patterns.

Similar to what was discussed in the adaptation section above, language background may have influenced the MMN findings observed in the present study. The tonal nature of Chinese may facilitate sensitivity to pitch-based differences in both groups, potentially reducing group differences in MMN responses. This possibility is consistent with evidence showing that native experience with tonal languages enhances pitch representation acuity, as measured using pure tones (Giuliano et al., 2011). Moreover, Meng et al. (2005), who also studied Chinese children, reported no significant MMN differences between dyslexic and control groups. However, enhanced pitch acuity does not necessarily translate into advantages in phonological processing (Ramus et al., 2003). Together, these findings suggest that, in tonal language contexts, dyslexia-related differences in MMN responses to tone contrasts may be attenuated. However, because all participants were children with Chinese dyslexia and no non-tonal language control group was included, this interpretation remains speculative. Future studies including non-tonal language control groups will be required to directly test this account.

The relatively long SOA (650 ms) used in our experiment may also have contributed to the absence of MMN differences between the groups. As reviewed by Bishop (2007), most prior studies that reported MMN differences employed shorter SOAs of 500 ms or less. Shorter SOAs are advantageous because, at faster presentation rates, the MMN is more easily distinguished from other components (Picton et al., 2000b). Alternatively, it is possible that children with dyslexia require additional time to process auditory input. Faster presentation rates may impose a higher cognitive load, effectively revealing processing difficulties in this population (Tallal, 2004).

Additionally, the frequency differences between the stimuli could have influenced the results. A difference of 10% or less between standards and deviants has been suggested as optimal for detecting significant MMN differences between individuals with and without dyslexia (Bishop, 2007). In our experiment, the stimuli ranged from 500 Hz to 800 Hz, with the smallest frequency difference being 50 Hz. However, larger steps were also included. These relatively large frequency differences may have reduced the sensitivity of the paradigm to detect MMN differences, potentially contributing to the null findings.

4.3. Limitations and future directions

One limitation of the present study is that we focused on neural adaptation but did not directly assess perceptual anchoring at the behavioural level. Although the tone discrimination task confirmed that participants were able to differentiate tones with a 50-Hz frequency

difference, it did not provide a stable contextual reference or anchor across trials, as in paradigms specifically designed to probe perceptual anchoring (e.g., Jaffe-Dax et al., 2015; Ozernov-Palchik et al., 2022). As a result, the present design cannot determine how neural adaptation relates to listeners' ability to form and use perceptual anchors behaviourally. Future studies could combine the current EEG paradigm with a behavioural perceptual anchoring task to directly examine the relationship between neural adaptation, anchoring, and learning from statistical regularities.

The present study focused on the strength of short-term neural adaptation under tightly controlled stimulus expectations. Previous studies (e.g., Jaffe-Dax et al., 2017, 2018) examined adaptation mechanisms related to longer-term memory decay or anchoring effects across extended timescales, for example by using inter-trial intervals of up to 9 s. Accordingly, the current design does not directly address these longer-timescale adaptation processes. Moreover, unlike paradigms that allow regularities to be learned or updated over time, the present roving paradigm used fixed probabilities and constant timing, thereby minimizing demands on statistical learning and expectation updating. Thus, the present paradigm primarily probes short-term, stimulus-driven neural adaptation under stable expectations, rather than longer-term statistical learning or memory decay processes.

Another limitation of the present study is that the sample sizes were unequal between groups, with more children with dyslexia than typically developing controls due to practical constraints in recruiting participants. Importantly, all analyses were conducted using statistical approaches that are robust to unequal group sizes, and retaining all available data maximised statistical power without biasing the results.

Finally, while the present study focused on group differences in neural adaptation and MMN responses and their relation to reading ability, a detailed dissociation between adaptation-based and prediction-based contributions to the MMN was not the primary focus of the current study. Using the same paradigm in adults, we previously showed that, consistent with predictive coding accounts, the MMN reflects the combined contribution of early sensory adaptation indexed by the N1 and a later model-updating process indexed by the P2 (Wong et al., 2024). In the present study, the largely comparable adaptation and MMN responses observed across groups suggest that, within this paradigm, adaptation-related contributions to the MMN are similar in children with and without dyslexia. Consistent with this interpretation, correlations indicate that several adaptation measures (P1b initial adaptation, P1b subsequent adaptation, and N250 subsequent adaptation) are related to MMN amplitude (Table S2). A more targeted investigation of the relative contributions of adaptation and model updating to MMN in development would require additional experimental manipulations and is therefore beyond the scope of the present study.

5. Conclusion

To conclude, we found minimal evidence for differences in neural adaptation, MMN, and late MMN responses between children with and without dyslexia, as well as across reading abilities, within a roving paradigm. Although these findings largely reflect null effects, they are theoretically informative. Specifically, they constrain adaptation-based accounts of implicit learning deficits in dyslexia by showing that differences in neural adaptation and MMN are not obligatory and may depend on task structure, stimulus expectations, and language background. Together, these findings suggest that dyslexia is not characterized by a neural adaptation deficit per se, but that group differences in neural adaptation and MMN may emerge only under specific conditions, such as when paradigms place greater demands on expectation formation or statistical learning. By demonstrating largely comparable neural responses under tightly controlled conditions, the present study helps refine theories of auditory processing in dyslexia and provides a useful benchmark for future work and meta-analytic synthesis.

CRediT authorship contribution statement

Brian W.L. Wong: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Lucas Yiu Hei Chan:** Writing – review & editing, Investigation. **Shuting Huo:** Writing – review & editing. **Urs Maurer:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization.

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Glossary

ANOVA	analysis of variance
DV	dependent variable
EEG	electroencephalogram
ERP	event-related potential
GFP	global field power
ICA	independent component analysis
ISI	inter-stimulus interval
MANOVA	multivariate analysis of variance
MMN	mismatch negativity
p-AUC	partial area under the curve
RMS	root mean square
SEM	standard error of the means
SOA	stimulus-onset asynchrony
TANOVA	topographic analysis of variance

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2026.109445.

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