Perceptual anchoring: Children with dyslexia benefit less than controls from contextual repetitions in speech processing

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HIGHLIGHTS

- School children with and without dyslexia listened to syllable pairs in repeating anchor and variable no-anchor conditions.
- Neural correlates show earlier adaptation effects from syllable repetition for control than dyslexia group.
- Neural correlates suggest less facilitated speech processing from contextual repetitions in children with dyslexia than controls.

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ABSTRACT

Objectives: Individuals with dyslexia perceive and utilize statistical features in the auditory input deficiently. The present study investigates whether affected children also benefit less from repeating context tones as perceptual anchors for subsequent speech processing.
Methods: In an event-related potential study, eleven-year-old children with dyslexia ($n = 21$) and without dyslexia ($n = 20$) heard syllable pairs, with the first syllable either receiving a constant pitch (anchor) or variable pitch (no-anchor), while second syllables were identical across conditions.
Results: Children with and without dyslexia showed smaller auditory P2 responses to constant-pitch versus variable-pitch first syllables, while only control children additionally showed smaller N1 and faster P1 responses. This suggests less automatic processing of anchor repetitions in dyslexia. For the second syllables, both groups showed faster P2 responses following anchor than no-anchor first syllables, but only controls additionally showed smaller P2 responses.
Conclusions: Children with and without dyslexia show differences in anchor effects. While both groups seem to allocate less attention to speech stimuli after contextual repetitions, children with dyslexia display less facilitation in speech processing from acoustic anchors.
Significance: Altered anchoring in the linguistic domain may contribute to the difficulties of individuals with dyslexia in establishing long-term representations of speech.

1. Introduction

Developmental dyslexia is a neurodevelopmental disorder characterized by difficulties in the acquisition of written language. Affected individuals experience problems in accurate or fluent reading and/or correct spelling (Diagnostic and statistical manual of mental disorders: DSM-5, 2013). These problems occur despite the absence of cognitive problems or other general learning difficulties (DSM-5, 2013). The most widely held explanation implicates phonological deficits as the causal factor for the difficulties observed in dyslexia (Ramus, 2003; Snowling, 2001; for a review, see Vellutino et al., 2004). This proposal holds that atypical reading and/or spelling of individuals with dyslexia result from their problems in storing, retrieving, and manipulating phonological information (Snowling, 1998, 2001; Vellutino et al., 2004).

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Alternatively, a broader perceptual processing deficit may precede and partially explain the phonological deficits observed in dyslexia. This hypothesis is based on growing evidence of impaired performance in several psychoacoustic tasks in individuals with dyslexia, such as frequency discrimination (Banai and Ahissar, 2004; Mengler et al., 2005; Witton et al., 2020), processing of fast temporal information (Hari and Renvall, 2001; Tallal, 1980, 1984), speech-perception in noise (Sperling et al., 2005; Ziegler et al., 2009), and tracking of amplitude modulations in speech (Goswami, 2011).

One prominent alternative proposal postulates that phonological deficits are partially based on a perceptual anchoring deficit in dyslexia, which means that deficient speech perception in dyslexia might surface as a difficulty in adapting to repeated information in the acoustic context (Ahissar et al., 2006; Chandrasekaran et al., 2009; Jaffe-Dax et al., 2015). Stimuli repetitions are one of the many available contextual cues on which listeners can rely during speech perception (Braida et al., 1984). Specifically, listeners automatically adapt their perceptual strategy in processing upcoming stimuli by forming mental 'anchors' or perceptual representations from regularities in the context (Ahissar, 2007). The processing of subsequent stimuli in the context of these anchors typically yields behavioral advantages. In their seminal study, Ahissar and colleagues (2006) reported that healthy adults significantly improved in their discrimination of two tones, when one of the tones was presented with a constant pitch across all tone pairs. No such improvement in discrimination performance was observed for adults and adolescents with dyslexia (Ahissar et al., 2006; Banai and Ahissar, 2006; Jaffe-Dax et al., 2015), suggesting a deficit in forming and utilizing perceptual representation from repeated information in the listening context (Banai and Ahissar, 2010b). Follow-up studies further support the notion that this 'anchoring deficit' is specific to individuals with written-language disorders and not driven by more general attentional difficulties that often co-occur with dyslexia, such as attention deficit disorders (Lieder et al., 2019; Oganian and Ahissar, 2012). Other evidence, however, indicates that individuals with dyslexia show perceptual problems specifically in combination with low attention skills (Willburger and Landerl, 2010).

The exact pathways in which perceptual anchoring deficits relate to difficulties in reading and spelling in individuals with dyslexia are not fully understood. One possibility is that perceptual anchoring may play a role in acquiring skills relevant for reading and spelling that need to be in place prior to the onset of formal written-language acquisition, such as phonological awareness or alphabetic knowledge (for discussion, see Banai and Ahissar, 2010a, 2017). Children learn from their linguistic environments and are supported by their sensitivity to and extraction of statistical regularities from the continuous sensory input that they are exposed to (Kidd, 2012; Kuhl, 2004; Männel and Friederici, 2013; Romberg and Saffran, 2010; Saffran et al., 1996). Thus, perceptual anchoring can be viewed as a domain-general statistical learning tool that allows children to tune in, extract, and form representations of phonological information relevant for reading and spelling across development (Arciuli, 2018; Banai and Ahissar, 2017).

The limited research on the developmental trajectory of perceptual anchoring provides some evidence of perceptual anchoring in preschool children (Banai and Yifat, 2011, 2012). A first study reported perceptual anchoring benefits in tone discrimination for 4- to 6-year-old children. These benefits resembled the behavioral effects reported for adults, yet with much more individual variability, not attesting an anchoring effect for each individual child (Banai and Yifat, 2011). In a second study, Banai and Yifat (2012) observed a positive correlation between perceptual anchoring in preschoolers and their phonological awareness (i.e., phoneme

identification at word-initial and word-final position). These studies support the idea that perceptual anchoring is a processing mechanism present throughout development and may underly the acquisition of skills relevant for reading and spelling (i.e., phonological awareness). There is more direct evidence for this proposal from a recent behavioral study, showing that children and adults with dyslexia experience reduced adaptation from repeated information in phonological categorization (Ozernov-Palchik et al., 2022).

Neuroimaging studies provide initial evidence to develop hypotheses on the neural correlates of perceptual anchoring in individuals with dyslexia. Functional magnetic-resonance-imaging (fMRI) and electroencephalography (EEG) studies report deficient neural adaptation to stimulus repetition (e.g., Chandrasekaran et al., 2009; Jaffe-Dax et al., 2017; Perrachione et al., 2016; Peter et al., 2019), suggesting less successful formation of stable short-term perceptual representations from repeated visual and acoustic information in adults with dyslexia. For children with dyslexia, a study by Chandrasekaran et al. (2009) reported an impaired adaption of brainstem responses to repeated, predictable speech stimuli in children with poor reading skills compared to children with typical reading skills. Adults with dyslexia were also shown to exhibit reduced gamma-band neural synchronization in the EEG to auditory stimuli (Lehongre et al., 2011) that is typically induced by neural adaptation (Hansen and Dragoi, 2011). Moreover, when adults were tested in an event-related potential (ERP) study on an auditory gating paradigm with tone pairs, only control participants but not those with dyslexia showed attenuated N1 responses to repeated tones indicating neural adaptation (Peter et al., 2019). Less efficient build-up of stable short-term neural representations from repeated input information in individuals with dyslexia leads to difficulties in employing such representations in the processing of subsequent stimuli. First evidence of electrophysiological indicators of perceptual anchoring from contextual repetitions comes from a tone-discrimination study in adults (Nahum et al., 2010). While this study focused on decision-driven ERP responses related to the discrimination task, early auditory ERP responses, especially the P2, also showed modulations depending on whether perceptual anchoring was supplied. Thus, in addition to behavioral effects demonstrating an impact of perceptual anchoring on stimulus discrimination and classification, the ERP technique provides insights into the underlying neural adaptation processes. Specifically, ERPs are informative of both sensory adaptation from anchor repetitions as well as modulated stimulus processing as a consequence of perceptual anchoring (i.e., P1, N1, and P2; see, e.g., Eggermont and Ponton, 2003; Sharma et al., 1997).

Taken together, the majority of behavioral and neuroimaging studies on perceptual anchoring has been conducted in adults, while developmental studies targeting perceptual anchoring in developmental dyslexia are lacking. This contrasts the proposal that deficient speech perception in dyslexia might result from difficulties in adapting to repeated information in the acoustic context (Ahissar et al., 2006; Chandrasekaran et al., 2009; Jaffe-Dax et al., 2015). Given that dyslexia is a neurodevelopmental disorder, alterations in perceptual anchoring during speech processing need to be investigated during development. To fill this gap, we adapted the pure-tone discrimination task of perceptual anchoring used in adults (Ahissar et al., 2006) to a passive-listening ERP experiment with syllabic stimuli and examined the auditory ERPs of children with and without dyslexia. Following the evidence reviewed above, we hypothesized that children with dyslexia show less pronounced perceptual adaptations to anchor repetitions. As a consequence, we expected diminished or no effects of perceptual anchoring on speech processing. To allow for subsequent assessment in younger

individuals, amplitude modulations of the ERP components P1, N1, and P2 were used as markers for alterations in neural processing of perceptual anchor effects.

2. Materials and methods

2.1. Participants

All children participating in the current study had previously taken part in the LEGASCREEN Consortium Project (see, e.g., Kraft et al., 2016; Neef, Muller, et al., 2017; Neef, Schaadt, et al., 2017), were monolingual German and recruited from the database of the Max Planck Institute for Human Cognitive and Brain Sciences, Germany. In the course of this project, all children had undergone reading and spelling screening at the age of 9.5 years and nonverbal IQ testing at the age of 5 years. At the age of around 11 years, 44 of these children (n = 23 children with dyslexia and n = 21 children without dyslexia) participated in the present ERP study. Note that the initially planned sample size calculated with n = 30 per participant group (see previous familiarization-test paradigms with younger children; Männel and Friederici, 2013; Paul et al., 2021) was not met, because of COVID-19 testing restrictions.

Children's assignment to the group with or without dyslexia, was based on their performance in the standardized German spelling test (Deutscher Rechtschreibtest; DERET; Stock and Schneider, 2008), tested at the age of 9.5 years within the LEGASCREEN project. Given the transparency of the German language (Landerl et al., 1997), spelling was used as criterion for dyslexia (see also Neuhoff et al., 2012), because spelling deficits are more characteristic for German dyslexic populations than deficient reading accuracy or speed (Wimmer, 1996).

In the spelling test DERET (Stock and Schneider, 2008), children were dictated sentences and asked to write them down, applying German phoneme-grapheme conversion rules; without any time limit per sentence. Grade-normed percentile ranks (PRs) were calculated for children's spelling accuracy (i.e., number of correctly spelled words). According to the DERET norms, children were classified with an (above-)average performance by a PR > 26 and below-average performance by a PR < 25 (Stock and Schneider, 2008). From the initial participant sample, we excluded one lower performing typical speller (PR = 27) and the two highest performing poor spellers (PR = 24), thus ensuring a minimum difference between the two groups of 11 points on the PR scale. Our final participant sample (n = 41) consisted of a group of 21 children with dyslexia (poor-spellers; DERET PR range of 1–20) and 20 typically developing children (typical spellers; DERET PR range of 31–82; see Table 1).

Furthermore, our assignment of children to the dyslexia/without-dyslexia groups was verified by children's reading comprehension performance. This was assessed with the German Reading Comprehension Test for 1–6 graders (Ein Leseverständnistest für Erst- bis Sechstklässler, ELFE 1–6; Lenhard and Schneider, 2006), tested at the age of 9.5 years within the LEGASCREEN project. This reading test comprises three subtests to evaluate word, sentence, and text comprehension. The number of correct responses was transformed to grade-normed PRs for school children. Confirming our group assignment, reading comprehension scores for the group of children with dyslexia were significantly lower compared to typically developing children (see Table 1).

To control for children's nonverbal intelligence, we used their performance in the German version of the Wechsler Preschool and Primary Scale of Intelligence (version III) (Wechsler, 2009), tested at the age of 5 years within the LEGASCREEN project. Performance was translated into age-normed standard scores (M = 100, SD = 15), and all children had scores $\geq$ 85, with no statistically sig-

nificant difference between groups (see Table 1). Participating children had no history of an attention deficit disorder or other cognitive deficits.

As can be seen from Table 1, there was a higher proportion of male than female participants in the group with dyslexia, which reflects the prevalence of this disorder in the male over female population. Note, however, that chi^2 statistics did not reveal any statistically significant differences in the distribution of sex between groups. In addition, three of the children with dyslexia were left-handed, while only one child without dyslexia was left-handed, yet again with no statistically significant differences in the handedness distribution between groups (Table 1). Apart from the group assignment, all participants were healthy, and parents confirmed the lack of hearing deficits or neurological problems for their children.

The study was approved by the ethics committee of the University of Leipzig (protocol number: 082/15-ek) and carried out in accordance with the American Psychological Association research standards (Declaration of Helsinki, 1994; World Medical Organization, 2013). Parental written consent was obtained after children and parents were informed in detail about the procedure and agreed to participation. Parents were reimbursed for their travel expenses by 7.50 € and children could pick a small toy as present, in appreciation of their participation.

2.2. Stimuli and paradigm

Children listened to syllables in a familiarization-test paradigm, while their EEG was recorded. They were presented with interleaved familiarization and test phases, yet for the purpose of the current study, we focused on the ERP analysis of anchor and no-anchor blocks in the familiarization phases to explore children's processing of stimulus repetition and the effect of constant versus variable acoustic context on the processing of subsequent speech stimuli (i.e., perceptual anchoring).

Familiarization phases consisted of four syllable pairs in either anchor or no-anchor blocks. For this, eight single instances of syllables were recorded by a female German native speaker with a 16-bit sampling rate and digitized at 44.1 kHz (see Table 2) and digitally synthesized. We engaged a female speaker for the stimulus recordings to parallel previous studies on speech processing in dyslexia (e.g., Banai and Ahissar, 2006; Christmann et al., 2015; Goswami et al., 2021; Schaadt et al., 2016). The eight recorded syllables were combined into four acoustically different syllable pairs, with their pitch (i.e., F0) manipulated to yield a constant pitch (anchor) condition and a variable pitch (no-anchor) condition. Thus, anchor and no-anchor conditions only differed in the pitch marking of the first syllables, but consisted of the same syllable pairs across conditions. Specifically, in the anchor condition, the first syllable had a constant repeated pitch across all trials (i.e., 279 Hz), whereas in the no-anchor condition the pitch of the first syllable varied across trials (i.e., 169 – 460 Hz). The frequency range of 169–460 Hz was chosen to cover speech-input relevant pitch modulations (Fernald et al., 1989). In contrast to the adaptive stimulus procedures of previous behavioral studies (e.g., Ahissar et al., 2006; Banai and Ahissar, 2006; Jaffe-Dax et al., 2015), we used a fixed number of pitch values (i.e., 169 Hz, 217 Hz, 246 Hz, 279 Hz, 316 Hz, 358 Hz, 460 Hz) with constant log(Hz)-frequency changes (see Table 2), keeping the perceptual discrimination difficulty constant across anchor and no-anchor pairs (see Fletcher and Munson, 1933).

Importantly, the second syllables were identical and had the same pitch across anchor and no-anchor conditions, thus allowing for the comparison of ERP responses to identical second syllables when preceded by first syllables with either a constant or variable pitch. The direction and magnitude of the frequency changes

Table 1
Demographic and literacy variables of children without and with dyslexia.

	Without dyslexia	With dyslexia	t-/ chi²-value	p-value
N	20	21		
Sex (male: female)	11: 9	15: 6	1.19	0.275
Age (years) at the present study	11.18 (1.17)	11.05 (1.13)	0.35	0.725
Non-verbal IQ [a] (SSc)	101.30 (10.50)	101.10 (12.44)	0.41	0.680
Spelling[b]	54.90 (14.38)	8.57 (5.61)	13.46	**< 0.001**
Spelling from dictation (PR)				
Reading[b]	74.08 (16.79)	16.15 (12.21)	12.57	**< 0.001**
Text reading comprehension (PR)				
Handedness (right: left)	19: 1	17: 3	1.00	0.317

Number in parenthesis = standard deviations (SD).
SSc = Standard scores (*Mean* = 100, *SD* = 15); PR = percentile rank.
[a] at 5 years old.
[b] at 9.5 years old.

Table 2
Syllable pitch manipulation for the anchor and no-anchor conditions of the familiarization phase.

Anchor Condition			No-anchor Condition		
First Syllable	Second Syllable	Freq Change	First Syllable	Second Syllable	Freq Change
bi: **(279 Hz)**	bɛ (217 Hz)	– – 0.77	bi: (460 Hz)	bɛ (217 Hz)	– – 0.77
bœ **(279 Hz)**	bɪ (246 Hz)	– 0.88	bœ (358 Hz)	bɪ (246 Hz)	– 0.88
bu: **(279 Hz)**	bɑ (316 Hz)	+ 1.13	bu: (217 Hz)	bɑ (316 Hz)	+ 1.13
bø **(279 Hz)**	bɔ (358 Hz)	+ + 1.28	bø (169 Hz)	bɔ (358 Hz)	+ + 1.28

Note. Freq Change = Direction and magnitude of log(Hz)-frequency changes, given as frequency ratio f_2/f_1.

between first and second syllables were identical between conditions (see Table 2). Yet, to control for possible effects of magnitude and direction of frequency changes between first and second syllables on the ERP responses, we created two further versions (counter-balanced across participants) of different pitch assignments to particular syllable pairs, such that a previously large pitch increase was exchanged with a small pitch decrease and a previously small pitch increase was exchanged with a large pitch decrease.

All syllables consisted of the same bilabial stop /b/ followed by a variation of 12 possible vowels that are categorically different in the German vowel space (Table 2). Stimuli length was set to 200 ms (short-vowel syllables) and 350 ms (long-vowel syllables), plus an additional 50 ms silence period before syllable onset and after syllable offset. Auditory stimuli were adjusted using Praat Version 6.0.28 (Boersma, 2001). All syllables were normalized to an average intensity of 70 dB sound-pressure level.

2.3. Procedure

Each experimental session consisted of two anchor blocks and two no-anchor blocks presented in an alternating manner (see Fig. 1A). The order of presentation, either starting with an anchor or a no-anchor block was counterbalanced across participants. Each of the four syllable pairs was repeated ten times within one block, resulting in a total of 40 trials per block and 20 repetitions of each syllable pair across the whole session.

The first syllable was auditorily presented with a stimulus onset asynchrony (SOA) of 700 ms, followed by the second syllable (see Fig. 1B). Between trials, there was a varying inter-trial-interval (ITI) of 1650–1750 ms (differing in 25 ms-steps). The presentation order of syllable pairs for anchor and no-anchor conditions, as well as ITIs were pseudo-randomized such that the same syllable or ITI would not be presented more than twice in a row.

2.4. EEG recordings and analysis

Children sat in a sound-proof chamber, on a chair located at a distance of 80 cm from a screen, with two loudspeakers located on each side of the screen. The acoustic stimuli were presented free-field at 70 dB (for similar presentation procedures in developmental studies on auditory processing, see Campos et al., 2023; Linnavalli et al., 2017; Ruhnau et al., 2013; Telkemeyer et al., 2011), while children's EEG was recorded. To minimize movement artifacts in the EEG recording and keep children engaged during the passive-listening paradigm, they were shown a children's cartoon without sound and not time-locked to the auditory stimuli on the screen during the entire experiment. As documented in the session protocols from online video monitoring, this implied that children were sitting facing the loudspeakers and focused their eyes on the screen positioned between the speakers, without any coarse movements or turns.

The EEG was recorded with Qrefa Acquisition Software, Version 1.0 beta (Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany) from 21 Ag/AgCl electrodes (F7/8, F3/4, Fz, FC3/4, T7/8, C3/4, Cz, CP5/6, P7/8, P3/4, Pz, O1/2) placed according to the International 10–20 System of Electrode Placement and secured in an elastic electrode cap (Easycap GmbH, Germany). Cz was used as online reference during recording, and an electrode positioned at FP1 as ground. Electrooculograms (EOG) were recorded laterally to the left and right eye, and supraorbitally and infraorbitally to the right eye. The EEG signal was amplified using a REFA system (Twente Medical Systems, The Netherlands) and digitized online at a rate of 500 Hz. Electrode impedances were kept below 5 kΩ in most cases (at least below 10 kΩ).

The EEG data was processed using EEGLAB software (Delorme and Makeig, 2004) and custom-written scripts in MATLAB version R2017 (The Math Works, 2017). EEG recordings were first algebraically re-referenced from Cz to the average of both mastoids

A Alternating Condition Block Design

Anchor Block	No Anchor Block	Anchor Block	No Anchor Block
CONSTANT PITCH Syllable Pairs (40)	VARIABLE PITCH Syllable Pairs (40)	CONSTANT PITCH Syllable Pairs (40)	VARIABLE PITCH Syllable Pairs (40)

B Trial Structure

Anchor Condition

Trial 1

First Syllable [constant pitch] — Second Syllable [variable pitch]

SOA: 700ms   ITI: 1650-1750ms   Trial 2...

No Anchor Condition

Trial 1

First Syllable [variable pitch] — Second Syllable [variable pitch]

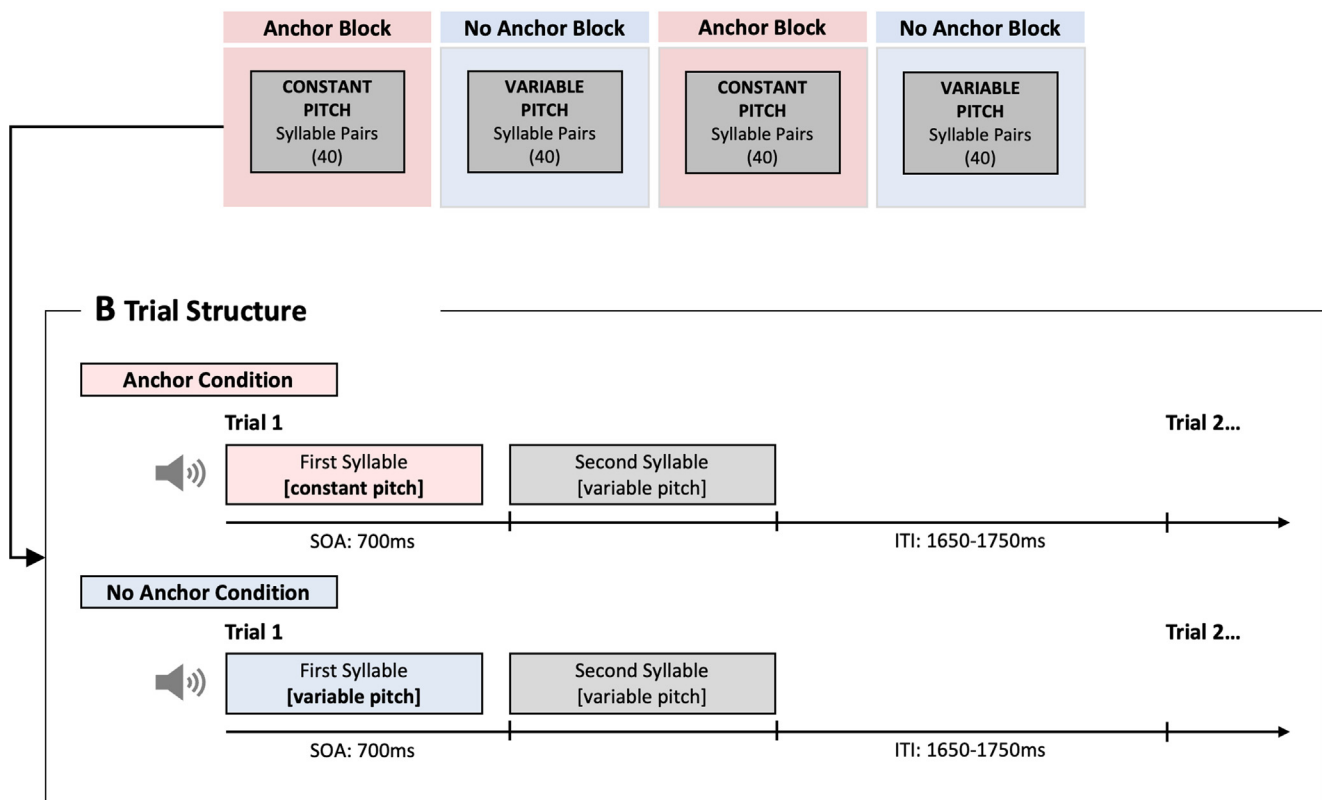SOA: 700ms   ITI: 1650-1750ms   Trial 2...

Fig. 1. Experimental design of the familiarization phase. (A) Alternating block design with two anchor and two no-anchor blocks (order counterbalanced across participants). (B) Trial structure. In the anchor condition, the first syllable of the pair has a constant, repeated pitch across trials; whereas in the no-anchor condition the first syllable has a variable pitch across trials, the variable pitch of the second syllables is identical between anchor and no-anchor conditions. SOA = stimulus onset asynchrony; ITI = inter-trial interval.

(M1/2). In preparation of an independent component analysis (ICA; Makeig et al., 1996) as artifact-correction method, two separately filtered data sets were generated from each EEG file. The first data set, intended for the final ERP analysis, was filtered with a band-pass filter of 0.5–30 Hz with a half-amplitude cutoff (−6dB) and a transition width of 5 Hz, including a lower high-pass filter allowing for more EEG data to remain in the analysis set. A second dataset was filtered with a band-pass filter of 1–30 Hz with a half-amplitude cutoff (−6dB) and a transition width of 5 Hz for the purpose of ICA-based artifact correction only, as stronger high-pass filters have been shown to render signal decomposition to be more effective (e.g., Winkler et al., 2015). These data filtered at 1–30 Hz were divided into epochs of 1000 ms and automatically screened for abnormal EEG values exceeding +/-100 µV in any of the EEG and EOG channels and for signal drifts that exceeded 100 µV. Among the resulting artifact-marked epochs, those with eye artifacts were retained for further eye-movement correction via ICA. For the ICA, individual EEG data were decomposed into single independent components and manually evaluated for representing eye-blink or heartbeat artifacts and accordingly removed. The ICA weight matrix and sphering matrix was then transferred to the other, 0.5 Hz high-passed filtered continuous dataset for each participant. The resulting ICA-corrected EEG datasets were segmented into epochs of 500 ms relative to syllable onsets and averaged for each electrode for the final analysis.

Because of the short SOA no baseline correction was employed, as the preceding evoked potential would distort the analysis of interest. Instead, we applied a band-pass filter with a steep filter function as has been suggested a methodologically valid alternative to baseline correction (Maess et al., 2016; Widmann et al., 2015).

As our focus was on the analysis of the auditory ERP components P1, N1, and P2, we determined time-windows (TWs) of interest by computing grand-average ERPs across conditions (i.e., anchor, no-anchor), groups (i.e., children with and without dyslexia), and 15 electrodes (i.e., Fz, F3/4, F7/8, FC3/4, Cz, C3/4, CP5/6, Pz, P3/4), leaving out the 6 most lateral temporo-occipital electrode positions (i.e., T7/8, P7/8, and O1/2). The resulting averaged data reflect the auditory ERP response to syllable processing in the current experiment, regardless of the type of condition, group assignment, or electrode position (i.e., collapsed localizer technique). However, as amplitude and timing of auditory ERPs are different depending on the presentation of single stimuli or stimulus pairs (for a review, see e.g., Hartkopf et al., 2019), we calculated separate averages for the ERPs to first and second syllables. As can be seen from Fig. 2, on the basis of these averages, TWs relative to the peaks of the ERPs of interest, namely P1, N1 and P2 could be determined: For the first syllable, average P1 peak ± 20 ms (70–110 ms), average N1 peak ± 20 ms (110–150 ms), and average P2 peak ± 30 ms (150–210 ms); for the second syllable, average P1 peak ± 10 ms (90–110 ms), average N1 peak ± 10 ms (125–145 ms), and average P2 peak ± 25 ms (150–200 ms).

2.5. Statistical analysis

Statistical analyses were performed using R Statistical Software, Version 3.5.2 (R Core Team, 2019) using R Studio, Version 1.1.463. Mean amplitude differences and peak-latency differences between
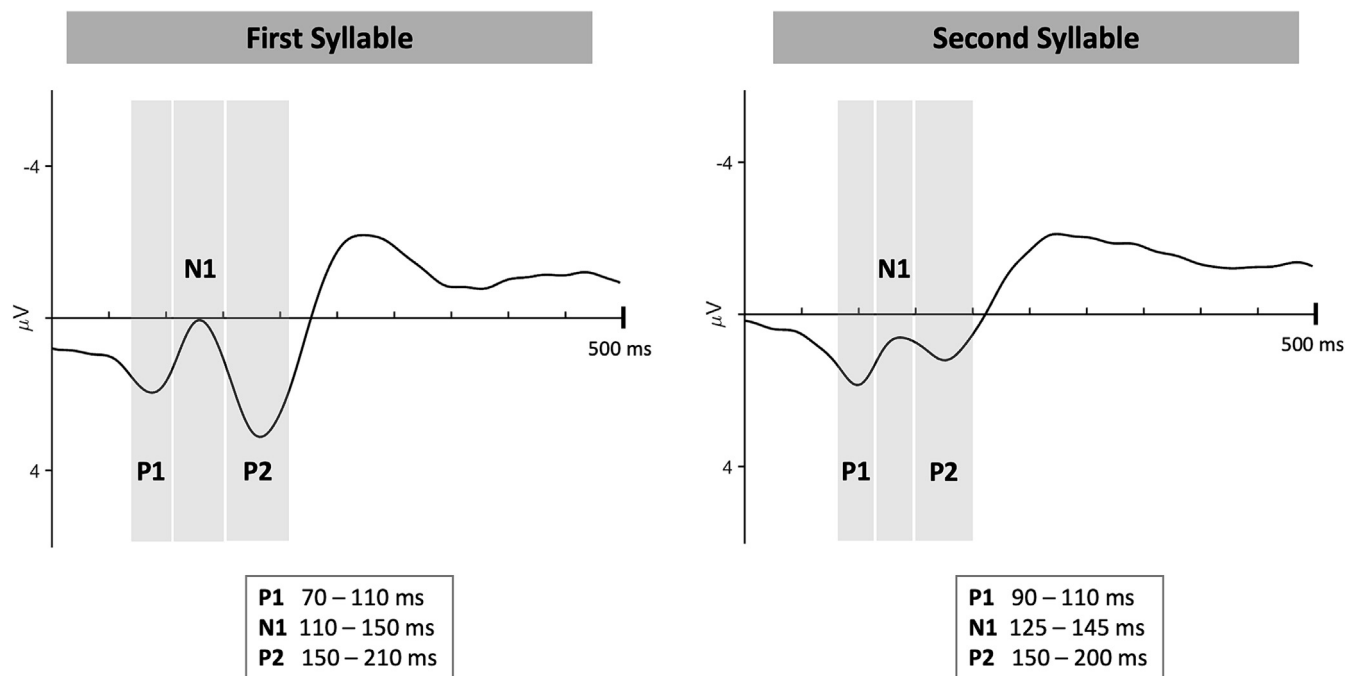
First Syllable

Second Syllable

P1	70 – 110 ms
N1	110 – 150 ms
P2	150 – 210 ms

P1	90 – 110 ms
N1	125 – 145 ms
P2	150 – 200 ms

Fig. 2. Grand-average event-related potentials (ERPs) calculated across participants (i.e., all children with and without dyslexia), across conditions (i.e., anchor and no-anchor), and across electrodes, but separately for the first and second syllables. Three time-windows of interest were determined for the studied ERP components (i.e., P1, N1, and P2).

anchor and no-anchor conditions were analyzed using mixed-model repeated-measures analysis of variance (rm-ANOVAs), separately for the first and second syllables of the syllable-pairs for each TW of interest. For statistical analyses, the following electrode regions of interest (ROI) were defined (leaving out the 6 most lateral temporo-occipital positions, T7/8, P7/8, and O1/2 (see previous studies evaluating auditory-evoked potentials in children; e.g., Sussman et al., 2008; Wunderlich et al., 2006): A frontal ROI (FR) including electrodes F7/8, F3/4, and Fz; a central ROI (CR) including electrodes FC3/4, C3/4, and Cz; and a posterior ROI (PR) including electrodes CP5/6, P3/4, and Pz (see Figs. 3 and 4).

Three-way rm-ANOVAs, one for each TW of interest and separately for mean-amplitude and peak-latency values, included the within-subject factors Condition (anchor, no-anchor) and ROI (frontal, central, posterior) and the between-subjects factor Group (without dyslexia, with dyslexia). All effects (Greenhouse-Geisser-corrected) involving the factor Condition are reported; and main effects or interactions with the factor Condition were further analyzed using one-sample t-tests (Bonferroni-corrected), if they reached statistical significance (p < 0.050) or a trend for statistical significance (between p > 0.050 and p < 0.060). For effect sizes η_p^2 is given ($\frac{sum\,of\,squares\,effect}{sum\,of\,squares\,effect + sum\,of\,squares\,error}$).

3. Results

3.1. First syllables

The rm-ANOVA for the first syllable testing the effect of repetition by contrasting the ERP responses to anchor syllables (constant pitch) and no-anchor syllables (variable pitch) did not reveal any statistically significant amplitude differences in the P1-TW (70–110 ms) (Table 3). Yet, the latency analysis revealed a significant interaction of Condition x Group x Region (Table 4), with post-hoc analyses showing that children without dyslexia, but not with dyslexia, showed a significantly shorter P1 peak latency in the anchor compared to the no-anchor condition at central electrodes.

In the N1-TW (110–150 ms), the amplitude analysis revealed a significant Condition x Group interaction (see Table 3). Post-hoc analyses showed that children without dyslexia, but not with dyslexia, displayed a significantly smaller N1 amplitude in the anchor condition than the no-anchor condition (i.e., repetition effect, Table 3, Fig. 3). For the latency analysis, there was a significant Condition x Group interaction, but post-hoc analyses did not reveal significant N1 latency differences between conditions for either group (Table 4).

For the P2-TW (150–210 ms), the amplitude analysis revealed a significant Condition x Region interaction, with post-hoc analyses showing that the condition difference of significantly smaller P2 responses to anchor compared to no-anchor syllables was present at the frontal ROI, with a statistical trend at the central ROI (across children groups; Table 3, Fig. 3). The latency analysis for this TW did not reveal any statistically significant P2 latency differences between conditions (Table 4).

3.2. Second syllables

The rm-ANOVA for the second syllables testing for the effect of anchoring, that is, syllable processing in the context of preceding constant-pitch or variable-pitch syllables, did not reveal any statistically significant condition effects of mean-amplitude values for the P1-TW (90–110 ms) nor the N1-TW (125–145 ms) (Table 5, Fig. 4). The latency analysis, however, revealed a statistical trend for an interaction of Condition x Group x Region in the P1-TW, with post-hoc analyses showing a statistical trend for a shorter P1 latency at the posterior ROI for children without dyslexia, but not with dyslexia, when the second syllable followed an anchor versus a no-anchor syllable (Table 6, Fig. 4).

For the P2-TW (110–150 ms), the amplitude analysis revealed a significant Condition x Group x Region interaction (Table 5). Post-hoc analyses demonstrated group differences between children with and without dyslexia, in that only children without dyslexia showed a significantly smaller ERP response at the posterior ROI,
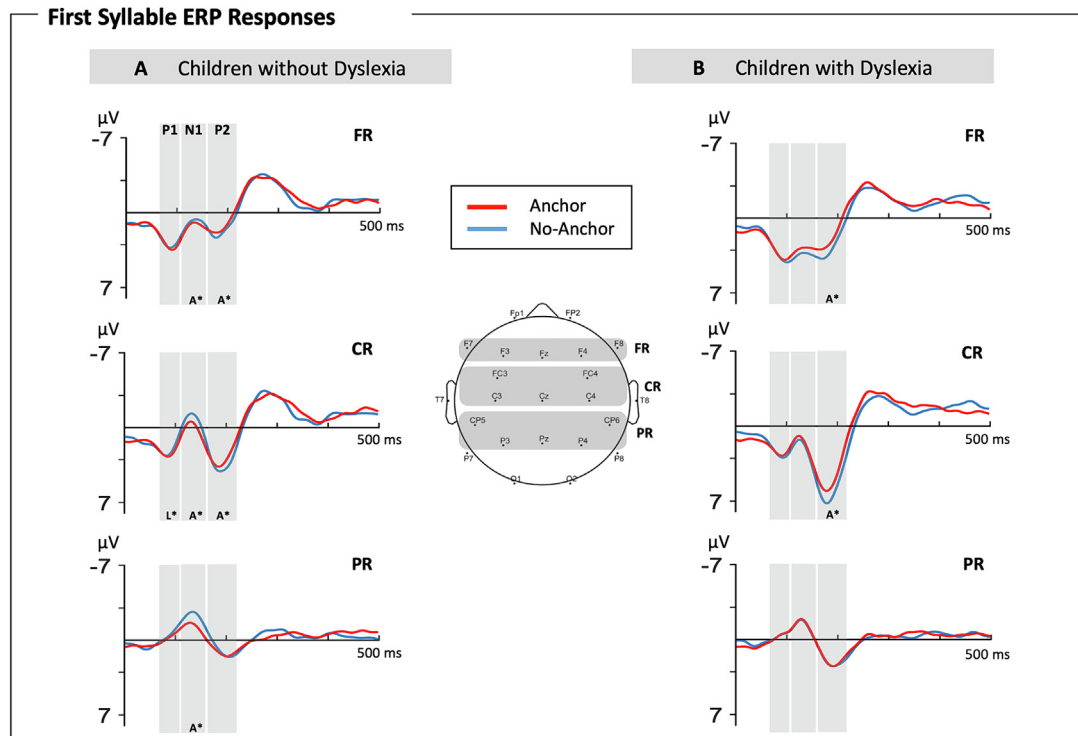
Fig. 3. Event-related potentials (ERP) responses to the first syllables for anchor (in red) and no-anchor condition (in blue) for children with dyslexia (A) and without dyslexia (B). Gray-shaded areas indicate analyzed time-windows (TW) and asterisks indicate statistically significant condition differences for mean amplitude (A) and peak-latency (L) values (Condition effect, Condition x Group interaction, Condition x Group x Region interaction). Children without dyslexia showed significantly faster responses in the P1-TW and smaller responses in the N1-TW for the anchor versus no-anchor condition. Both groups of children showed significantly smaller responses in the P2-TW for the anchor versus no-anchor condition. FR = Frontal Region, CR = Central Region, PR = Posterior Region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

when the second syllable followed an anchor versus a no-anchor first syllable (Fig. 4). Moreover, the latency analysis revealed a significant condition effect that could be explained by a shorter P2 peak-latency (across groups), when the second syllable followed anchor versus a no-anchor first syllables (Table 6).

4. Discussion

The aim of the present study was to investigate whether speech processing in school children with dyslexia differs from their typically developing peers regarding their use of repeated contextual information. Such perceptual anchoring has been demonstrated for tone discrimination in typically developing children and adults (Ahissar et al., 2006; Banai and Ahissar, 2006; Banai and Yifat, 2011, 2012). The current study, however, is the first to study perceptual-anchor effects during speech perception in children with dyslexia.

In our paradigm using syllable pairs, both children with and without dyslexia showed repetition-induced neural adaptations in the anchor-condition of the first syllables, evidenced by amplitude and latency effects of the auditory ERPs. Specifically, children of both groups showed smaller P2 amplitudes to anchor versus no-anchor syllables. Control children additionally showed smaller N1 amplitudes and shorter P1 latencies. These results suggest that children with and without dyslexia were able to perceive the pitch regularity in the anchor condition, but showed distinct ERP patterns across groups in doing so: While controls showed repetition modulations already for the earlier sensory ERP components P1 and N1, children with dyslexia only showed effects for the later component P2. As P1 has been associated with sensory processing

and gating (Boop et al., 2008; Woodman, 2010) and the N1 with change detection of physical and temporal stimulus parameters (Joos et al., 2014; Näätänen and Picton, 1987), our results suggest an altered, most likely less automatic auditory repetition processing in children with dyslexia.

The comparison of ERP responses for the second syllables between groups also revealed distinct patterns of how pitch repetitions of the first syllables (i.e., anchor condition) modulated the ERP responses for the second syllable. Specifically, both groups showed faster P2 responses for the anchor condition, but controls additionally showed faster P1 and smaller P2 responses. These findings imply that across groups the detection and integration of the pitch regularity in the anchor condition modified the processing of identical second syllables. However, the observed group differences also suggest that for children without dyslexia the preceding pitch regularity resulted in earlier and more pronounced modulations of subsequent syllable processing. We will discuss the implications of these results in more detail below.

Our findings on the processing of pitch repetitions are in line with previous reports of impaired stimulus-specific rapid neural adaptation for individuals with dyslexia (e.g., Gertsovski and Ahissar, 2022; Perrachione et al., 2016; Peter et al., 2019). These deficits imply that listeners experience problems in rapidly detecting, adapting and filtering redundant information by attenuating the neural response to repeated stimuli (Ulanovsky et al., 2003). For example, Stefanics et al. (2011) reported for 8- to 10-year-old children with dyslexia deficient auditory processing in response to intensity and fast rise-time changes, apparent as delayed P1 latencies compared to those of controls. Moreover, Peter et al. (2019) studied repetition responses in the EEG of adults and observed repetition-driven amplitude attenuations in both adults
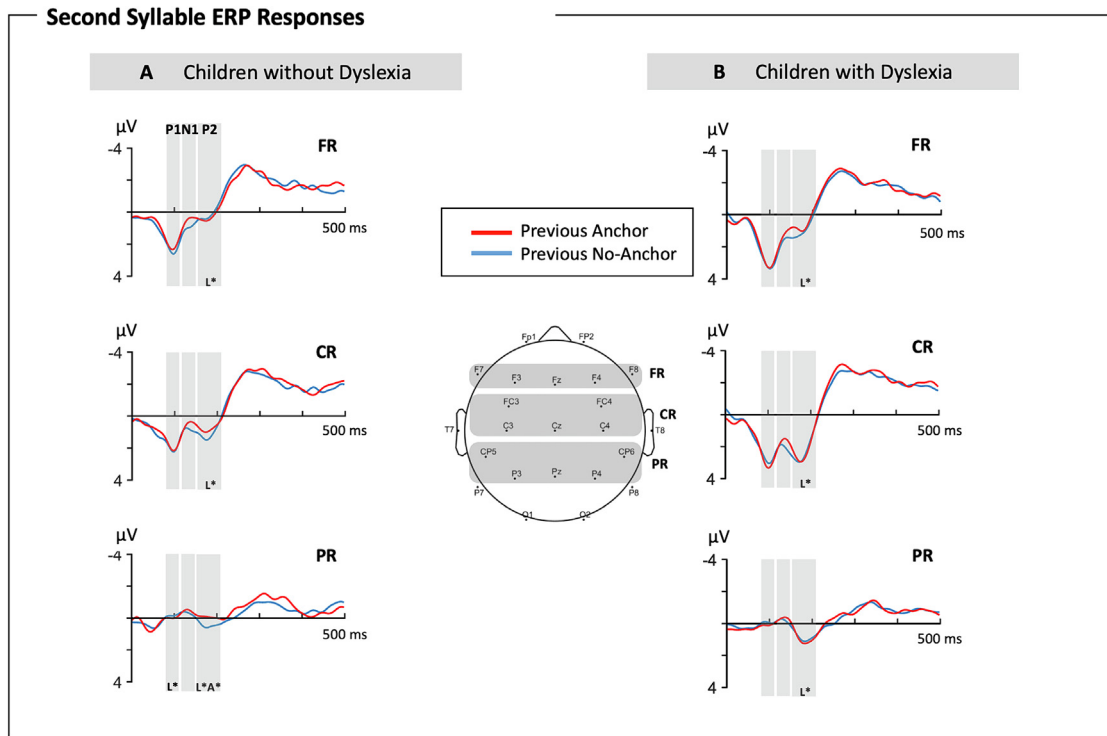
Fig. 4. Event-related potentials (ERP) responses to the second syllables following previous anchor (in red) and no-anchor first syllables (in blue) for children with dyslexia (A) and without dyslexia (B). Gray-shaded areas indicate analyzed time windows (TW) and asterisks indicate statistically significant condition differences for mean amplitude (A) and peak-latency (L) values (Condition effect, Condition x Group x Region interaction). Only children without dyslexia showed a statistical trend for faster responses in the P1-TW and significantly smaller responses in the P2-TW following previous anchor versus no-anchor syllables, while both groups showed significantly faster responses in the P2-TW. FR = Frontal Region, CR = Central Region, PR = Posterior Region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
First syllables: Statistical results for mean amplitudes of the event-related components in the P1, N1, and P2 time windows relative to syllable onset.

First Syllables: Mean amplitudes					
Time-Window (ms)	Effect	F/t	df	p-value	η_p^2
P1: 70–110	Condition	0.09	1/39	0.759	0.002
	Condition x Group	0.92	1/39	0.341	0.02
	Condition x Region	0.10	1.27/49.57	0.803	0.003
	Condition x Region x Group	0.13	1.27/49.57	0.776	0.003
N1: 110–150	Condition	1.29	1/39	0.262	0.03
	Condition x Region	3.25	1.43/55.95	0.062	0.08
	Condition x Group	**8.92**	**1/39**	**0.005**	**0.19**
	Post-hoc: Without Dyslexia	**2.97**	**19**	**0.008**	**0.11**
	Post-hoc: With Dyslexia	1.29	20	0.212	0.02
	Condition x Region x Group	0.50	1.43/55.95	0.548	0.01
P2: 150–210	Condition	1.90	1/39	0.175	0.05
	Condition x Region	**5.87**	**1.31/51.07**	**0.012**	**0.13**
	Post-hoc: Frontal	**2.10**	**40**	**0.042**	**0.06**
	Post-hoc: Central	1.98	40	0.054	0.06
	Post-hoc: Posterior	0.64	40	0.523	0.01
	Condition x Group	2.43	1/39	0.127	0.06
	Condition x Region x Group	0.24	1.31/51.07	0.685	0.01

Note. Condition = anchor vs no-anchor.

with and without dyslexia. Yet, neurotypical adults showed significantly stronger attenuation for the N1 than individuals with dyslexia, while no group difference occurred for the later P2. Similarly, in our study, we observed differences between children groups for the P1 and N1, but not the P2 response, suggesting reduced and less automatic neural adaptation in children with dyslexia during processing of speech information.

The impact of perceptual anchoring on subsequent speech processing displayed differently across children groups. Specifically,

only control children showed faster P1 and less pronounced P2 responses to syllables following the anchor than no-anchor conditions, while both groups showed faster P2 responses. Previous studies reported the P1 latency to slow down with increasing task difficulty, indicating that participants invested more attentional resources with increased demands (Volosin and Horvath, 2020). Similarly, the P2 has been be associated with early attention allocation during stimulus processing (Näätänen, 1992, pp. 222), with a more pronounced P2 amplitude and a longer P2 latency being

Table 4
First syllables: Statistical results for peak latencies of the event-related components in the P1, N1, and P2 time windows relative to syllable onset.

Time Window (ms)	Effect	F/t	df	p-value	η_p^2
First Syllables: Peak latencies					
P1: 70–110	Condition	0.583	1/39	0.450	0.02
	Condition x Region	2.51	2/78	0.093	0.06
	Condition x Group	1.94	1/39	0.172	0.05
	Condition x Group x Region	**3.96**	**2/78**	**0.026**	**0.09**
	Post-hoc: Without Dyslexia – Frontal	0.55	19	0.463	0.01
	Post-hoc: Without Dyslexia – Central	**8.94**	**1/39**	**0.005**	**0.19**
	Post-hoc: Without Dyslexia – Posterior	0.42	19	0.838	0.001
	Post-hoc: With Dyslexia – Frontal	0.09	20	0.765	0.002
	Post-hoc: With Dyslexia – Central	0.35	20	0.557	0.01
	Post-hoc: With Dyslexia – Posterior	0.08	20	0.774	0.002
N1: 110–150	Condition	0.41	1/39	0.527	0.01
	Condition x Region	1.83	2/78	0.172	0.05
	Condition x Group	**4.29**	**1/39**	**0.045**	**0.10**
	Post-hoc: Without Dyslexia	1.00	19	0.323	0.03
	Post-hoc: With Dyslexia	3.76	1/39	0.060	0.09
	Condition x Group x Region	0.26	2/78	0.743	0.01
P2: 150–210	Condition	0.89	1/39	0.351	0.02
	Condition x Region	1.83	2/78	0.527	0.01
	Condition x Group	1.45	1/39	0.236	0.04
	Condition x Group x Region	0.46	2/78	0.613	0.01

Note. Condition = anchor vs. no anchor.

Table 5
Second syllables: Statistical results for mean amplitudes of the event-related components in the P1, N1, and P2 time windows relative to syllable onset.

Time-Window (ms)	Effect	F/t	df	p-value	η_p^2
Second Syllables: Mean amplitudes					
P1: 70–110	Condition	0.01	1/39	0.910	0<.001
	Condition x Region	1.44	1.21/47.19	0.241	0.04
	Condition x Group	0.33	1/39	0.568	0.01
	Condition x Region x Group	0.11	1.21/47.19	0.786	0.003
N1: 110–150	Condition	3.53	1/39	0.068	0.08
	Condition x Region	0.23	1.50/58.39	0.723	0.01
	Condition x Group	0.23	1/39	0.633	0.01
	Condition x Region x Group	0.14	1.50/58.39	0.805	0.004
P2: 150–210	Condition	1.38	1/39	0.246	0.03
	Condition x Region	0.46	1.37/53.53	0.559	0.01
	Condition x Group	0.33	1/39	0.566	0.01
	Condition x Region x Group	**5.05**	**1.37/53.53**	**0.019**	**0.12**
	Post-hoc: Without Dyslexia – Frontal	0.29	19	0.771	0.002
	Post-hoc: Without Dyslexia – Central	1.16	19	0.262	0.04
	Post-hoc: Without Dyslexia – Posterior	**2.40**	**19**	**0.027**	**0.10**
	Post-hoc: With Dyslexia – Frontal	1.37	20	0.187	0.03
	Post-hoc: With Dyslexia – Central	0.15	20	0.875	0.001
	Post-hoc: With Dyslexia – Posterior	0.17	20	0.862	0.001

Note. Condition = anchor vs. no anchor.

Table 6
Second syllables: Statistical results for peak latencies of the event-related components in the P1, N1, and P2 time windows relative to syllable onset.

Time Window (ms)	Effect	F/t	df	p-value	η_p^2
Second Syllables: Peak latencies					
P1: 90–110	Condition	0.76	1/39	0.389	0.02
	Condition x Region	0.16	2/78	0.850	0.004
	Condition x Group	0.19	1/39	0.663	0.005
	Condition x Group x Region	3.25	2/78	0.052	0.08
	Without Dyslexia/ Posterior	3.96	1/39	0.054	0.09
N1: 125–145	Condition	0.82	1/39	0.371	0.02
	Condition x Region	1.07	2/78	0.33	0.03
	Condition x Group	2.91	1/39	0.100	0.06
	Condition x Group x Region	2.66	2/78	0.100	0.06
P2: 150–200	**Condition**	**4.08**	**1/39**	**0.050**	**0.10**
	Condition x Region	2.59	2/78	0.090	0.06
	Condition x Group	0.35	1/39	0.558	0.009
	Condition x Group x Region	2.61	2/78	0.090	0.06

Note. Condition = anchor vs. no anchor.

related to higher task difficulty (Kim et al., 2008) and higher attention allocation (Lijffijt et al., 2009). Thus, shorter latencies and less pronounced amplitudes in our study might indicate in turn that children have allocated less attention to the second syllables when presented in an anchor context than no-anchor context. This effect is more pronounced in children without dyslexia. As a result of more efficient neural adaptation to repetition, children without dyslexia might afford to allocate less attentional resources to the processing of the second syllables in the anchor condition. Alternatively, the repeating information may be an attentional cue, guiding children's attention towards upcoming information, which then required less processing resources. Both explanations point to higher attentional costs (Golob et al., 2002) in children with dyslexia compared to children without dyslexia when processing syllables in constant contexts. This means that affected children are less sensitive to stimulus statistics and benefit less from contextual repetitions in processing upcoming information when compared to their typically developing peers. In line with this interpretation, a recent study by Beach et al. (2022) suggests that in dyslexia, top-down prediction signals are less effective at tuning feedforward sensory processing, reducing perceptual efficiency and posing additional neurocomputational, and thus physiological costs on perception.

In summary, our findings suggest that reduced neural adaptation to constant information in children with dyslexia compared to their healthy peers result in higher neurocomputational costs when processing subsequent syllables. This may indicate an altered anchoring mechanism in dyslexia. It has been proposed that adaptation-related problems are associated with constrains to overcome the brain's internal noise and establish perceptual constancy underlying short-term perceptual facilitation and supporting long-term perceptual learning (Hornickel and Kraus, 2013; Jääskeläinen et al., 2007; Jaffe-Dax et al., 2015). These shortcomings hence likely contribute to the typically observed behavioral difficulties in individuals with dyslexia. Indeed, Banai and Yifat (2012) could show that perceptual anchoring performance is positively associated with phonological awareness abilities in pre-school children, an important precursor of successful reading and writing acquisition (Snowling, 1998).

The current study extends previous research on perceptual anchoring in several ways. First, most previous studies tested the effect of perceptual anchoring selectively on frequency discrimination of individuals with and without dyslexia (Ahissar et al., 2006; Banai and Ahissar, 2006; Jaffe-Dax et al., 2015). Only few studies tested perceptual anchoring in both non-linguistic and linguistic domains, by parallel evaluation of tone discrimination and speech discrimination or categorization (Banai and Ahissar, 2006; Banai and Yifat, 2012; Ozernov-Palchik et al., 2022). For example, Ozernov-Palchik et al. (2022) found that both children and adults with dyslexia have altered adaptations skills for tones and syllable categories, but could not statistically confirm a causal link between perceptual anchoring and categorical speech perception. While these findings provide an important first step in the evaluation of perceptual anchoring in the linguistic domain, we here directly demonstrate the impact of perceptual anchoring on speech processing within one paradigm. This paradigm experimentally mimics language-learning situations of children, who use statistical information in the speech input from early on (Kidd, 2012; Kuhl, 2004; Männel and Friederici, 2013; Romberg and Saffran, 2010; Saffran et al., 1996).

Second, there is only a limited number of developmental studies on perceptual anchoring so far. While Banai and Yifat (2012) established that children between 4 to 6 years of age behaviorally show perceptual anchoring in frequency discrimination, there is barely any work on perceptual anchoring in children with dyslexia.

Ozernov-Palchik et al. (2022) reported that 7- to 10-year-old children with dyslexia show both altered adaptation processes in tone discrimination and syllable categorization compared to their healthy peers. The closer developmental study of perceptual anchoring in dyslexia across domains is particularly relevant, as reduced neural adaptation in adults with dyslexia has been observed for several kinds of stimuli (e.g., spoken and written words, visual objects and faces; Gertsovski and Ahissar, 2022; Perrachione et al., 2016). These findings may point to a general impairment in the capacity to establish short-term representations of stimulus regularities (i.e., perceptual anchoring) in dyslexia (e.g., Ahissar et al., 2006; Chandrasekaran et al., 2009; Hornickel and Kraus, 2013), that should further be investigated from the developmental perspective. As previous developmental studies support the idea that perceptual anchoring is a processing mechanism present throughout development, we here tested the effect of perceptual anchoring on speech processing in 10-year-old children with and without dyslexia. Future investigations could, for example, focus on infants carrying a familial (genetic) risk for developing dyslexia to better understand the underlying developmental trajectories.

Third, most previous studies on perceptual anchoring in adults and all of the studies in children have focused on behavioral correlates (e.g., Banai and Yifat, 2011; Banai and Yifat, 2012; Ozernov-Palchik et al., 2022). While behavioral measures are essential to assess individuals' discrimination and categorization abilities, neural measures additionally provide information on potential compensation processes leading to comparable behavior or deficient subprocesses resulting in lacking responses or deviating behavior. To this end, the current study aimed to establish neural measures of perceptual anchoring and used an adaptation of Ahissar et al. (2006)'s experimental procedure in a passive-listening ERP study with syllabic stimuli. Our study provides first indications that in dyslexia, neural processes of perceptual anchoring and their effect on speech processing might be altered during development. Further investigations with combined measures of neural activity and children's behavioral performance are necessary. Active paradigms might enable the additional analysis of task-related ERP components N2 and P3, and larger sample sizes will allow for the evaluation of subsequent recognition tests that directly show potential benefits of perceptual anchoring on the learning and recognition of speech stimuli.

5. Conclusion

In conclusion, our ERP study on perceptual anchoring in speech processing revealed pronounced group differences in response patterns between children with and without dyslexia. Children with dyslexia showed less automatic neural adaptation to repetitions, forming perceptual anchors, compared to their healthy peers. In turn, children with dyslexia seemed to show less facilitation in speech processing via reduced attention allocation in the context of acoustic anchors.

CRediT authorship contribution statement

Claudia Männel: Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Jessica Ramos-Sanchez:** Formal analysis, Visualization, Writing – original draft. **Hellmuth Obrig:** Conceptualization, Writing – review & editing. **Merav Ahissar:** Conceptualization, Writing – review & editing. **Gesa Schaadt:** Conceptualization, Writing – original draft, Writing – review & editing, Project administration.

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