Neural processing of amplitude and formant rise time in dyslexia

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ABSTRACT

This study aimed to investigate how children with dyslexia weight amplitude rise time (ART) and formant rise time (FRT) cues in phonetic discrimination. Passive mismatch responses (MMR) were recorded for a/ba/-/wa/contrast in a multiple deviant odd-ball paradigm to identify the neural response to cue weighting in 17 children with dyslexia and 17 age-matched control children. The deviant stimuli had either partial or full ART or FRT cues. The results showed that ART did not generate an MMR in either group, whereas both partial and full FRT cues generated MMR in control children while only full FRT cues generated MMR in children with dyslexia. These findings suggest that children, both controls and those with dyslexia, discriminate speech based on FRT cues and not ART cues. However, control children have greater sensitivity to FRT cues in speech compared to children with dyslexia.

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1. Introduction

Developmental dyslexia is characterised by difficulties in learning to read despite normal intellectual functioning, normal hearing and vision and an adequate learning environment (Snowling, 2000; Vellutino et al., 2004). The characterising feature of children with dyslexia is a phonological deficit (i.e., deficits in the ability to attend to and mentally manipulate speech sounds) (Ramus et al., 2013, 2003; Snowling, 2000), and this is considered as the proximal cause in (most) children with dyslexia (Snowling, 2000; Vellutino, 1979). However, the precise nature of the phonological deficit in dyslexia is under debate. It is unclear whether the phonological representations (underlying sound structure of specific words stored in long-term memory) are themselves impaired (Ahissar, 2007) or whether the ability to access them is limited (Boets et al., 2014; Ramus and Szenkovits, 2008).

Many theories have tried to ascertain the cause of the phonological deficit in dyslexia. One group of theories holds that it stems from a more basic auditory processing deficit (Chandrasekaran et al., 2009; Tallal, 1980; Vandermosten et al., 2010). According to one prominent auditory processing deficit theory, children with dyslexia are impaired in tracking amplitude rise time cues (ART) in the auditory signal (Goswami et al., 2002). ART refers to the time from the onset of an acoustic stimulus to its maximum amplitude.

Accurate perception of ART will lead to accurate perception of auditory rhythm. Speech rhythm assists the listener in segmenting the syllable into onset (the word initial phoneme) and rime (phonemes that follow the onset). Therefore if subtle differences in ART are not perceived, it will lead to deficits in the acquisition of phonological skills as the segmentation of speech into distinct phonological units is impaired (Goswami et al., 2002).

Many behavioural studies have shown a deficit in the processing of ART in children with dyslexia. Goswami et al. (2011) compared the discrimination of a phonetic minimal pair (/ba/versus/wa/) when the contrast was based on ART differences between/ba/and/wa/versus when it is based on differences between/ba/and/wa/in the rise time of the first and second formants (F1, F2, formant rise time; FRT). They showed that children with dyslexia were superior to control children in discrimination based on FRT cues, but impaired in discrimination based on ART cues. ART thresholds were also a significant predictor of phonological skills in these children. They concluded that the development of phonological skills in dyslexia is affected by insensitivity to ART cues. Richardson et al. (2004) also found that children with dyslexia are less sensitive to ART. Similar findings have been obtained in languages other than English (Finnish: Hämäläinen et al., 2005, Hungarian: Surányi et al., 2009; French: Muneaux et al., 2004). However, this cross-linguistic evidence is not conclusive as Hämäläinen et al. (2009) and Georgiou et al. (2010) did not find any difference between children with dyslexia and typically reading children on their sensitivity to ART.

Behavioural studies of auditory processing have the disadvantage that performance is affected by non-auditory factors such as attention and motivation, so some of the discrepancies in previ-

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ous studies could be explained by such factors. Neurophysiological measures such as mismatch negativity (MMN) provide an alternative. MMN is an event related potential (ERP) component that reflects the early stages of change detection in the auditory system. The MMN is elicited by any discriminable change in a repetitive sequence of sounds, or by a sound violating an abstract rule or regularity in the preceding auditory context (Näätänen et al., 1978, 2001). In a simple MMN paradigm an infrequent stimulus (deviant) is presented among a series of repeatedly presented stimuli (standard). The MMN is represented by a negative peak (between 100 and 250 ms in adults) in the difference waveform between the ERPs to deviants and ERPs to the standards. MMN is a result of a pre-attentive memory based comparison process in which each incoming sound is compared with the memory trace formed by the preceding sounds. If the features of the incoming sound (frequency, amplitude, etc.) do not match the memory trace, the MMN is generated. The MMN has been widely used in studies investigating auditory and speech perception in normal and clinical populations (for reviews see Näätänen et al., 2007, 2012). In infants and young children the difference waveform between standards and deviants shows a positive peak (rather than a negative peak) and this is referred to as mismatch response (MMR) (Cheng et al., 2013; Dehaene-Lambertz and Baillet, 1998; Ruhnau et al., 2013). Neural maturation is hypothesised to account for the polarity change of the mismatch response over age (He et al., 2007; Trainor et al., 2003). The polarity change also depends on the discriminability between the standard and deviant stimuli with easy to discriminate contrasts maturing earlier compared to more difficult contrasts (Cheng et al., 2015; Maurer et al., 2003; Morr et al., 2002).

A few studies have investigated the processing of ART cues in dyslexia using MMN. Hämäläinen et al. (2008) presented 8–10-year-old Finnish children with harmonic tone pairs with the tones having either 130 ms or 10 ms ART. The standard stimuli had both tones with long rise time whereas the deviant stimuli had the first tone with a long rise time and the second tone with a short rise time. The stimulus pairs were presented with two within-pair intervals of 10 ms or 255 ms. They found a larger MMN response in the dyslexia group when the ISI was 255 ms and was interpreted as the effect of larger N1 response (which overlapped with MMN) to short ART stimuli in dyslexia. In contrast, Hakvoort et al. (2015) did *not* find a reduction in MMN amplitude for ART manipulations in 11–12-year-old children with dyslexia. They used pure tone stimuli with 10 ms ART as standard and 90 ms, 180 ms and 270 ms ART as deviants with 250 ms ISI. No effect of deviance magnitude was also observed. They concluded that ART processing – when measured independent of attention – is not impaired in children with dyslexia. Plakas et al. (2013) investigated the discrimination on pure tone stimuli based on ART or on frequency in pre-school children at genetic risk of dyslexia (at least one parent with dyslexia) using MMN (15 ms ART as standard, 90 ms ART as deviant). They found that sensitivity to *both* ART and frequency were impaired in children at risk of dyslexia, although sensitivity to both ART and frequency did not predict reading skills at grade 2.

Most of the behavioural and MMN studies on ART processing in dyslexia (except Goswami et al., 2011) have used non-speech stimuli (either pure tones or harmonic tones). Speech differs from non-speech as it has multiple acoustic cues to signal phonetic contrasts. For example, the stop-glide contrast (/ba/vs/wa/) is cued by both ART and FRT (/ba/has short ART and FRT whereas/wa/has long ART and FRT). One question that could be asked is whether listeners perceptually attend to both cues, or if they prefer to attend to one cue because the other is redundant. This is the notion of perceptual weighting.

Behavioural studies have shown that adults use FRT and not ART in phonemic identification (Nittrouer and Studdert-Kennedy, 1986; Walsh and Diehl, 1991). Recently Nittrouer et al. (2013) investi-

gated how adults and 4- to 6-year-old children weight ART and FRT cues in phonemic identification. Synthetic stimuli were presented with varying ART and FRT cues, and it was found that both adults and children based their phonemic decisions almost entirely on FRT cues. Similar findings were reported by Lowenstein and Nittrouer (2015) in 10- to 12- year-old children and adults with hearing impairment, although they also reported large variability across participants' use of FRT vs ART cues in making judgements. Using the MMN paradigm Moberly et al. (2014) studied the perceptual weighting of ART and FRT cues in adults and found a significant MMN for both ART and FRT deviants with larger MMN amplitude for FRT deviants indicating superior processing of FRT cues by adults. Therefore even though adults and children weight FRT cues above ART behaviourally, adults can preattentively discriminate speech sounds based on ART cues.

Perceptual weighting is important for the theories of dyslexia; if there is a deficit in the processing of a certain acoustic cue (e.g., ART deficit as predicted by Goswami et al., 2002), and if the cue is not heavily weighted then the perceptual consequence of the deficit would be minimal. To investigate this issue, this study investigated the weighting of ART and FRT cues in children with dyslexia using an MMN paradigm. If both cues are weighted equally, then similar MMNs will be generated for both ART and FRT. If one cue is weighted more than the other, then corresponding increases in MMN amplitude are expected.

2. Material and methods

2.1. Ethics statement

The ethics committee for Human Research at Western Sydney University approved all the experimental methods used in the study (Approval number: H9660). Informed consent was obtained from the parents of all the child participants. Children also gave verbal assent for the study.

2.2. Subjects

Seventeen children (3 female) with dyslexia and seventeen (5 female) age-matched control children participated in the study. Children's ages ranged from 6.0 to 11.8 years (M = 8.9 years, SD = 17.1 months). Children were recruited via advertisements in local media or via a database of families who previously expressed interest to participate in infancy and child research. All participants reported having no hearing difficulties. Families' socio-economic status was calculated based on the average household weekly income of their area of residence (Australian Bureau of Statistics). All families came from middle or higher middle socio-economic backgrounds, but the families in the control group came from areas with higher income than families in the dyslexia group, $t(32)$ = 4.64, p < .001. An additional 5 children with dyslexia were tested, but their data were removed from analysis due to excessive artifacts in their electroencephalogram (EEG) epochs (more than 30% of their epochs were rejected).

2.3. Behavioural measurements

Group assignment (dyslexia and control) was determined based on children's performance on the tests from the screening battery set out below. Children were assigned to the dyslexia group if a) they obtained a score of 1.5SD below the age-appropriate mean in at least one reading task, *and* at least one phonological processing task, *and* b) had average scores (not lower than 1SD from the age appropriate mean) on the grammatical competence tests, *and* c) had average non-verbal IQ score and no indications of Autism

Spectrum Disorder (ASD) or attention deficit hyperactivity disorder (ADHD). Children were assigned to the control group if they obtained average scores (±1*SD*) on all the tasks of the screening battery and had no indications of ASD or ADHD.

Word and non-word reading: The sight word efficiency and the phonemic encoding efficiency sub-tests of the Test of Word Reading Efficiency (TOWRE; Torgesen et al., 2012) were administered. The TOWRE consists of two lists, one of 66 words and another of 66 non-words. In two separate trials, children are required to read as many items as possible from each list in 45 s. A standardised score (*M* = 100, *SD* = 10) is computed based on how many words are read accurately in this time for each test.

Phonological processing: (1) Phonological awareness: Four sub-tests of the phonological awareness battery of the Comprehensive Test of Phonological Processing (CTOPP; Wagner et al., 2013) were administered. *Elision* – children were required to pronounce a word while omitting one of its component sounds, e.g. "say cup without/k/". *Blending words*—children were required to hear two parts of a word and were asked to combine them and produce the resulting word, e.g., "/pen/and/səl/make pencil". *Sound matching*—in this test, children saw two images of objects and were required to point to the object whose label contained a target sound, e.g., when shown the objects sun and ball, the child is asked to show the one that starts with/s/. *Phoneme isolation*—children are required to listen to a word and identify one of its component sounds, e.g., "what is the second sound of the word train". A composite standardised score for phonological awareness is then computed (*M* = 100, *SD* = 10). (2) Phonological short-term memory (PTSM): all children completed the digit and non-word repetition subtests of the CTOPP (Wagner et al., 2013). Children were presented with sequences of digits or non-words that increased with complexity after each trial and were required to repeat them in the same order as they were presented. This yields a composite standardised score for phonological memory (*M* = 100, *SD* = 10).

Rapid Symbolic Naming: The rapid digit naming and rapid letter naming subtests of the CTOPP were administered. Children were presented with a list of 36 items (digits or letters respectively) on a card and required to name as many as possible in the period of 2 min. The number of accurately named items in that time is used to calculate a standardised composite rapid symbolic naming score (*M* = 100, *SD* = 10).

Working memory: Children completed the forward and backward number repetition subtests of the Clinical Evaluation of Language Fundamentals test (CELF, Semel et al., 2006). A composite standardised working memory score was obtained based on the number of items that the child could successfully recall in each subtest (*M* = 10, *SD* = 3).

Expressive vocabulary: The expressive vocabulary subtest of the Wechsler Individual Achievement Test (WIAT, Breaux, 2010) was completed. The experimenter showed children an image and described it (e.g., "tell me the word that means a brush for cleaning teeth"), and children were required to name the image. The test is discontinued after 4 consecutive incorrect answers or when the entire set of 17 items is completed, yielding a standardised expressive vocabulary score (*M* = 100, *SD* = 10).

Grammatical competence: The Test of Reception of Grammar (TROG, Bishop, 2003a) and the Recalling Sentences subtest of the CELF (Semel et al., 2006) were administered. In the TROG, children were shown a card with four images and heard a sentence. They were required to point to the image on the card that was described by the sentence. The total number of correct responses is used to calculate the standardised reception of grammar score (*M* = 100, *SD* = 10). In the Recalling Sentences subtest, children heard a sentence and were required to repeat it *verbatim*. Responses are scored according to the number of errors made in each repetition, and used to compute a standardised score for this subtest (*M* = 10, *SD* = 3).

Non-Verbal Intelligence: Children complete the matrices subtest of the Kaufman Brief Intelligence Test (KBIT; Kaufman and Kaufman, 2004). The number of matrices completed correctly out of a maximum of 46 items is used to compute a standardised non-verbal intelligence score (*M* = 100, *SD* = 10).

Parental questionnaires: In addition to the screening battery, children's parents completed the Children's Communication Checklist (CCC-2, Bishop, 2003b) and the Swanson, Nolan, and Pelham rating scale (SNAP-IV, Swanson, 1992). The CCC-2 is used to assess children's general communicative abilities and identify communicative deficits characteristic of SLI or Autism Spectrum Disorder (ASD). The SNAP-IV is used to identify behavioural patterns characteristic of ADHD or other behavioural disorders. No children who were included in the final sample showed any indications of ASD or ADHD.

2.4. Event related potentials

2.4.1. Stimuli

The stimuli were the synthetic tokens taken from Nittrouer et al. (2013) for the/ba/-/wa/contrast. Both formant rise time (FRT) and amplitude rise time (ART) cue the/ba/-/wa/contrast. Since the contrast used in the study involves a manner distinction of stops (/ba/) vs glides (/wa/), the initial and final frequencies of formant transitions are the same for both initial consonants. However, the rate of change of formant transition and amplitude change differs between/ba/and/wa/. The formant and amplitude rise times are more rapid for/ba/than for/wa/as the vocal tract opens more quickly for/ba/(Lowenstein and Nittrouer, 2015). Five stimuli from the synthetic/ba/-/wa/continuum from Nittrouer et al. (2013) were used. All the stimuli had 320 ms duration with a fundamental frequency of 100 Hz and an intensity of 75 dB SPL. The starting and steady state frequencies for the formant were also same across the stimuli. F1 started at 450 Hz and rose to the steady state frequency of 760 Hz. F2 started at 800 Hz and rose to the steady state frequency of 1150 Hz. F3 was constant at 2400 Hz. The stimuli however differed in the time taken to reach the steady state frequencies (FRT) and amplitudes (ART). The stimuli were:

1 ART/ba/-FRT/ba/:/ba/like ART (10 ms),/ba/like FRT (30 ms)
2 ART/ba/-FRT/.5wa/:/ba/like ART (10 ms), FRT midway between/ba/and/wa/(70 ms)
3 ART/ba/-FRT/wa/:/ba/like ART (10 ms),/wa/like FRT (110 ms)
4 ART/.5wa/FRT/ba/: ART midway between/ba/and/wa/(40 ms),/ba/like FRT (30 ms)
5 ART/wa/FRT/ba/:/wa/like ART (70 ms),/ba/like FRT (30 ms)

Fig. 1 shows waveforms and spectrograms of the stimuli. For detailed stimulus descriptions see Nittrouer et al. (2013).

2.4.2. Paradigm

The stimuli were presented in two oddball blocks with multiple deviants (an ART block and an FRT block). In both blocks ART/ba/-FRT/ba/stimuli served as the standard. For the ART block ART/.5wa/FRT/ba/and ART/wa/FRT/ba/were presented as deviants whereas ART/ba/-FRT/.5wa/and ART/ba/-FRT/wa/were the deviants in the FRT block. Each block consisted of 1000 stimuli, of which 800 were standards (80%) and 100 deviants of each type (10% each). Each block began with 20 standards following which the standards and deviants were presented in a pseudorandom order with the constraint that a minimum of 2 and a maximum of 8 standards separated the deviants. The stimuli were presented with a constant inter-stimulus-interval (stimulus offset to next stimulus onset) of 500 ms through speakers. The presentation of the stimulus blocks was counterbalanced across participants. Stimulus delivery
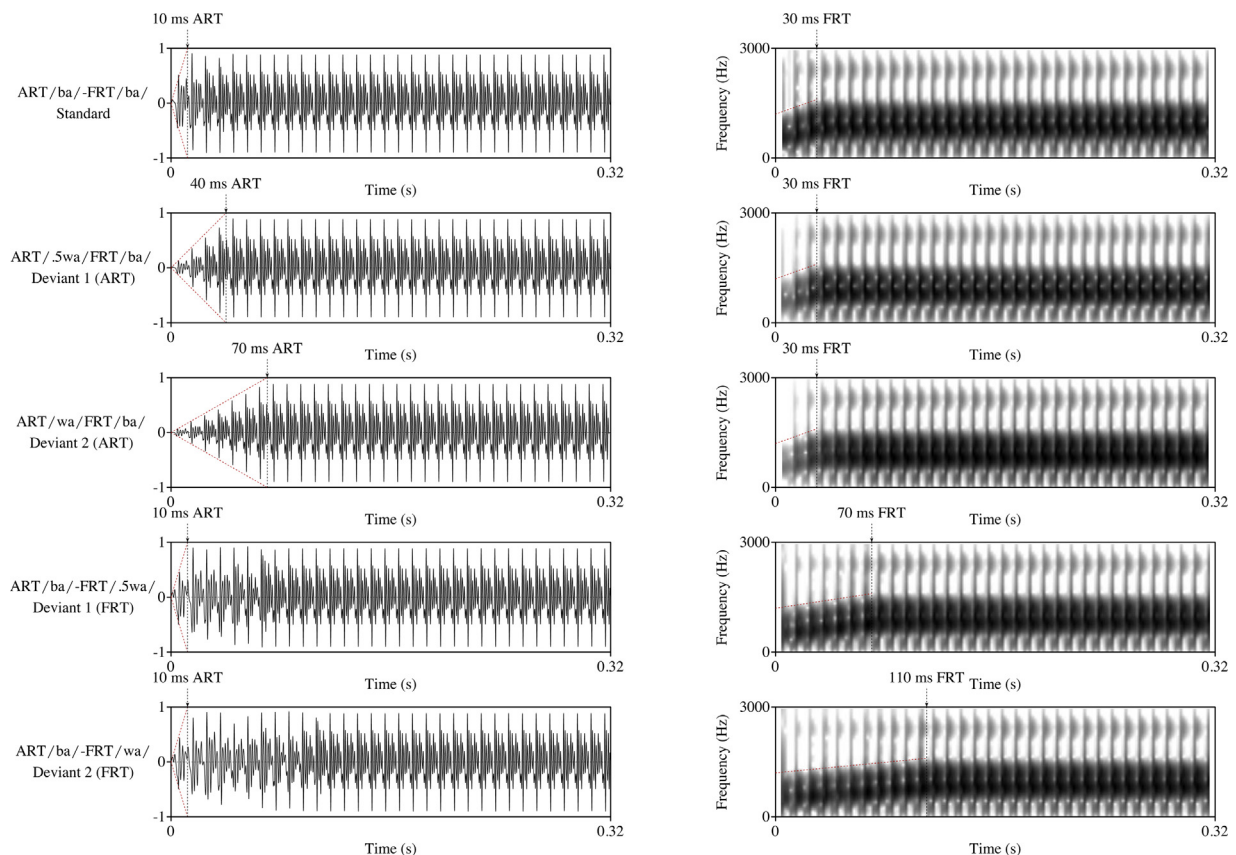
Fig. 1. Waveforms and spectrograms of the stimuli used in the experiment.

was controlled using Presentation 16.3 (Neurobehavioral System Inc., www.neurobs.com) running on a PC.

2.4.3. EEG recording

Children sat 1 m from an LCD screen and watched a silent video of their choice. They were instructed to ignore the sounds they heard and concentrate on the video. While they watched the video and ignored the sounds, their continuous EEG was recorded using 129 channel Hydrocel Geodesic Sensor Net (HCGSN), NetAmps 300 amplifier and NetStation 4.5.7 software (EGI Inc.) at a sampling rate of 1000 Hz with the reference electrode placed at Cz. The electrode impedances were kept below 50 kΩ. The continuous EEG was saved for offline analysis.

2.4.4. Offline analysis

The offline analysis of the EEG was performed using EEGLAB (http://sccn.ucsd.edu/eeglab/; Delorme and Makeig, 2004), ERPLAB (http://erpinfo.org/erplab/; Lopez-Calderon and Luck, 2014) and fieldtrip (http://fieldtrip.fcdonders.nl; Oostenveld et al., 2011) toolboxes in MATLAB 2012a (Natick, MA, USA). The continuous EEG was downsampled to 250 Hz. Portions of EEG containing large artifacts were visually identified and removed. The continuous EEG was then band pass filtered using non-causal Butterworth infinite impulse response (IIR) filter with half power cutoffs at 0.3 and 30 Hz and a roll off of 12 dB/octave. Ocular artifact correction was performed using independent component analysis (ICA) as implemented in EEGLAB ('run_ica' function). Noisy EEG channels were removed before ICA (average: 6 channels/subject; range 0–20). Independent components with known features of eye blinks (based on activity power spectrum, scalp topography, and activity over trials) were identified visually for each participant. The contributions of these components were then removed from the continuous EEG.

Noisy EEG channels were then interpolated using spherical spline interpolation. The EEG was then divided into epochs starting from 100 ms before the onset of the stimulus to 600 ms post-stimulus onset. Epochs were baseline corrected between −100 ms and 0 ms relative to stimulus onset. To remove additional artifacts, we used a moving window peak to peak procedure in ERPLAB with a 200 ms moving window, a 100 ms window step and a 100 μV voltage threshold. The epochs were then digitally re-referenced to the common average reference. The epochs were averaged separately for standards and deviants (excluding the first 20 standards and the standards that immediately follow a deviant). This resulted in six ERP waveforms per participant (ART-Standard, ART-Deviant1, ART-Deviant2, FRT-Standard, FRT-Deviant1 and FRT-Deviant2). Each participant had at least 75% accepted trials for each deviant type. A $2 \times 2 \times 2$ mixed analysis of variance (ANOVA) with the factors group (dyslexia, control), block (ART, FRT), deviant type (deviant1, deviant 2) on the percentage of accepted trials did not show any significant effects (all $F < 2$), ensuring no systematic signal to noise ratio differences across conditions and participant groups.

The difference ERP waves were computed by subtracting the ERP to the standard stimulus in each block from the deviants in the same block. There were 4 difference waves per participant. Individual ERP waves were averaged to obtain the grand average ERP for each condition. The grand averaged difference waves showed positivity at frontal electrodes. The responses are called the mismatch response (MMR) rather than mismatch negativity (MMN) as the responses were positive at frontal electrodes where mismatch responses are generally measured.

2.4.5. Statistical analysis

Statistical analyses were performed in two steps. The first analysis investigated whether the MMR elicited was statistically

significant. The second analysis investigated the difference in the MMR amplitude between children with dyslexia and control children.

2.4.5.1. Significance testing of MMR. The standard and deviant waveforms (for each deviant) were subjected to nonparametric cluster based permutation tests (Maris and Oostenveld, 2007) to assess whether the conditions differed significantly at any time point. The analysis was entirely data driven and included every time point at each electrode in the analysis. Initially, a series of *t*-tests were computed at every electrode and every time point. From this analysis, clusters of electrodes and time points where the response significantly differed from zero were identified. Then clusters were formed over space by grouping electrodes (at least 3 adjacent electrodes) that had significant initial *t*-test (p < .05) at the same time point. To control for Type I errors due to multiple comparisons a permutation approach was used to determine the probability of the difference being real. This permutation test involved comparing the clusters identified in the first step by randomly assigning conditions and repeating the multiple *t*-tests (1000 iterations). If the mismatch response is real, then the *t*-tests comparing randomly permuted conditions should yield no significant results. A cluster is considered significant if the *p* value in the cluster statistics is less than 0.05 (i.e., less than 50 of the random permutations are significant).

If a significant cluster was obtained, then the MMR latency was computed as the latency of the most positive peak in the cluster (positive mismatch response was obtained in both the groups, see Section 3) at Fz (channel 11 in HCGSN, Fig. 2). The peak latency was calculated at Fz as the mismatch response is most prominent at Fz. MMR amplitude was calculated from 72 electrodes which were divided into 8 groups: frontal left, frontal right, central left, central right, parietal left, parietal right, occipital left and occipital right (Fig. 2). The waveforms from all the electrodes within the electrode group were averaged together to represent the activity at different scalp regions. Similar groupings of electrodes are used commonly for the analysis of MMR response from infants and children (Butler and Trainor, 2012; Corrigall and Trainor, 2014; Slugocki and Trainor, 2014). The MMR amplitude for individual subjects was computed as the mean amplitude in a uniform 50 ms time window around the peak latency.

2.4.5.2. Comparison between dyslexia and control. This analysis was conducted only for FRT since no statistically significant MMR was seen for ART in either of the groups (see Section 3.2.1). The MMR amplitudes for FRT were subjected to a repeated measures ANOVA with the between subject factor, group (dyslexia, control) and within subject factors, deviance magnitude (deviant1, deviant2), hemisphere (left, right), and location (frontal, central, parietal, occipital). As the deviant1 in the FRT condition did not elicit a significant MMR in dyslexia group (see Section 3.2.1), the amplitude was calculated from the 50 ms window centred around the peak latency for the deviant 2, since a more valid time window could not be identified.

2.4.5.3. Relationship between MMR and behavioural measures. Person correlation coefficients were calculated between MMR amplitude and measures of reading and phonological processing. The analysis was restricted to deviant 2 in the FRT condition as only this condition produced significant MMR in both groups.

Table 1

Mean scores for the tasks of the screening battery and independent-sample *t*-test values for comparison between dyslexia and control groups performance. Standard deviation in parenthesis.

	Dyslexia	Control	t (df = 32)
Word Reading	79.06 (12.11)	100.47 (13.81)	−4.81[**]
Non-Word Reading	78.59 (9.55)	100.59 (14.41)	−5.25[**]
Phonological Awareness	83.59 (11.55)	103 (11.82)	−4.84[**]
PSTM	84.65 (14.46)	103.65 (12.13)	−4.15[**]
Rapid Symbolic Naming	86.47 (10.89)	103.94 (14.67)	−3.94[**]
Working Memory	7 (3.18)	10.94 (2.33)	−4.12[**]
Expressive Vocabulary	82.82 (37.14)	105.12 (11.12)	−2.37[†]
Test of Reception of Grammar	96.06 (10.93)	107.53 (10.07)	−3.18[*]
Recalling Sentences	8.71 (2.87)	11.18 (1.88)	−2.97[*]
Non-Verbal Intelligence	101.18 (8.98)	114.88 (10.76)	−4.03[**]

PTSM: Phonological short-term memory.

[*] p < 0.01.
[**] p < 0.001.
[†] p < 0.05.

Table 2

Significant clusters in the cluster permutation tests.

Group	Comparison	Cluster type	Time window	p
Control	Standard vs FRT Deviant 1	Positive	224–316 ms	0.023
		Negative	224–316 ms	0.003
	Standard vs FRT Deviant 2	Positive	180–288 ms	0.001
		Negative	184–292 ms	0.001
Dyslexia	Standard vs FRT Deviant 2	Positive	196–272 ms	0.037

3. Results

3.1. Behavioural measures

Table 1 presents the means, standard deviations, and results of independent-samples *t*-tests for each task from the screening battery. Children in the control group outperformed children with dyslexia on all tasks. It must be noted, however, that although control group had higher non-verbal IQ scores than dyslexia group, all the children in the dyslexia group had scores within the normal range (i.e., not more than 1*SD* below the standardised mean).

3.2. Event related potentials

3.2.1. Significance testing of MMR

The standard and deviant waveforms from the 8 electrode groups are depicted in Fig. 3. The deviant minus standard waveforms are shown in Fig. 4.

The difference waves showed a positive peak between 200 and 300 ms with larger amplitude for FRT condition compared to ART. The cluster based permutation tests on the ERPs for standards and deviant confirmed this. For the ART condition, the difference between the ERPs to standard and deviants did not reach significance in either the control or the dyslexia group. For the FRT condition both deviant 1 (ART/ba/FRT/.5wa/) and deviant 2 (ART/ba/FRT/wa/) generated significant MMR in controls whereas only deviant 2 (ART/ba/FRT/wa/) generated significant MMR in children with dyslexia. Table 2 depicts the latency range and *p* value for the clusters. Illustrations of the topography of each statistical effect are shown in Fig. 5. Note that the topography is dynamic within the cluster (i.e., a slightly different topography at each time point within the cluster). Therefore the topography at the peak MMR is shown in Fig. 5. For the topography at each time point, refer to Supplementary materials.

The topography revealed a positive cluster in the frontal locations and a negative cluster in the posterior locations. The posterior reversal of the polarity is indicative of the source of the activity in the auditory cortex (Trainor et al., 2011).
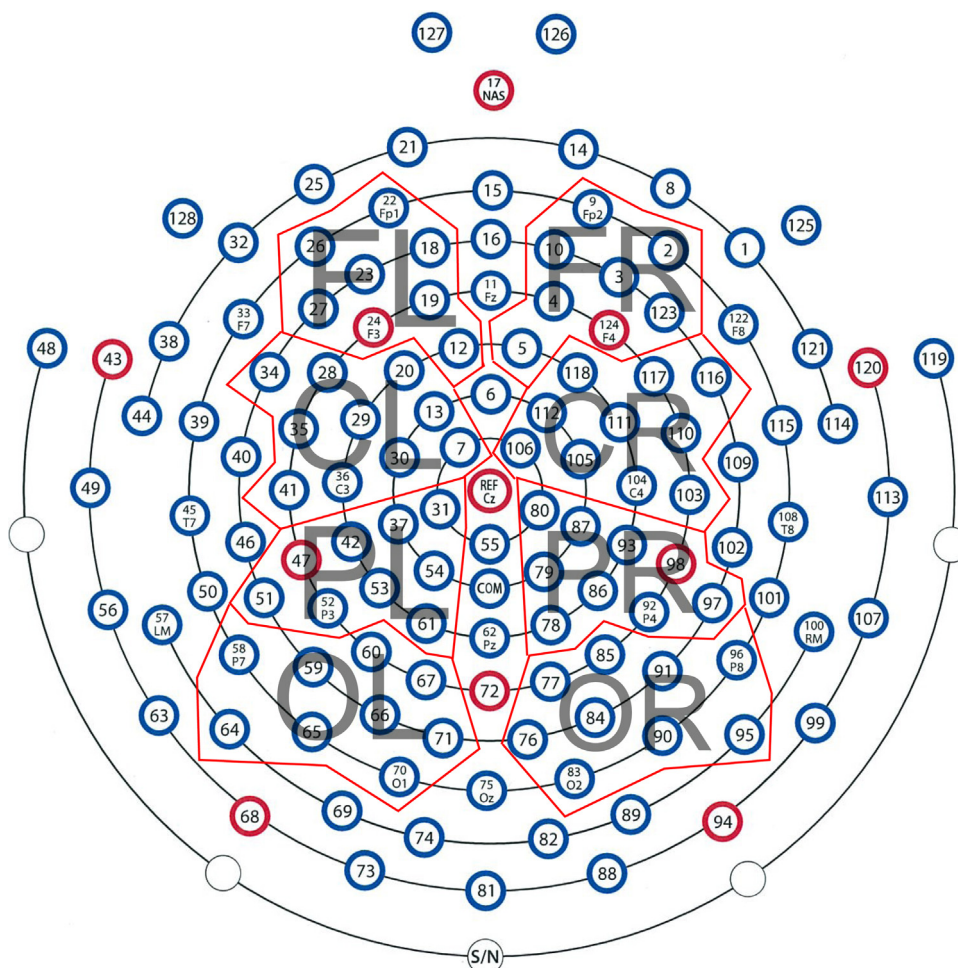
Fig. 2. Electrode groupings used for the analysis. FL-frontal left, FR-frontal right, CL-central left, CR-central right, PL-parietal left, PR-parietal right, OL-occipital left, OR-occipital right.

3.2.2. Comparison between dyslexia and control

The 4–way ANOVA on MMR amplitude for FRT revealed a main effect of condition F (1, 32) = 7.45, p = 0.01, partial η^2 = 0.19, where Deviant 2 (M = 0.05, SE = 0.04) generated a larger MMR compared to Deviant 1 (M = −0.05, SE = 0.03). There was also a main effect of location F (3, 96) = 24.57, p = 0.001, partial η^2 = 0.43. MMR at anterior (M = 0.59, SE = 0.13) and central (M = 0.35, SE = 0.08) locations were more positive compared to parietal (M = −0.24, SE = 0.07) and occipital locations (M = −0.71, SE = 0.13). There was also a significant 3-way interaction between condition, hemisphere and group F (1, 32) = 11.49, p = 0.002, partial η^2 = 0.26. No other main effects or interactions were significant (all F < 2.2, all p > 0.05).

To better understand the 3-way interaction between condition, hemisphere and group, post hoc 2-way ANOVAs were run between hemisphere and group for each condition. For the Deviant 1 ANOVA there was a main effect of group, F (1, 32) = 4.48, p = 0.048, partial η^2 = 0.11, showing that controls had a larger MMR (M = 0.2, SE = 0.04) compared to the dyslexia group (M = −0.11, SE = 0.04). For Deviant 2, there was a significant interaction between hemisphere and group, F (1, 32) = 6.63, p = 0.015, partial η^2 = 0.17. Follow-up one way ANOVAs computed for each hemisphere showed a main effect of group only in the right hemisphere F (1, 32) = 5.97, p = 0.02, partial η^2 = 0.16 where controls generated a larger MMR in the right hemisphere (M = 0.27, SE = 0.1) than the dyslexia group (M = −0.08, SE = 0.1).

3.2.3. Relationship between MMR and behavioural measures

Correlations between the MMR amplitude for deviant 2 in the FRT condition and behavioural measures are shown in Table 3. The results show that MMR amplitude did not correlate significantly with any behavioural measures in either the dyslexia or the control groups either at p = 0.05 or p = 0.003 (Bonferroni adjusted p value, controlling for 20 multiple comparisons).

4. Discussion

This study investigated the neural time course of cue weighting (ART vs FRT) in control children and in children with dyslexia. Mismatch responses (MMR) was recorded for synthetic/ba/-/wa/stimuli with either partial (deviant 1) or full (deviant 2) cues. For FRT, there was a significant MMR for both FRT deviants in control children whereas children with dyslexia had MMR only for the large FRT deviant. In contrast, for ART neither of the ART deviants elicited MMR for either the dyslexia or control groups. In the following sections we discuss the unexpected finding of the positive mismatch response (MMR), and cue weighting in dyslexia and control children.

4.1. Presence of positive mismatch response

The difference waveforms between the deviants and standards showed a positive mismatch response in this study. Positive mis-
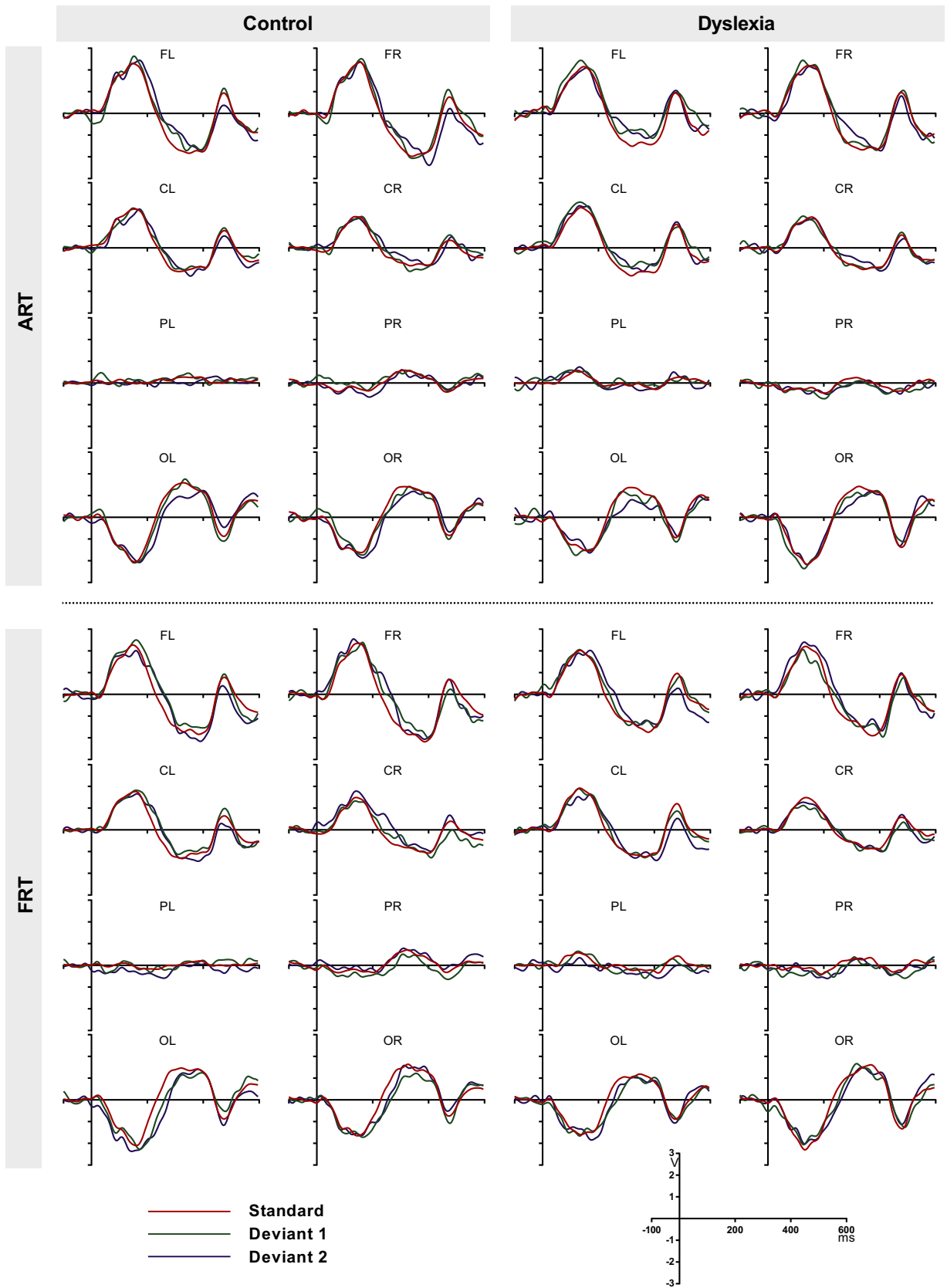
Fig. 3. The standard and deviant ERPs in the amplitude rise time (ART; top) and formant rise time (FRT; bottom) conditions for control children (left; N = 17) and children with dyslexia (right; N = 17).
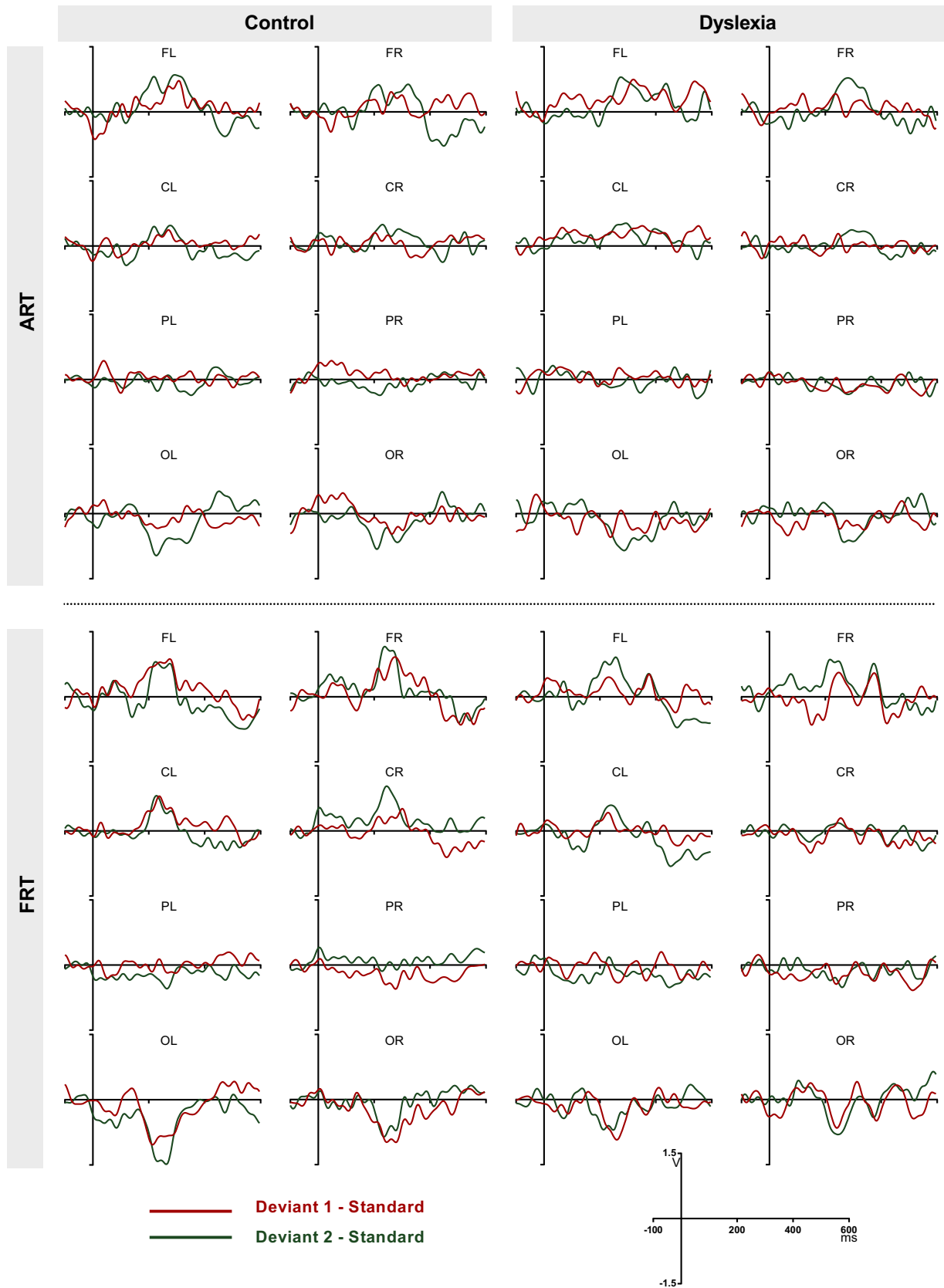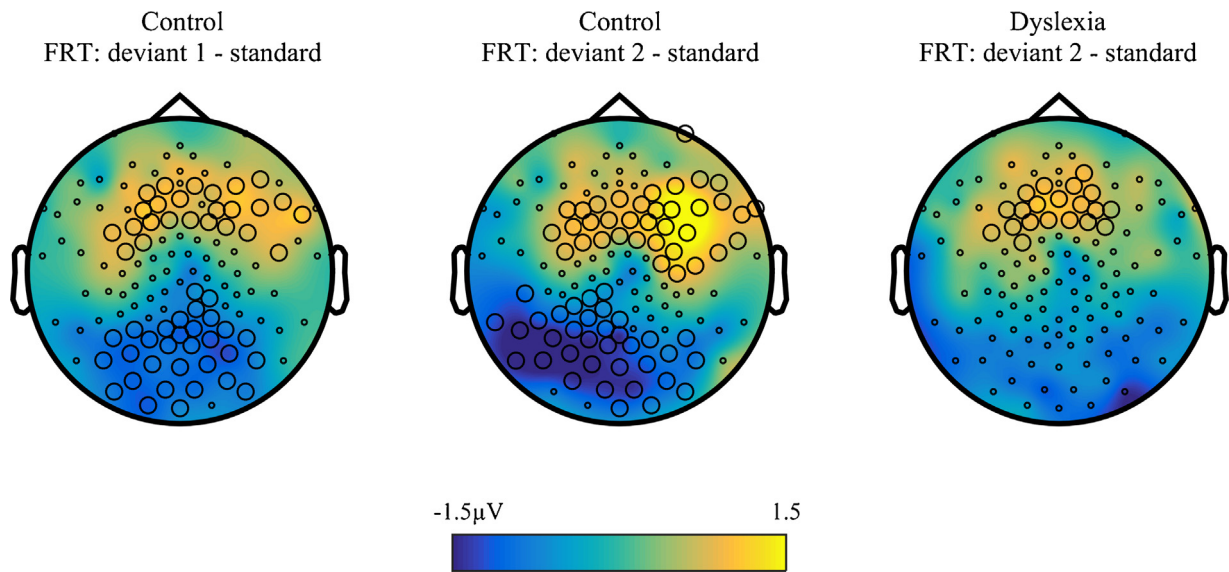
Fig. 4. The deviant minus standard waveform for amplitude rise time (ART; top) and formant rise time (FRT; bottom) conditions for control children (left N = 17) and children with dyslexia (right; N = 17).

Control
FRT: deviant 1 - standard

Control
FRT: deviant 2 - standard

Dyslexia
FRT: deviant 2 - standard

-1.5μV   1.5

Fig. 5. Topography of the deviant-standard wave at the MMR peak. Asterisks represent electrodes belonging to a statistically significant cluster.

Table 3
Person correlation coefficients between behavioural measures and MMR amplitude for FRT deviant 2.

		Behavioural Measure				
		Word Reading	Non-Word Reading	Phonological Awareness	PTSM	Rapid Symbolic Naming
Control	MMR FL	−0.05	−0.23	0.34	0.38	−0.21
	MMR FR	0.15	0.03	0.12	0.34	0.03
Dyslexia	MMR FL	0.36	0.40	−0.22	0.04	0.12
	MMR FR	0.31	0.04	0.09	−0.12	−0.08

All p > 0.05. PTSM: Phonological short-term memory. MMR FL: MMR amplitude at frontal left electrodes. MMR FR: MMR amplitude at frontal right electrodes.

match responses are common in infants below one year of age (Dehaene-Lambertz and Baillet, 1998; He et al., 2007; Slugocki and Trainor, 2014; Trainor et al., 2003), but between 6 months and 2 years the mismatch response changes polarity from positive to negative (Morr et al., 2002; Trainor et al., 2003), suggested to be due to neural maturation (He et al., 2007; Trainor et al., 2003).

More recently there have been reports of positive mismatch responses to speech stimuli in school aged children (Liu et al., 2014; Ruhnau et al., 2013) whereas some found both positive and negative mismatch response in children (Lee et al., 2012). Positive mismatch responses (MMR) were observed for less salient more difficult to discriminate deviants, whereas negative mismatch responses (MMN) were generated by deviants more easily discriminated from the standard. Therefore it appears that the polarity of the mismatch response is not only determined by maturational factors, but also by characteristics of the stimuli (Kuo et al., 2014; Lee et al., 2012). Since the contrasts used here are subtle and difficult to discriminate (Nittrouer et al., 2013), the positive mismatch responses may be due to this difficulty. Even though there is a consensus that the MMR in infants and children might reflect less mature speech discrimination process, its functional significance is not clear. The posterior reversal of the polarity of the positive mismatch response is similar to the more common negative mismatch responses indicating that the source of the response is auditory cortex.

4.2. Cue weighting in dyslexia and control children

For the FRT condition, the control children and children with dyslexia differed in their MMR response. Both groups elicited significant MMR for the full FRT cue (110 ms), but only the control group elicited significant MMR for the partial FRT cue (70 ms). There-

fore, all children, dyslexia and control, relied upon FRT as the more prominent cue to distinguish the stop-glide (e.g.,/ba/-/wa/) contrast (Lowenstein and Nittrouer, 2015; Nittrouer and Studdert-Kennedy, 1986; Nittrouer et al., 2013Walsh and Diehl, 1991). However, there was no evidence for use of this cue in the partial condition among children with dyslexia. This finding suggests a deficit in perceiving subtle FRT cues for discriminating speech sounds in children with dyslexia.

This finding is at odds with the findings of Goswami et al. (2011) who found excellent phonetic discrimination based on FRT cues in children with dyslexia. We propose three potential explanations for these apparently contradictory results. First the MMR method used in the present study shows early stages of change detection whereas the behavioural discrimination used by Goswami et al. reveals later stages of change detection. Second, the tasks used in the two studies differed in their processing demands. The task here involved passive weighting of two cues that co-occur in natural speech (ART vs. FRT). The Goswami et al. task on the other hand required children to use the information from just one of these cues to make a judgement about whether two stimuli were the same or different. Gordon et al. (1993) found that native listeners weighted speech cues differently when they were distracted from or attending to the speech sounds, indicating that the classification of speech sounds is influenced by attentional resources involved. Third, the standard/ba/stimulus in Goswami et al. had an ART of 30 ms and FRT of 25 ms whereas the standard/ba/in the present study had an ART of 10 ms and FRT of 30 ms. It is possible that differences in ART influence the discrimination based on FRT. If the amplitude rises slowly (long ART as in Goswami et al.), initial portions of the formants may not be perceived. It will be interesting to directly compare the two paradigms to identify more precisely the source of the deficit in auditory processing found in dyslexia.

One of the striking findings here is the lack of mismatch response to the ART stimuli. Neither the partial ART cue (40 ms; deviant 1) and full ART cue (70 ms; deviant 2) elicited a significant MMR, indicating that speech discrimination based on ART as measured by MMR did not occur at the neural level. Many previous studies have investigated discrimination based on ART cues in speech and non-speech stimuli using behavioural methods and MMN methods and the findings are mixed. Using harmonic tone-pair stimuli, Hämäläinen et al. (2008) found MMN responses in both control children and children with dyslexia. However, using pure tone stimuli, Stefanics et al. (2011) did not find significant MMN responses to ART deviants. Using the same stimulus as the one used in our study, Moberly et al. (2014) found significant MMN for the ART/wa/FRT/ba/stimuli in adults. Behavioural studies using the cue weighting paradigm, however, show a clear trend; Nittrouer et al. (2013) and Lowenstein and Nittrouer (2015) found that child and adult listeners labelled the stimuli almost exclusively using the FRT cues. Similarly Souza et al. (2015) found that normal hearing listeners weight formant cues higher than amplitude cues whereas individuals with hearing impairment weight cues depending on the availability of spectral cues.

The discrepancy between this and the previous studies might lie in the magnitude and the type of contrast used. The ART differences used here are above the *jnd* previously reported for ART (24.58 ms for controls; 32.80 ms for children with dyslexia; Goswami et al., 2011) and such differences are expected to generate MMR responses in general (Näätänen et al., 2007). However in the case of ART, Stefanics et al. (2011) did not find an MMN for an ART difference of 75 ms in 8- to 10-year-old children whereas Plakas et al. (2013) found significant MMN for 75 ms ART deviant in 41-month-old children (the response was absent in children who were at risk of dyslexia). Also Hämäläinen et al. (2008) obtained MMN for an ART difference of 120 ms for 8–10 year old children. The ART differences used in the present study are more representative of the ART in speech, and large ART differences would introduce an intensity effect (stimuli with long ART will sound softer; Thomson et al., 2009). It is possible that in case of ART, larger differences are required to generate MMR.

The absence of MMR to ART could also be explained by the generation mechanisms of the mismatch response and the variability in the detection of deviant ART stimuli. Horvath et al. (2008) argued that the amplitude of MMN reflects the percentage of detected deviants, each of which elicits MMN responses with equal amplitude. Therefore to elicit a reliable MMN, the deviants need to be detected consistently within the experimental block. Using the same stimuli in a behavioural paradigm, Nittrouer et al. (2013) found that 4- to 6-year-old children detected the ART/wa/FRT/ba/stimulus (deviant 2 in ART) as/wa/about 25% of the time (see Fig. 4 in Nittrouer et al., 2013). Similarly Lowenstein and Nittrouer (2015) also found the detection of ART/wa/FRT/ba/stimuli as/wa/to be ~25% for 10 year olds and ~50% for 8 year olds (see Figs. 3 and 4 in Lowenstein and Nittrouer, 2015). Souza et al. (2015) found large individual variability in weighting of ART and FRT cues in adult participants. Since detection of a deviant stimulus based on the ART cues is difficult, it is possible that in a passive paradigm the ART deviants are not detected in sufficient trials to generate a significant MMR response. Moreover the use of ART cues seems to depend on age. Therefore, future studies involving comparison across multiple age groups are required to understand the use of ART cues in children.

Finally, the MMR for FRT did not correlate with any behavioural measure of reading or phonological processing either in control or in children with dyslexia. Therefore based on the present results, the link between the ART processing and phonological skills is questionable. Similar lack of correlation is reported between frequency MMN and behavioural measures in children with specific language impairment (Bishop et al., 2010; Halliday et al., 2014). They explained the lack of correlation on the basis of MMN reliability. MMN reliability is high when 300 deviant trials are used, and it decreases with fewer deviant trials (Bishop and Hardiman, 2010). The number of artefact-free deviant trials in the present study was ~85, which might be sufficient to show an effect at group level, but not enough to show differences at an individual level. Therefore the relationship between ART MMR and phonological as well as reading skills requires further investigation.

To conclude, both typically reading children and children with dyslexia, discriminated speech based on FRT cues and not ART cues. In both the groups mismatch responses (MMR) are generated only for changes in FRT cues and not for ART cues. However, only typically reading children generate MMR for partial FRT cues indicating superior processing of FRT cues by typically reading children compared to children with dyslexia. In the light of differences found between control and children with dyslexia in their response to ART and FRT cues, the lack of such differences here requires investigation and explication via systematic manipulations of level of processing (behavioural versus electrophysiological), paradigm (cue weighting versus discrimination thresholds), and stimulus characteristics (speech vs noise).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.dcn.2016.03.006.

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