Dyslexic individuals orient but do not sustain visual attention: Electrophysiological support from the lower and upper alpha bands

Rob H.J. Van der Lubbe[a,b,*], Elian de Kleine[a], Karolina Rataj[c]

[a] Faculty of Behavior, Management, and Social Sciences, University of Twente, the Netherlands
[b] Faculty of Physics, Adam Mickiewicz University, Poznań, Poland
[c] Faculty of English, Adam Mickiewicz University, Poznań, Poland

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ABSTRACT

Individuals with developmental dyslexia have been characterized by problems with attentional orienting. In the current study, we specifically focused on possible changes in endogenous visual orienting that may be reflected in the electroencephalogram. A variant of the Posner cuing paradigm was employed with valid or invalid central cues that preceded target stimuli that were presented in the left or right visual field. The target stimuli consisted of vertical or horizontal stripes with low (two thick lines) or high (six thin lines) spatial frequencies. We examined lateralized alpha power in the cue-target interval as recent studies revealed that a contra vs. ipsilateral reduction in alpha power relates to the orienting of attention. An initial orienting effect in the lower alpha band was more pronounced for dyslexic individuals than for controls, suggesting that they oriented at an earlier moment in time. However, in contrast with controls, at the end of the cue-target interval no clear contralateral reduction in the upper alpha band was observed for dyslexic individuals. Dyslexic individuals additionally displayed slower responses, especially for invalidly cued high spatial frequency targets in the left visual field. The current data support the view that dyslexic individuals orient well to the cued location but have a problem with sustaining their attention.

1. Introduction

Developmental dyslexia has been defined as "an unexpected difficulty in reading in individuals who otherwise possess the intelligence and motivation considered necessary for fluent reading, and who also have had reasonable reading instruction" (Ferrer et al., 2010; p. 93). About 7% of the population is affected by developmental dyslexia (Banfi et al., 2017), which points to the importance of a better understanding of this condition. In studies on developmental dyslexia, it has frequently been observed that dyslexic individuals have problems with visuospatial attentional orienting (e.g., see Banfi et al., 2017; Collis et al., 2013; Facoetti and Turatto, 2000; Facoetti et al., 2001; Facoetti et al., 2003; Goswami et al., 2014; Klimesch et al., 2001; Ruffino et al., 2014; Vidyasagar and Pammer, 2010; Vidyasagar, 2013). This view has also been linked with structural changes in the brains of dyslexic individuals. Płoński et al. (2016) reported exclusive changes in the left hemisphere including the superior and middle temporal gyri, the subparietal sulcus, and the prefrontal areas (see also Roux et al., 2012). Other researchers noted the relation with processing along the magnocellular pathway (Livingstone et al., 1991; for reviews, see Stein, 2001, 2014), which has also been linked to the dorsal pathway (Gori et al., 2016), and the posterior parietal cortex (Jaśkowksi and Rusiak, 2005; Lobier et al., 2014; Valdois et al., 2018). Recently, Giraldo-Chica et al. (2015) observed that only the left lateral geniculate nucleus of the thalamus was smaller in individuals with dyslexia, which points to reduced processing along the magnocellular pathway in the left hemisphere. Nevertheless, the idea that dyslexic individuals experience problems with visuospatial attentional orienting (i.e., the *attentional deficit* hypothesis) has also been criticized. Ramus et al. (2018) recently argued that the apparent consensus on this hypothesis is based on a rather selective review of the evidence. Furthermore, Lukov et al. (2015) presented results indicating that visuospatial attention deficits do not underlie different types of dyslexia (see also Ziegler et al., 2010; Collis et al., 2013). Given this rather mixed state of affairs, we decided to further explore attentional orienting in developmental dyslexia.

Several different although related aspects of attentional orienting need to be distinguished to better characterize the *attentional deficit* hypothesis for dyslexic individuals. The first crucial distinction is between endogenous and exogenous spatial orienting, which are often examined with different variants of the Posner cuing paradigm (e.g., see

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Posner et al., 1980). The second important aspect is the time course of orienting as there are some differences between dyslexic individuals and controls with regard to the moment at which attention is directed after a relevant cue (Hari and Renvall, 2001).

1.1. Endogenous and exogenous orienting in dyslexic individuals

Endogenous and exogenous orienting are triggered by different processes although they may be considered to be related (e.g., see Chica et al., 2013). Endogenous orienting refers to the voluntary direction (e.g., set by instruction or internal goals) of attention to a location (e.g., see Van der Lubbe et al., 2006). In most studies, centrally presented cues are used that point to the to-be-attended location. At a behavioral level, the orienting effect is often estimated as the difference in performance between more frequent (e.g., 80%) validly cued, and less frequent (e.g., 20%) invalidly cued targets. As processing of the cue requires some time, cuing effects usually emerge after a short stimulus onset asynchrony (SOA) of about 300 ms. Endogenous orienting has been related to a bilateral dorsal frontal-parietal network (Corbetta and Shulman, 2002).

Exogenous orienting refers to the automatic and involuntary attraction of attention by specific stimulus features, e.g., the onset or offset of a stimulus (e.g., see Van der Lubbe et al., 2005), or the presence of a deviant (pop-out) stimulus that contrasts with its surroundings. Exogenous orienting can be examined by comparing performance between targets at cued and uncued positions that have equal probabilities of occurrence, and has been related to a right lateralized ventral frontal-parietal network (Corbetta and Shulman, 2002), especially the right temporo-parietal junction. Exogenous orienting effects vanish with increasing SOAs and may even invert with SOAs longer than 250 ms, which has been denoted as inhibition of return (IOR) (e.g., see Klein, 2000). A recent study suggests that endogenous and exogenous orienting have slightly different effects on processing in visual brain areas (see Bekisz et al., 2016).

Importantly, some researchers have argued that their results with dyslexic children (e.g., see Facoetti and Turatto, 2000; Facoetti et al., 2001) point to a selective impairment of right parietal functions related to exogenous orienting (for a recent overview see Liu et al., 2018), as no exogenous orienting effects were observed for these children, although this impairment maybe be restricted to children that have a low pseudo-word reading accuracy (see Facoetti et al., 2006). Most relevant for the current study, Facoetti et al. (2001) used an endogenous orienting task (Exp. 2) and observed that especially responses to invalidly cued left targets were delayed in dyslexic children relative to controls. Invalidly cued targets are thought to require exogenous orienting triggered by their onsets, therefore, these findings were related to a deficit in the right parietal cortex. This view on dyslexia has been denoted as the left-side *mini-neglect* hypothesis, assuming a diminished ability to orient to stimuli in the left visual field, comparable to neglect patients (e.g., see Blumenfeld, 2010). Thus, these studies point to differences in dyslexic participants in exogenous orienting that may be related to the right parietal cortex (see also Lobier et al., 2014). Other studies, however, point to anatomical changes in the left hemisphere (e.g., see Giraldo-Chica et al., 2015). Furthermore, Kermani et al. (2018) recently argued that reading experience actually biases visual search and therefore may modulate observed asymmetries in search efficiency between dyslexic individuals and controls.

Results of several other studies suggest that dyslexic individuals have deficits in endogenous orienting (Buchholz and McKone, 2004; Buchholz and Aimola Davies, 2005, 2008). Buchholz and McKone (2004) revealed that high-functioning adults with developmental dyslexia (i.e., university students that met the criteria of dyslexia) performed comparably to a control group on a visual search task with pop-outs that trigger exogenous orienting, while they performed worse on a visual search task that required endogenous orienting. Interestingly, higher search slopes were observed in the latter task for individuals

with reduced phonological abilities. Buchholz and Aimola Davies (2008) used the Attentional Network Task developed by Fan et al. (2002), which enables to separate effects of alertness, orienting, and executive control. No differences between dyslexic adults and controls were observed with regard to alerting effects and executive control. However, attentional orienting appeared to be more difficult for the dyslexic participants with cues at 6.5°, while results were comparable for cues at 3°. These results suggest that dyslexic individuals have problems with directing their attention in the peripheral visual field. In a very recent study, Liu et al. (2018) compared Chinese children with poor reading abilities with controls, and observed no endogenous orienting effect for poor reading children whereas a clear orienting effect was observed for controls. The absence of an orienting effect for the poor reading children might be related to slower processing of the cue, and/or a slower recruitment of attentional processes. Slower processing of the cue in dyslexic individuals (e.g., see Judge et al., 2013), or the slower subsequent recruitment of attention likely has an impact on exogenous and endogenous orienting effects.

1.2. The time course of orienting effects in dyslexic individuals

Several studies indicate that the time course of orienting in dyslexic individuals differs from controls. It has been argued that *sluggish attentional shifting* (SAS) can account for the impaired processing of rapid stimulus sequences in dyslexia (see Hari and Renvall, 2001). Additionally, there is support that the SAS hypothesis concerns both the visual and the auditory modalities (Lallier et al., 2009, 2010b). The SAS hypothesis may also explain the commonly observed response delays in dyslexic participants (e.g., see Facoetti et al., 2000a, 2000b, 2003; Jonkman et al., 1992; Wijers et al., 2005). Furthermore, Facoetti et al. (2000b) observed that dyslexic children were not able to orient fast to a peripheral cue as no cuing effects were observed with short stimulus onset asynchronies (SOAs) between the cue and the to-be-detected targets (see also Facoetti et al., 2005). By employing different cue sizes and different SOAs in their third experiment, Facoetti et al. (2000b) were also able to show that cue size was no longer effective in dyslexics with long SOAs, which suggested that unlike controls, dyslexic children were not able to sustain their attention focused over time. Facoetti et al. (2009) additionally showed no exogenous orienting effects in visual and auditory tasks in dyslexic children that had problems with reading non-words at short SOAs of 100 ms, while these cues were effective for controls. For longer SOAs of 250 ms exogenous orienting effects were present for these children while they were absent for the controls. These results were corroborated by Ruffino et al. (2014). Altogether, most of the results of these studies suggest that exogenous orienting effects may be delayed in dyslexic individuals, in line with the SAS hypothesis, although there is also some support that dyslexics have problems with sustaining their attention.

Interestingly, although spatial attention is often linked to the right parietal cortex, there is quite some evidence that participants are not only able to attend to a specific location, but also to a specific moment in time (i.e., temporal orienting; for a review, see Nobre, 2001). Coull et al. (2000) revealed that temporal orienting involves a left-lateralized frontal-parietal network. Given the reported changes in the left hemisphere (see above), and the aforementioned differences in orienting over time, one could argue that the observed attentional differences between dyslexic individuals and controls are actually more related to changes in temporal orienting than in spatial orienting. Support for this idea comes from studies examining attentional masking (Ruffino et al., 2010), changes in the attentional blink (Facoetti et al., 2008; Lallier et al., 2010a), and temporal order judgements (Jaśkowksi and Rusiak, 2008; Ortiz et al., 2014). A more direct way to examine the time course of spatial orienting is to use direction-dependent measures derived from the electroencephalogram (EEG).

1.3. The time course of orienting in dyslexic individuals examined with EEG

Wijers et al. (2005) used an endogenous orienting variant of the Posner paradigm to examine whether high-functioning dyslexic individuals differed from age- and gender-matched controls. A target letter was presented with an SOA of 750 ms after the cue and required only a response on 25% of the trials. Dyslexic individuals responded slower than controls and also tended to miss more targets. Event-related potentials (ERPs) were derived from the EEG and showed three direction-dependent effects during the orienting phase. First, between 200 and 300 ms increased contralateral (relative to the cued side) negativity was observed above occipital sites. This negativity, known as the early directing attention negativity (EDAN; e.g., see Harter et al., 1989; Hopf and Mangun, 2000; Van der Lubbe et al., 2006) has been related to selection of the relevant side of the arrows (Van Velzen and Eimer, 2003), but recently it has also been linked to microsaccades (Meyberg et al., 2017). Secondly, the EDAN was followed by a posterior contralateral positivity that remained until stimulus onset. This positivity, referred to as the late directing attention positivity (LDAP; e.g., see Harter et al., 1989; Hopf and Mangun, 2000; Van der Lubbe et al., 2006), is thought to reflect the influence of spatial attention on visual processing. Importantly, Wijers et al. observed no differences between dyslexic individuals and controls for the EDAN and the LDAP. Thirdly, between 350 and 750 ms, a frontal negativity was observed that may be related to the anterior directing attention negativity (ADAN; Eimer et al., 2002; Nobre et al., 2000). Although this component has been frequently linked to attentional orienting, there is still considerable discussion about its functional role (see Green et al., 2005; Hopf and Mangun, 2000; Meyberg et al., 2017; Seiss et al., 2007; Van der Lubbe et al., 2006; Van Velzen et al., 2006). For control participants, differences between left and right cues were presented above the right hemisphere, while for dyslexic participants an additional effect was present above the left hemisphere. Wijers et al. concluded that their findings support the hypothesis about a disregulated interhemispheric asymmetry in dyslexia (Eckert and Leonard, 2003a; Eckert et al., 2003b). Importantly, the findings reported by Wijers et al. do not really support the SAS hypothesis, as one would expect to observe differences between dyslexic participants and controls above posterior sites, where effects of visuospatial orienting are largest (e.g., see Van der Lubbe et al., 2006). For example, the LDAP might have been delayed or less pronounced for dyslexic individuals as compared to controls, but this is not what they observed.

Importantly, the aforementioned components (EDAN, LDAP, and ADAN), are all lateralized components derived from ERPs, also referred to as ERL (event-related lateralized) components, which implies that only lateralized activity that is time-locked to cue onset remains. Recent studies have indicated that the moment of attentional orienting likely varies over trials (and participants), and this variability may imply that certain effects cancel out due to the averaging procedure used to compute ERPs (e.g., see Van der Lubbe and Utzerath, 2013). The lack of a posterior group difference in the study of Wijers et al. could be due to this variability. Interestingly, several studies revealed that effects of endogenous orienting in the cue-stimulus interval are also clearly visible in lateralized activity in the posterior alpha (α) band (8–13 Hz; e.g., see Worden et al., 2000; Thut et al., 2006), which is based on the analysis of the raw EEG (i.e., before averaging across trials). The common observation is that alpha power is reduced above sites contralateral to the side to which attention was directed as compared to ipsilateral sites. Van der Lubbe and Utzerath (2013) followed the ideas of Thut et al. (2006) by computing ipsi-contralateral differences in alpha power weighted by the sum of their powers, which reduces overall inter-individual power differences. Additionally, in the method employed by Van der Lubbe and Utzerath an average is computed across left and right cued sides, which results in the so-called lateralized power spectra (LPS) index. The advantage of the latter procedure is that overall hemispheric differences in alpha power unrelated to the

attended side cancel out (for a comparable procedure with the lateralized readiness potential, see Coles, 1989; De Jong et al., 1988). Van der Lubbe and Utzerath revealed that after correcting for overall hemispheric differences, a clear decrease in contralateral vs. ipsilateral alpha power was present. In line with several other studies (e.g., see Klimesch et al., 2007, 2011; Klimesch, 2012; Thut et al., 2006), this contralateral reduction was interpreted as a release of inhibition that facilitates selection of the forthcoming lateral stimulus. Since this method reduces the impact of trial-to-trial as well as between-participant variability, it is an excellent tool to investigate attention-related differences between dyslexic individuals and controls during the orienting phase.

1.4. The current study

Our interest was especially directed at endogenous orienting. This type of orienting seems most relevant for reading, as reading is commonly driven by internal rather than by external goals. A version of the Posner paradigm with central cues was used that validly indicated the side where the target appeared on 80% of the trials after an SOA of 1000 ms. As targets non-alphanumeric stimuli were employed as we intended to demonstrate that observed effects are not limited to letter-like stimuli (in contrast with the suggestion by Collis et al., 2013). We chose to use horizontal or vertical gratings with only two thick lines (low spatial frequency: LSF) or six thin lines (high spatial frequency: HSF). Magnocellular cells are more sensitive to LSF stimuli (see Stein, 2001, 2014), therefore suboptimal performance for these stimuli might be observed for dyslexic individuals.

Changes in the time course of endogenous orienting will be examined by using the aforementioned ERL components, and especially by computing the LPS for the lower (α_1) and higher (α_2) alpha bands (Van der Lubbe and Utzerath, 2013) as the latter method may be more sensitive in assessing changes in orienting. The main aim of the current study was thus to further test whether developmental dyslexia is related to a delay or changes in endogenous attentional orienting, which accords with the SAS hypothesis (e.g., Hari and Renvall, 2001). The *mini-neglect* hypothesis (e.g., Facoetti et al., 2001) implies that dyslexic individuals may especially have problems with responding to invalidly cued targets on the left while orienting effects may be small for targets on the right. To further examine the *mini-neglect* hypothesis and also control for possible group differences in executive functions we compared the performance of dyslexic individuals and controls on a few neuropsychological tasks (Trail Making, Bourdon-Wiersma, and Balloons) that have been employed to assess problems with executive functions, visual perception, and visual attention (see also Vieira et al., 2013).

2. Methods

2.1. Participants

Twenty-nine participants were tested in this study. Due to measurement problems, the data of three participants could not be used, which left 26 participants. Twelve of the participants (the experimental group) had been diagnosed as dyslexic (6 male, 6 female, 11 right-handed, 1 left-handed) while 14 participants were employed as controls (9 male, 5 female, all right-handed).[1] Handedness was assessed with the Annett's Handedness Inventory (Annett, 1970). All participants were recruited among the local student population at the University of Twente, the Netherlands, and had normal or corrected-to-normal vision. None of the participants were colorblind or had a history of neurological or psychiatric disease. Participants of the experimental

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[1] Earlier analyses of participants from the control group were reported by Van der Lubbe and Utzerath (2013).

group were also asked to bring their dyslexia statement to the experiment. Before the experiment, participants signed an informed consent form. The employed experimental procedures were approved by the ethical committee at the Faculty of Behavioral Sciences at the University of Twente.

2.2. Tasks and stimuli

A small dyslexia test battery was used, the DST[NL] (a Dutch dyslexia screening test) to examine whether the experimental and the control group differed on the relevant characteristics. A large number of the participants of the experimental group were already familiar with some of the subtests (seven participants). Therefore, we only reported results on these tests for the remaining five participants of the experimental and all participants of the control group. All participants additionally had to complete three neuropsychological tasks (Trail Making, Bourdon-Wiersma, and Balloons) that are clinically used to assess problems with executive functions, visual perception, and visual attention. The Trail Making task (Reitan, 1958) consists of two parts. Part A is a relatively simple task in which the participant has to connect consecutive numbers (1–2–…), while in part B, they have to alternate between numbers and letters (1-A-2-B- …). The idea is that part B tests more complex executive functions related to the frontal lobes (e.g., see Miskin et al., 2016). The Bourdon-Wiersma test (Lezak, 1995) requires participants to select a group of dots (e.g., 4) on a sheet of 50 lines of dot patterns consisting of 3, 4, or 5 dots. This test checks for problems with visual perception and vigilance. The Balloons task (Edgeworth et al., 1998) is also a paper and pencil test that consists of two versions. Version A is a control test with pop-out stimuli (select balloons with a lower vertical line among balloons without a line) that checks for visual impairments and exogenous orienting, while version B is a form of absence search (select balloons without a line among balloons with a line) that is thought to require inspection of each individual stimulus. In all neuropsychological tasks that we examined, the time taken in seconds to complete the tests was used as the dependent variable.

The main task during which EEG was measured was an endogenous version of the Posner (1980) cuing paradigm (e.g., see Van der Lubbe et al., 2006). The task consisted of 672 experimental trials in total, separated in four blocks of 168 trials each. The experimental trials were preceded by 20 practice trials. The total duration of the task was approximately 70 min. An overview of the relevant events on a trial is displayed in Fig. 1.

On every trial a default display was presented consisting of a central white fixation dot ($0.16 * 0.16°$) on a black background. The fixation dot was flanked on the left and right by two open light grey circles (at $12.06°$, with $r = 0.61°$). Start of a trial was indicated by an auditory warning signal ("BEEP!!") and an enlargement of the fixation dot for 400 ms. Participants had to keep their eyes directed at the fixation dot. Six hundred milliseconds after offset of the warning signal a rhomb replaced the fixation dot. The rhomb (height $1.31°$, width $2.62°$) consisted of two colored triangles (red and green), pointing to the left and the right. Either the green or the red triangle was defined as task relevant. The relevant triangle pointed to the side of a subsequently presented to be discriminated target with a validity of 80%. Task relevance of the red or green triangle changed halfway the experiment. The rhomb was presented for 400 ms. After an SOA of 1000 ms relative to the rhomb the target was presented on 95% of the trials. On 80% of the trials the target appeared on the cued side, on 15% of the trials the target appeared on the uncued (or invalidly cued) side, whereas on 5% of the trials, no target occurred (catch trials).

We employed different types of targets that could appear in the left or the right open circle, which were presented for a duration of 300 ms. They either had a high or a low spatial frequency (HSF: six thin lines of $0.08°$; LSF: two thick lines of $0.25°$), and were presented in either a vertical or a horizontal orientation. Participants were instructed to press a left button with their left index finger (CTRL left) when a target
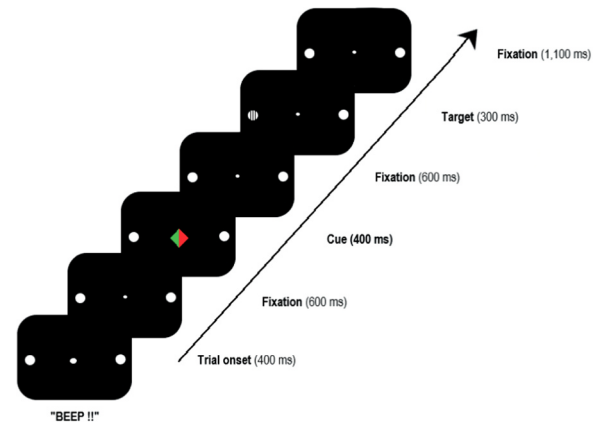

Fig. 1. Setup of trial. A rhomb, consisting of a green and a red triangle, was presented 1000 ms after an auditory warning signal. Either the red or the green part of the rhomb signaled the most probable side at which a target would occur. The target occurred 1000 ms after cue onset. The target was presented for 300 ms and consisted of a vertical or horizontal lines with either a low (two thick lines) or a high (six thin lines) spatial frequency. Participants were instructed to respond with a left or right button press depending on the orientation (vertical or horizontal) of the target lines.

with a horizontal orientation was presented and a right button with their right index finger (CTRL right) when a target with a vertical orientation was presented. Participants were instructed to respond as fast and accurately as possible.

2.3. Apparatus and EEG recording

Participants were seated on a comfortable chair in a darkened room at approximately 70 cm from a 17-in. monitor. Presentation software (Neurobehavioral Systems, Inc., 2012) installed on one computer was used to control stimulus presentation and send relevant markers to the EEG amplifier to code the onset of relevant events. The left and right CTRL buttons, which had to be pressed with the index fingers of the left and right hand, were located on a standard QWERTY keyboard.

EEG was recorded using passive Ag/AgCl ring electrodes placed on standard scalp sites according to the extended 10–20 system at 61 locations mounted in an elastic cap (Braincap, Brain Products GmbH). A ground electrode was affixed at the forehead. The horizontal and vertical electro-oculogram (hEOG and vEOG) were measured by using electrodes located above and below the left eye and by using electrodes located at the outer canthi of the left and right eye. Electrode gel and standard procedures were used to reduce resistance ($< 5 k\Omega$). EEG and EOG data were amplified using a 72-channel QuickAmp (Brain Products GmbH). This amplifier has a built-in average reference. Data sampling with a frequency of 500 Hz and digital filters (TC $= 5.0$ s, low-pass filter 100 Hz, notch filter 50 Hz) was carried out with BrainVision Recorder software (Brain Products GmbH), which was installed on a separate acquisition computer.

2.4. Processing of the behavioral data

Standard procedures were used to score performance on the neuropsychological tasks. The behavioral data of the endogenous cuing task were analyzed by employing Matlab-scripts on the marker data for those trials that contained no detectable eye movements ($|hEOG| < 60 \mu V$, from 0 to 1200 ms after cue onset).

Reaction times (RT) faster than 100 ms were considered as premature, while RT slower than 2000 ms were categorized as misses. Only trials with correct responses were used to compute the average RT for each combination of Spatial Frequency of the target (LSF or HSF), Cue Validity (valid or invalid), Stimulus Side (left or right) and Response

Side (left or right). The effects of the factors Spatial Frequency, Cue Validity, Stimulus Side, Response Side, and the between-subjects factor Group (dyslexic individual or control) on RT were analyzed with a repeated measures ANOVA. Proportions of correct responses (PC) for each category were transformed (arcsin) to meet normality assumptions, and were subsequently analyzed in the same way as RT. Proportions of misses for each category underwent a similar procedure and analysis as PCs. All statistical analyses were performed with IBM SPSS 20 (IBM Corporation).

2.5. Processing of the EEG data

The raw EEG was analyzed with Brain Vision Analyzer software (version 2.1.0.327) by selecting first a −1000 to 3000 ms time window relative to cue onset. Low cutoff (TC = 2.5 s) and high cutoff (25 Hz) filters together with a notch filter of 50 Hz were applied, and a baseline was set from −100–0 ms. Trials with detectable eye movements (see above) were removed. EEG data were first checked for large artifacts (Min/max: ± 250 μV, low activity for 50 ms > 0.1 μV). Next, Independent Component Analysis (ICA) was carried out to remove components that had a non-cortical origin. After resetting the baseline, the EEG data were checked for residual artefacts (Min/max: ± 150 μV, low activity for 50 ms > 0.1 μV). Next two different analyses were performed to examine the cue-target interval.

For the ERLs, we first determined ERPs for left and right cue trials by computing their individual averages. Next, a double subtraction was carried out for each symmetrical electrode position. As an example, for the PO8/7 electrode pair we took Δ(PO8-PO7) for left cues and Δ(PO7-PO8) for right cues and computed their average, which results in the individual ERL for the PO8/7 electrode pair. This procedure was carried out for the following 26 electrode pairs: AF4/3, AF8/7, C2/1, C4/3, C6/5, CP2,1, CP4/3, CP6/5, F2/1, F4/3, F6/5, F8/7, FC2/1, FC4/3, FC6/5, Fp2/1, FT8/7, O2/1, P2/1, P4/3, P6/5, P8/7, PO4/3, PO8/7, T8/7, TP8/7. Individual averages for 20 ms time windows from 100 to 1000 ms after cue onset for the PO8/7 electrode pair were used for statistical analyses to assess deviations from zero (which signifies the presence of signals that depend on the locus of attention) and potential group differences. Application of the procedure of at least two subsequent significant time windows (44) with two critical tests per time window implies an adjusted critical p-value (α'') of 0.0238 ($p < \sqrt{(0.05/(44 * 2))}$; see also Van der Lubbe et al., 2014).[2]

To obtain the LPS for the alpha bands (α_1, α_2), we performed wavelet analyses on single trials for left and right cues for all EEG channels. A Complex Morlet ($c = 5$) was chosen (see also Van der Lubbe and Utzerath, 2013). Power (μV^2) was determined within the lower (α_1: 7.2–10.7 Hz) and the upper (α_2: 9.4–14.0 Hz) α bands for each sample point. Next, an average was computed for left and right cue trials. For each average a single subtraction was computed on the obtained power values for all symmetrical electrode pairs: (ipsilateral-contralateral)/(ipsilateral + contralateral). Subsequently, these outcomes per cue were averaged to obtain the individual LPS estimates for the lower and upper

α bands. For the statistical analyses, we again focused on the PO8/7 electrode pair, and as we examined two bands we now had to use a critical p-value (α'') of 0.0169.

3. Results

3.1. Dyslexia screening and neuropsychological test outcomes

A control analysis revealed that after removal of the data of three participants with measurement problems, the control group (M_{age} = 20.4 yrs, SD = 2.3) was slightly younger than the experimental group with high-functioning dyslexic individuals (M_{age} = 23.3 yrs, SD = 4.3), $F(1,24) = 4.5$, $p = .043$. This difference seems due to the involvement of more students from the first and second years in the control group. To exclude the possibility of a confounding in subsequent analyses, Age was initially always included as a covariate. A control analysis on the obtained handedness scores revealed no group differences, $F(1,24) = 0.5$.

The scores on the subtests of the DST[NL] were first statistically evaluated with a MANOVA (Wilk's Lambda), while using Age as a covariate. This analysis revealed no effect of Age, $F(6,10) = 1.6$, and no group difference, $F(6,10) = 1.0$. However, separate ANOVAs per subtest revealed group differences on the nonsense sentence reading subtest, $F(1,16) = 5.2$, $p = .036$, $\eta_p^2 = 0.25$, controls: 82.2 points (SD = 1.3) vs. dyslexic participants: 79.0 points (SD = 5.0), and especially on the nonsense word reading subtest, $F(1,16) = 14.4$, $p = .002$, $\eta_p^2 = 0.47$, controls: 75.9 s (SD = 16.0) vs. dyslexic participants: 109.6 s (SD = 14.1).

A MANOVA performed on the results of the neuropsychological tasks (see Fig. 2) revealed no overall group difference, $F(5,19) = 1.3$, and no effect of Age, $F(5,19) = 1.3$. ANOVAs per subtest revealed no group differences for the Trail Making and the Bourdon-Wiersma tests, $F(1,24) < 2.4$, suggesting no differences in executive functions, visual perception, and vigilance. However, a group difference was observed on version B of the Balloons task, $F(1,24) = 4.5$, $p = .044$, $\eta_p^2 = 0.16$, but not on version A, $F(1,24) = 0.01$, $p = .929$, $\eta_p^2 < 0.001$. Indeed, no difference seems present between dyslexic participants and controls on version A of the Balloons task, where controls used on average 29.0 s (SD = 3.0) while the dyslexic individuals used on average 28.6 s (SD = 3.3). On version B of the Balloons task, controls used on average 91.8 s (SD = 6.2) while the dyslexic individuals used on average 72.3 s (SD = 6.7). The latter results suggest that the dyslexic individuals were actually better in absence search than the controls.

3.2. Behavioral results on the endogenous cuing task

Results on correct RTs (see Fig. 3) revealed no main effect or any relevant interaction involving the factor Age, therefore, this factor was excluded from further analyses. The dyslexic individuals responded on average slower than the control group (dyslexic individuals: 882 [95% CI: 808–957] ms; controls: 766 [697−835] ms), $F(1,24) = 5.6$, $p = .027$, $\eta_p^2 = 0.19$. Responses were overall faster for validly than for invalidly cued targets (795 [745−845] vs. 853 [800−906] ms), $F(1,24) = 61.2$, $p < .001$, $\eta_p^2 = 0.72$. No interaction between Cue Validity and Group was observed, $F(1,24) = 0.5$.

A main effect of Spatial Frequency was observed, revealing on average faster responses for LSF than for HSF stimuli (768 [716−820] vs. 881 [827−934] ms), $F(1,24) = 68.5$, $p < .001$, $\eta_p^2 = 0.74$. A main effect of Response Side was observed, which was due to faster responses with the left than with the right CTRL button (left: 798 [744−852] ms; right: 850 [800−900] ms), $F(1,24) = 24.9$, $p < .001$, $\eta_p^2 = 0.51$. This effect may be due to the slight asymmetry in the positions of the CTRL buttons on a standard QWERTY keyboard. We also obtained a significant interaction between Spatial Frequency and Response Side, $F(1,24) = 14.3$, $p < .001$, $\eta_p^2 = 0.37$. For LSF stimuli the difference between left and right buttons was rather small (left: 759 [704−815]

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[2] Application of the conservative Bonferroni correction procedure with m multiple tests implies that the criterion-value per single comparison (α') is determined as the standard criterion value (α) divided by the number of tests [$\alpha' = (\alpha / m)$]. With 44 relevant time windows and two tests per time window, and a standard criterion value of α of 0.05, α' would thus amount to 0.05/88 = 0.000568. If we assume that the criterion-value has to be overstepped for two successive time windows (α'') and the probabilities of α' are assumed to be independent, then α'' equals the square root of α' [$\alpha'' = \alpha' = \sqrt{(\alpha / m)}$]. Similarly, if we examine the reasoning of Talsma et al. (2001) and formalize their computation of α on the basis of an employed criterion per test (α'') of 0.05, then the following can be stated: [$\alpha = \alpha'' * \alpha'' * m = \alpha''^2 * m$]. This expression implies [$\alpha''^2 = \alpha / m$], and consequently results in [$\alpha'' = \sqrt{(\alpha / m)}$]. In our example of 88 tests and the standard criterion value of 0.05, α'' therefore approximates the value of 0.0238.
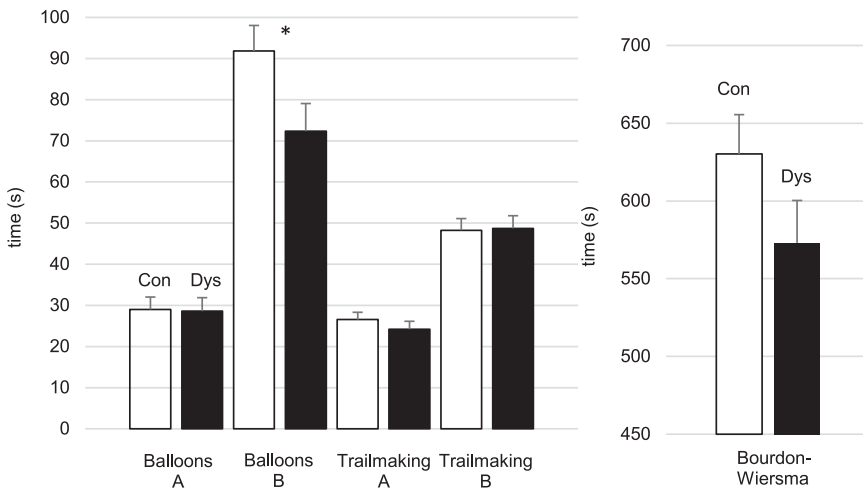
Fig. 2. Average time (in seconds) taken by the control (Con) and dyslexic (Dys) individuals to perform the Balloons tasks, the Trail Making tasks, and the Bourdon-Wiersma task. Version A of the Balloons task can be considered as a feature search task, while version B is thought to require serial inspection of each individual item and implies a form of absence search. Performance on the Trail Making tasks has been related to executive functions, while performance on the Bourdon-Wiersma task is related to visual processing. The displayed vertical lines represent standard error bars. $*p < 0.05$.
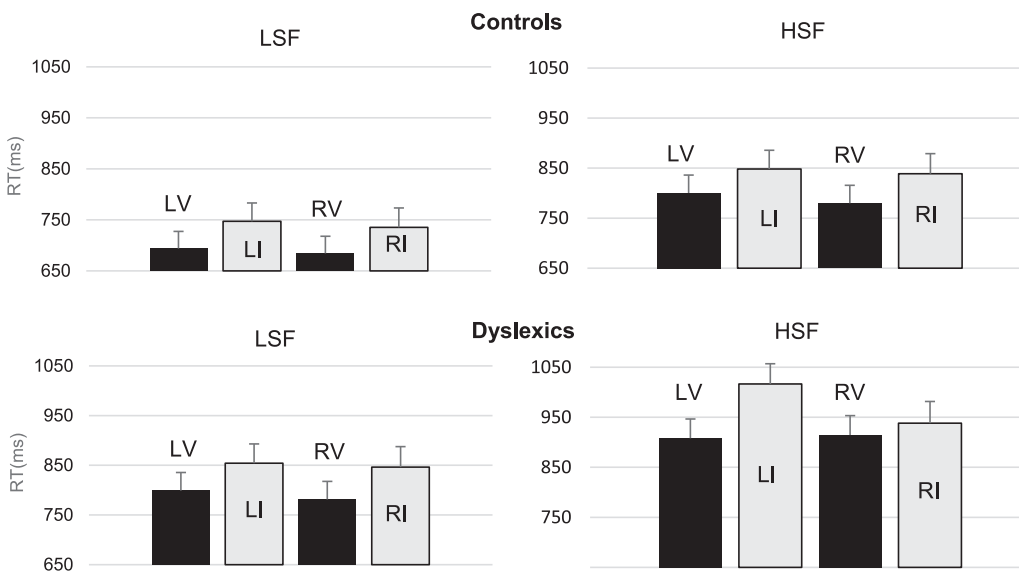

Fig. 3. Average reaction times (RT) for control and dyslexic individuals in the endogenous orienting task. Separate RTs are displayed for left validly cued (LV) targets with a low (LSF) and a high spatial frequency (HSF), left invalidly cued (LI) targets, right validly cued (RV) targets, and right invalidly (RI) cued targets. The displayed vertical lines represent standard error bars.

ms; right: 776 [724−829] ms; $\Delta = 17$ ms), while for HSF stimuli the difference was much larger (left: 837 [779−894] ms; right: 924 [871−978] ms; $\Delta = 87$ ms).

An interaction between Stimulus Side, Cue Validity, and Group was observed, $F(1,24) = 5.1$, $p = .033$, $\eta_p^2 = 0.18$. Separate analyses for the control group revealed no interaction between Stimulus Side and Cue Validity, $F(1,13) = 0.2$, $p = .691$, $\eta_p^2 = 0.01$, while separate analyses for the dyslexic individuals showed such an interaction, $F(1,11) = 5.6$, $p = .037$, $\eta_p^2 = 0.34$. The effect of Cue Validity for participants in the control group was indeed about the same for stimuli on the left (valid: 747 [665−829] ms; invalid: 798 [712−883] ms; $\Delta = 51$ ms) and on the right side (valid: 732 [651−813] ms; invalid: 787 [699−875] ms; $\Delta = 55$ ms), while for dyslexic individuals it was larger for stimuli on the left (valid: 854 [790−917] ms; invalid: 935 [867−1003] ms; $\Delta = 81$ ms) than for stimuli on the right side (valid: 848 [779−917] ms; invalid: 892 [820−965] ms; $\Delta = 44$ ms). However, we also observed an interaction between Spatial Frequency, Stimulus Side, Cue Validity, and Group, $F(1,24) = 6.0$, $p = .022$, $\eta_p^2 = 0.20$, which indicates that the above described interaction between Stimulus Side, Cue Validity, and Group was modulated by Spatial Frequency. Separate analyses for the control group also revealed no interaction between Spatial Frequency, Stimulus Side and Cue Validity, $F(1,13) = 0.2$, $p = .658$, $\eta_p^2 = 0.02$, indicating that the effect of Cue Validity for this group was rather constant, while separate analyses for the dyslexic

individuals revealed an interaction between Spatial Frequency, Stimulus Side and Cue Validity, $F(1,11) = 8.7$, $p = .013$, $\eta_p^2 = 0.44$.

Inspection of Fig. 3 clarifies the origin of the latter interaction. For LSF stimuli, the dyslexic individuals show comparable validity effects for stimuli on the left (valid: 799 [726−872] ms; invalid: 854 [774−934] ms; $\Delta = 55$ ms) and on the right side (valid: 781 [706−856] ms; invalid: 846 [761−932] ms; $\Delta = 65$ ms; Cue Validity * Side: $F(1,11) = 0.3$, $p = .575$, $\eta_p^2 = 0.03$). However, for HSF stimuli, the validity effect was much larger for stimuli on the left (valid: 908 [846−971] ms; invalid: 1017 [951–1082] ms; $\Delta = 109$ ms) than for stimuli on the right side (valid: 915 [845−984] ms; invalid: 938 [871–1005] ms; $\Delta = 23$ ms; Cue Validity * Side: $F(1,11) = 10.0$, $p = .009$, $\eta_p^2 = 0.48$).

Furthermore, we examined whether the Group difference on RT remained when analyses were restricted to LSF stimuli. A separate analysis revealed a main effect of Cue Validity, $F(1,24) = 51.4$, $p < .001$, $\eta_p^2 = 0.68$ (valid: 740 [689−790] ms; invalid: 796 [741−850] ms; $\Delta = 56$ ms) and a main effect of Group, $F(1,24) = 4.4$, $p = .047$, $\eta_p^2 = 0.15$ (dyslexic individuals: 820 [95% CI: 744–896] ms; controls: 715 [644−786] ms), but no other main effects or interactions.

Finally, we also obtained a significant interaction between Spatial Frequency, Stimulus Side, Response Side and Group, $F(1,24) = 7.4$, $p = .012$, $\eta_p^2 = 0.24$. Separate analyses for the control group revealed a trend to an interaction between Spatial Frequency, Stimulus Side, and
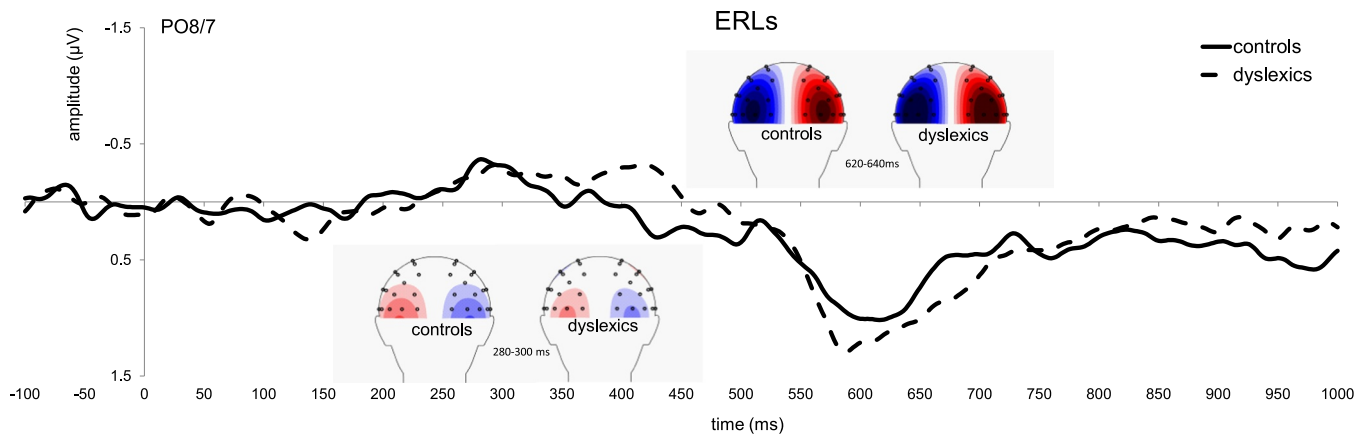
Fig. 4. Grand averages of the event-related lateralizations (ERLs) for controls and dyslexic individuals. ERLs are based on a double subtraction technique applied on event-related potentials (ERPs) that estimates the voltage difference between contralateral and ipsilateral electrodes that depends on attentional orienting while correcting for overall hemispherical differences. The displayed contra-ipsilateral electrode pair PO8/7 is located above occipital cortex. Topographies of the ERLs for most relevant time windows (280–300 ms and 620–640 ms) indicate that effects were most pronounced above occipital cortex. The earliest lateralized effect is often denoted as the EDAN (early directing attention negativity), while the later opposite effect is mostly denoted as the LDAP (late directing attention positivity).

Response Side, $F(1,13) = 4.6$, $p = .052$, $\eta_p^2 = 0.26$. However, no interaction between Stimulus Side and Response Side was observed, neither for LSF stimuli nor for HSF stimuli, $F(1,13) < 1.5$, $p > .243$, $\eta_p^2 < 0.10$. Separate analyses for the dyslexic individuals also revealed no interaction between Spatial Frequency, Stimulus Side, and Response Side, $F(1,11) = 3.0$, $p = .112$, $\eta_p^2 = 0.21$.

Analyses on the transformed PC scores revealed no significant effects when the factor Age was included as a covariate, only a tendency to an interaction was observed between Spatial Frequency and Age, $F(1,23) = 3.5$, $p = .074$, $\eta_p^2 = 0.13$. After leaving out Age as a covariate, analyses revealed a main effect of Spatial Frequency, $F(1,24) = 102.7$, $p < .001$, $\eta_p^2 = 0.81$, which seems due to a larger amount of correctly responded trials for LSF than for HSF stimuli (transformed values: 1.29 [1.24–1.34] vs. 0.84 [0.76–0.92]; means before transformation 93.8 vs. 70.4%). In addition a main effect of Response Side was observed, $F(1,24) = 21.4$, $p < .001$, $\eta_p^2 = 0.47$, which seems due to a larger amount of correctly responded trials with the left than with the right response button (transformed values: 1.14 [1.08–1.21] vs. 0.99 [0.93–1.04]; means before transformation 86.4 vs. 77.8%). An interaction between Spatial Frequency and Stimulus Side, $F(1,24) = 6.8$, $p = .015$, $\eta_p^2 = 0.22$, and also between Spatial Frequency, Stimulus Side, Response Side was observed, $F(1,24) = 10.2$, $p = .004$, $\eta_p^2 = 0.30$. Separate analyses for LSF stimuli revealed only a main effect of Response Side, $F(1,24) = 4.7$, $p = .041$, $\eta_p^2 = 0.16$. However, separate analyses for HSF stimuli revealed an interaction between Stimulus Side and Response Side, $F(1,24) = 5.5$, $p = .027$, $\eta_p^2 = 0.19$. The latter effect seems due to a drop in performance when a right button press was required to a HSF stimulus on the right (left button presses: left stimulus 0.92 [0.78–1.06], right stimulus 0.99 [0.88–1.11]; right button press: left stimulus 0.81 [0.70–0.91], right stimulus 0.64 [0.53–0.74]; means before transformation, left button presses 75.1 vs 80.3%, right button presses 69.4 vs. 57.0%).

Analyses on the transformed proportion of misses revealed no significant interaction with the factor Age when it was included as a covariate, therefore, this factor was excluded from further analyses. The dyslexic individuals missed more targets than the controls (0.015 [0.008–0.022] vs. 0.005 [-0.002–0.011]; means before transformation 1.5 vs. 0.5%), $F(1,24) = 4.9$, $p = .037$, $\eta_p^2 = 0.17$, and overall more misses were observed for HSF than for LSF stimuli (0.014 [0.007–0.02] vs. 0.006 [0.002–0.01]; means before transformation 1.4 vs. 0.6%), $F(1,24) = 13.8$, $p = .001$, $\eta_p^2 = 0.37$. We observed some significant interactions, but given the rather low amount of misses overall (before transformation 0.98% [0.50–1.48%]), we decided not to detail these effects.

3.3. Event-related lateralizations (ERLs)

ERLs for both groups and topographical maps for relevant time windows are displayed in Fig. 4.

Analyses of lateralized amplitudes determined for the PO8/7 electrode pair including the covariate Age did not reveal relevant effects involving this factor, therefore, this factor was excluded from further analyses. ANOVAs for each 20 ms time window revealed a negative deviation from zero from 280 to 320 ms, $Fs(1,24) > 8.4$, $ps < .009$, $\eta_p^2 > 0.25$. This deviation was most significant in the 280–300 ms time window (-0.31 µV [-0.52 to −0.11]), $F(1,24) = 9.7$, $p = .005$, $\eta_p^2 = 0.29$. Positive deviations from zero were observed from 520 to 820 ms, and from 960 to 1000 ms, $Fs(1,24) > 6.0$, $ps < .022$, $\eta_p^2 > 0.20$. This positive deviation was most significant in the 620–640 ms time window (1.04 µV [0.78–1.30]), $F(1,24) = 68.2$, $p < .001$, $\eta_p^2 = 0.74$. Importantly, no significant group differences were observed for any of two successive time windows.

3.4. Lateralized power spectra (LPS)

LPS estimates for the lower α_1 band and the upper α_2 band and topographical maps for relevant time windows for both groups are displayed in Figs. 5 and 6.

Analyses of LPS estimates for the lower α_1 band determined for the PO8/7 electrode pair including Age as a covariate revealed an effect of the covariate from 440 to 500 ms, $F(1,23) > 7.6$, $p < .012$, $\eta_p^2 > 0.24$, while the influence of the other factors including the intercept, did not meet our significance criterion. After excluding the factor Age from our analyses, we observed a positive deviation from zero from 400 to 760 ms, and from 820 to 1000 ms, $F(1,24) > 6.8$, $p < .015$, $\eta_p^2 > 0.22$, being most significant in the 540–560 ms time window (0.042 [0.026–0.059]), $F(1,24) = 28.5$, $p < .001$, $\eta_p^2 = 0.54$. These positive estimates imply that contralateral power was reduced as compared to ipsilateral power. These analyses also revealed a group difference from 400 to 460 ms, $F(1,24) > 8.1$, $p < .010$, $\eta_p^2 > 0.25$. However, the analysis including the covariate Age indicates that this effect may be due to small age differences between the groups. Further inspection of the covariate revealed that for the time window in which its influence was most significant (460–480 ms), a highly significant positive correlation between Age and LPS amplitude was observed ($r = 0.602$, $p = .001$). Inspection of the data suggested that this effect could be due to an outlier in the experimental group. After removal of this outlier, the effect of Age was no longer significant. Positive deviations from zero were still observed from 400 to 740 and from 840 to
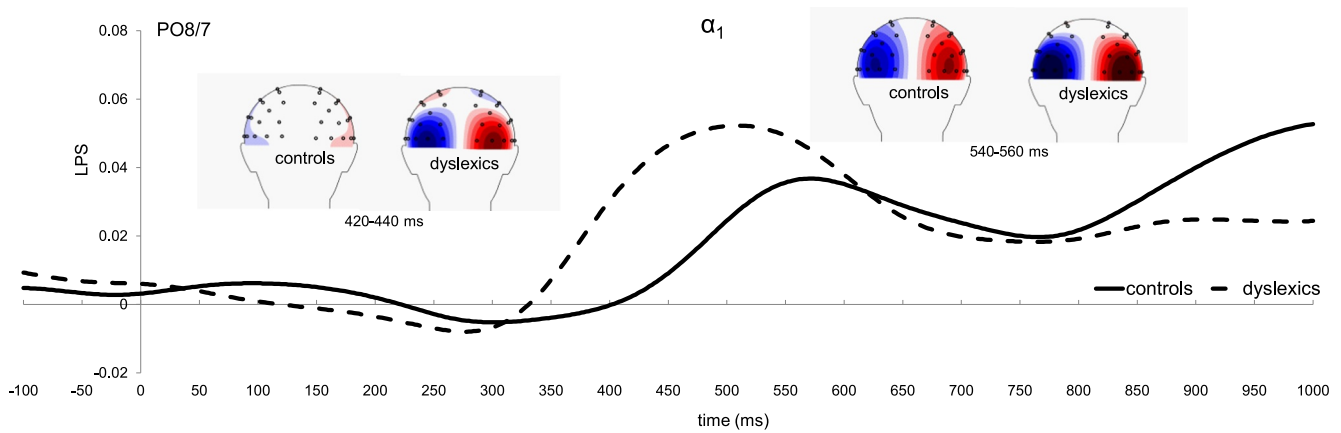
Fig. 5. Grand averages of lateralized power spectra (LPS) estimates for the lower alpha band (α_1) for controls and dyslexic individuals. The LPS is based on a double subtraction technique that estimates the difference in power for a specific frequency band between ipsilateral and contralateral electrodes that depends on attentional orienting. This method is based on power estimates on a single trial basis, which has the advantage that trial-to-trial changes are not cancelled out. Like ERLs, this method corrects for overall hemispherical differences. The displayed ipsi-contralateral electrode pair PO8/7 is located above occipital cortex. Topographies of the LPS for most relevant time windows (420–440 ms and 540–560 ms) indicate that effects were most pronounced above occipital cortex.
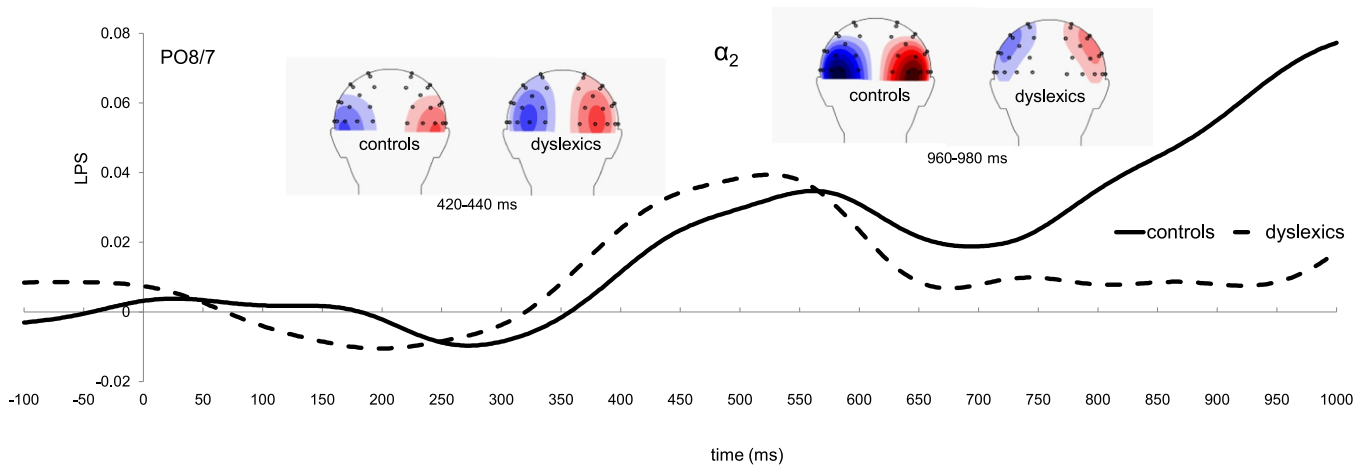

Fig. 6. Grand averages of lateralized power spectra (LPS) estimates for the upper alpha band (α_2) for controls and dyslexic individuals. The displayed ipsi-contralateral electrode pair PO8/7 is located above occipital cortex. Topographies of the LPS for most relevant time windows (420–440 ms and 960–980 ms) indicate that effects for controls were most pronounced above occipital cortex.

1000 ms, $F(1,23) > 7.3$, $p < .013$, $\eta_p^2 > 0.24$, and a Group difference was still present from 420 to 460 ms being most significant in the 420–440 ms time window, $F(1,23) = 7.5$, $p < .013$, $\eta_p^2 = 0.25$. Interestingly, this difference reflects a more positive deviation for the dyslexic individuals than for the control group (420–440 ms; dyslexic individuals: 0.034 [0.017–0.051]; controls: 0.004 [-0.011–0.019]).

Analyses of LPS estimates for the upper α_2 band determined for the PO8/7 electrode pair showed no significant effect of the covariate Age, while this same analysis revealed an effect of Group from 900 to 1000 ms, $F(1,23) > 7.7$, $p < .p < .011$, $\eta_p^2 > 0.25$. After exclusion of the covariate Age, the analyses revealed a positive deviation from zero from 380 to 620 ms, and from 900 to 1000 ms, $F(1,24) > 7.6$, $p < .011$, $\eta_p^2 > 0.24$, being most significant in the 420–440 ms time window (0.025 [0.017–0.033]), $F(1,24) = 37.5$, $p < .001$, $\eta_p^2 = 0.61$. An effect of Group was present from 940 to 1000 ms, $F(1,24) > 6.9$, $p < .015$, $\eta_p^2 > 0.22$, being most significant in the 960–980 ms time window, $F(1,24) = 7.5$, $p = .011$, $\eta_p^2 = 0.24$. The dyslexic individuals (0.011 [-0.023–0.045]) showed a weaker positive deviation from zero than the control group (0.072 [0.041–0.104]).

Given the observed group differences on the LPS estimates for the upper alpha band from 940 to 1000 ms, we explored whether there was any relation between individual response speed in the endogenous

orienting task and the observed reduction in contralateral alpha power. Analyses for the dyslexic individuals showed a trend to a negative correlation between the LPS and RT ($r = -.49$, $p = .055$ [1-tailed]), suggesting that faster responses may be related to a stronger contralateral alpha reduction (lower panel Fig. 7). No such effect was present for the controls ($r = .02$, $p = .480$ [1-tailed]; upper panel Fig. 7).

We also explored whether there was a relation between the LPS estimates for the upper alpha band from 940 to 1000 ms and performance on any of the neuropsychological tasks per group. After Bonferroni correction, no effects were observed for the controls ($p > 0.23$), but for the dyslexic individuals we observed a significant relation between performance on the Bourdon-Wiersma test and the LPS ($r = -.70$, $p = .006$ [1-tailed]; see lower panel Fig. 8).

Finally, since performance on the Posner task and performance on the Balloons B task is thought to index endogenous orienting, we examined whether there was a relation with performance on these tasks. A trend to a significant correlation was observed between the response times (including both groups) in the Balloons B task and the validity effect (invalidly – validly cued RT) in the Posner task ($r = .29$, $p = .077$ [1-tailed]).
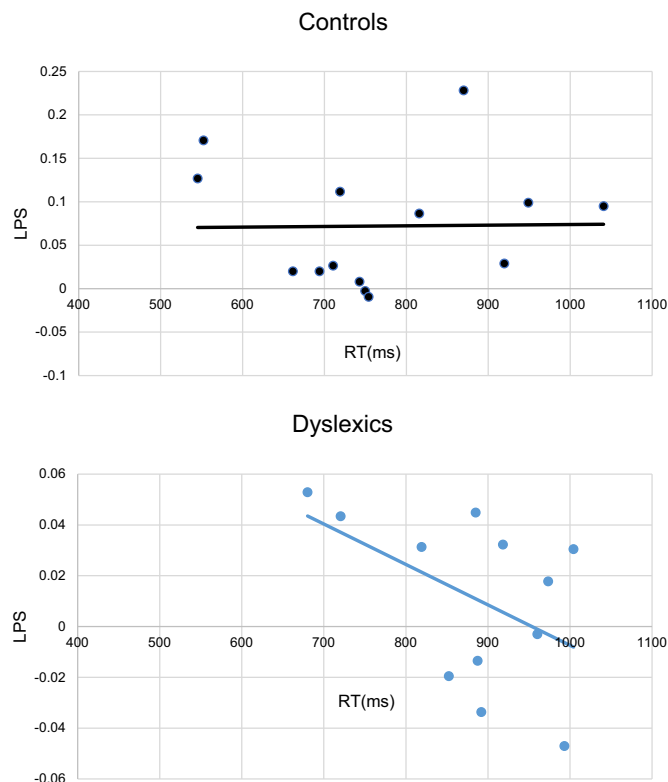
Fig. 7. Individual lateralized power spectra (LPS) estimates in the upper alpha band as measured above occipital cortex from 940 to 1000 ms after cue onset (along the ordinate), related with overall reaction time (RT) in the endogenous orienting task (along the abscissa). Positive LPS estimates indicate a contralateral reduction in alpha power while negative LPS estimates indicate an ipsilateral reduction. Data for the control group are displayed in the upper panel while data for the dyslexic individuals are displayed in the lower panel. The thick lines in the plots describe the overall trends for both groups. Note that different scales were used for the two groups along the ordinate as LPS data were much smaller for the dyslexic individuals than for the controls.

Fig. 8. Individual lateralized power spectra (LPS) estimates in the upper alpha band as measured above occipital cortex from 940 to 1000 ms after cue onset (along the ordinate), related with the time needed to perform the Bourdon-Wiersma test (along the abscissa). Data for the control group are displayed in the upper panel while data for the dyslexic individuals are displayed in the lower panel. The thick lines in the plots describe the overall trends for both groups. Note that different scales were used for the two groups along the ordinate as LPS data were much smaller for the dyslexic individuals than for the controls.

4. Discussion

Several researchers (e.g., see Banfi et al., 2017) have postulated that developmental dyslexia is characterized by problems with attentional orienting, which may be denoted as the *attentional deficit* hypothesis. Other researchers, however, have argued that this apparent consensus is due to a rather selective view on the evidence (see Ramus et al., 2018). Part of the confusion in the literature may be related to the different attentional deficits that have been reported (see also Valdois et al., 2018). Several researchers indicated that dyslexic individuals have problems with exogenous orienting (e.g., Facoetti et al., 2001), which can be related to the *mini-neglect* hypothesis while other researchers pointed to specific problems with endogenous orienting (e.g., see Buchholz and McKone, 2004; Liu et al., 2018). Furthermore, there is also support for changes in temporal orienting, either by a delayed recruitment of attention (the SAS hypothesis; Hari and Renvall, 2001), or by having problems with sustaining attention (Facoetti et al., 2000b). The goal of the current paper was to further examine the evidence related to endogenous orienting as the ability to voluntarily direct attention towards a specific location seems crucial for reading. We focused not only on behavioral differences between dyslexic individuals and controls, both in neuropsychological tests and an endogenous orienting task, but were especially interested in examining an electrophysiological index for attentional orienting that is based on local EEG changes in the lower and higher alpha band, assessed with LPS.

Before focusing on possible group differences related to attentional orienting, it is relevant to establish whether the dyslexic individuals
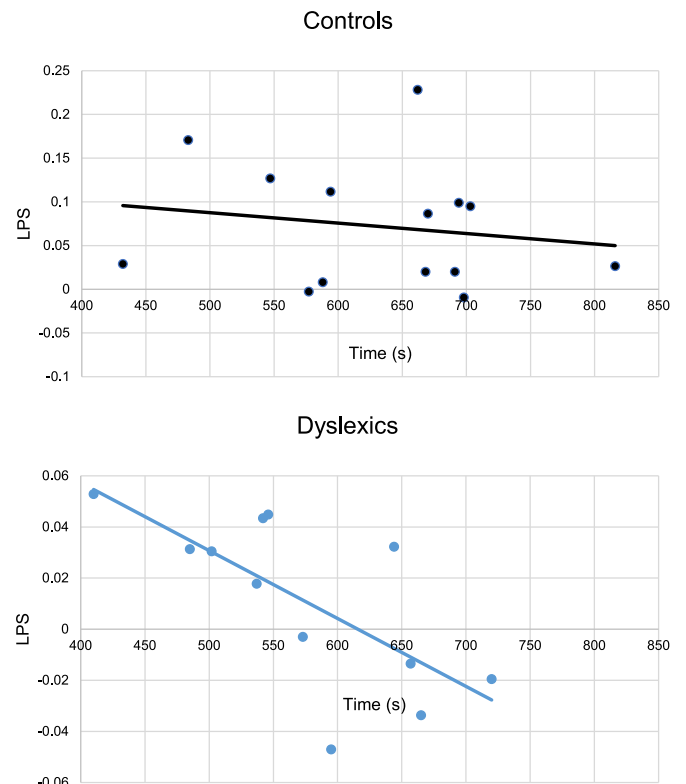
scored worse on the Dutch dyslexia screening test (DST[NL]) than the controls. Several members of the experimental group were already familiar with this test, however, the results revealed that the remaining five members of the experimental group scored worse when compared to the control group, especially on the nonsense word reading subtest. The latter result is a common observation in research on dyslexia, which suggests that the tested dyslexic individuals can be characterized as having a phonological decoding problem (e.g., see Facoetti et al., 2006).

The data of the neuropsychological tests did not support the presence of an attentional deficit in our dyslexic participants. First, results on the Trail-making tests were comparable for dyslexic individuals and controls suggesting no differences in executive functions. Secondly, results on the Bourdon-Wiersma, and Balloons-A test revealed no group differences, suggesting that visual perception, exogenous orienting, and overall vigilance (Bourdon-Wiersma) were unaffected.[3] Unexpectedly, analysis of the Balloons-B test showed faster overall search times for dyslexic individuals as compared to controls (see Fig. 2), which suggests that our dyslexic participants had no difficulty with endogenous orienting (but see Vieira et al., 2013; Siéroff, 2017). This improved performance might be related to increased development of the parvocellular system for dyslexic participants (e.g., see Stein, 2001), but could also be linked to effective interventions to deal with dyslexia as we

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[3] A recent study, however, indicates that dyslexic individuals may have some problems with perception as they displayed poorer binocular stability (Przekoracka-Krawczyk et al., 2017).

examined high-functioning dyslexic individuals.

In stark contrast to the results of our neuropsychological tests, results of our endogenous version of the Posner cuing task provide support for the presence of attentional deficits and give more insight into the underlying neurophysiological processes. First, major group differences were observed as dyslexic individuals responded slower (see Fig. 3) and missed more targets than controls, which replicates and extends the related findings of Wijers et al. (2005). The question is whether this performance difference can be ascribed to attentional differences or whether other processes (e.g., slower decision making or even motoric processes) are responsible for the observed group difference. Overall, responses were clearly faster for validly cued than for invalidly cued targets for both groups. However, a complex interaction was observed involving the factor Group. Follow-up analyses suggested that the effect of Cue Validity was quite constant for controls, while for dyslexic individuals the effect of Cue validity was dependent on the spatial frequency of the presented targets, and the visual field in which they appeared. The effect of Cue Validity was largest for HSF targets in the left visual field (109 ms) and smallest for HSF targets in the right visual field (23 ms). These observations resemble the findings from Facoetti et al. (2001), and support the *mini-neglect* hypothesis. Thus, dyslexic individuals seem to have problems with orienting towards the invalidly cued left visual field. No comparable effect was found with LSF stimuli, which may imply that this effect only becomes visible when detailed visual processing is required. However, the *mini-neglect* hypothesis does not explain the overall observed delay for dyslexic individuals. This observation leaves open the possibility that the overall group difference is related to differences in endogenous orienting.

Our LPS estimates for the lower alpha band (see Fig. 5) indicate that attention-related effects (i.e., a contralateral vs. ipsilateral reduction) in alpha power are present in both groups at around 550 ms. Interestingly, this contralateral reduction started earlier for dyslexic individuals (~ 350 ms) than for the controls (~ 430 ms), which suggests that our dyslexic individuals oriented at an earlier moment in time than the controls, which obviously does not support the SAS hypothesis. Support for the presence of an *attentional deficit* on the basis of the EEG data comes from the LPS estimates for the upper alpha band (see Fig. 6). Although here attention-related changes in alpha power are also present in both groups at around 500 ms, shortly before target onset (940–1000 ms after cue onset) the attention-related effect is only clearly present for the controls but not for the dyslexic individuals. These results again do not confirm the SAS hypothesis of Hari and Renvall (2001; see also the ERL results below). However, the results suggest that dyslexic individuals had problems with sustaining their attention to the relevant side. With the current number of participants it may be difficult to demonstrate that the latter effect on the LPS is actually related to the delay observed on RT. Nevertheless, correlational analyses for the dyslexic individuals revealed that larger LPS estimates, which are indicative of normal orienting, may be related to faster responses (see Fig. 7). Thus, increased response delays for dyslexic participants may be related to a reduced ability to sustain attention. An additional comparison with performance on the neuropsychological tests revealed that for dyslexic individuals, faster responses on the Bourdon-Wiersma test were also related to larger LPS values (see Fig. 8). In other words, a larger score on our neurophysiological index for attention in the endogenous orienting task was related to faster selection of the relevant group of dots in the Bourdon-Wiersma task. These correlations suggest that individual differences in response speed for the dyslexic participants are at least partly related to attentional orienting. No such effects were observed for the controls, which suggests that the individual differences on RT in the control group are related to other processes, like decision making and motoric processes. Although the current evidence is preliminary as it is based on a low number of participants, it definitely points to a need for further research that examines the link between lateralized alpha power and behavior in dyslexia.

One could argue that the discrepancy in results between the lower and higher alpha bands in our study is related to a distinction that was already pointed out by Klimesch (1999). Klimesch noticed that the lower alpha band is related to general task demands while the upper alpha band was more related to task-specific semantic information. Nevertheless, the observed effects in the current study are both task-specific as our method implies that unspecific effects are subtracted out. One possibility that we did not explore, is that there are differences in the individual alpha frequencies (IAF) between the groups, which is certainly an issue that should be incorporated in future studies (e.g., see González et al., 2018). For example, a difference in IAF between groups might explain why lateralized effects on power in the lower alpha band actually emerged earlier for dyslexic individuals than for controls in our study.

The observed group difference on the LPS data for the upper alpha band could be related to temporal orienting and a left-lateralized fronto-parietal network (Nobre, 2001). This finding could be investigated in future research by, e.g., employing a paradigm used by Rohenkohl and Nobre (2011), in which the relation between alpha power and temporal orienting was examined. They specifically observed a reduction in alpha power on trials in which targets were expected, but not presented. If such an effect was observed for controls but not for dyslexic individuals, it would provide further support for the hypothesis that dyslexics have specific problems with temporal orienting.

Participants in our study had more problems with identifying HSF than LSF targets, as slower responses and more errors were observed for HSF targets. It may be argued that our HSF targets are more related to parvocellular processing while the LSF targets may be more related to magnocellular processing. The observed performance differences between dyslexics and controls, however, do not suggest that dyslexic individuals encountered more problems with LSF stimuli, thus, our results do not support the idea of a selective impairment of magnocellular pathways. Nevertheless, the spatial frequency of our LSF stimuli may not have been sufficiently low to selectively recruit magnocellular pathways. Thus, our results should not be considered as evidence against the magnocellular hypothesis.

ERLs computed from ERPs related to the onset of the left and right cues demonstrated the presence of both the EDAN and the LDAP above occipital sites (see Fig. 4). Both lateralized components showed time courses and topographies that were quite comparable to those reported in earlier studies on participants without dyslexia (e.g., see Van der Lubbe et al., 2006). In line with the results of Wijers et al. (2005), we did not observe differences in these components between dyslexic participants and controls. Finally, we did not replicate the group difference on anterior negativity that was reported by Wijers et al. (2005), thus, our findings do not support the presence of an anterior inter-hemispheric asymmetry in dyslexic participants.

In a theoretical article, Vidyasager (2013) pointed to possible differences in neurophysiological oscillations between dyslexic individuals and controls. There, however, it was argued that dyslexic individuals might show an impairment in low gamma frequencies, partly based on the idea that reading is related to the speed of visual search, which is estimated to be about 20–45 ms per item ($\approx$ 20–50 Hz). Recently, Scheeringa et al. (2016) proposed that gamma oscillations are related to a bottom-up flow of information (feed-forward, or stimulus-induced), while alpha oscillations are related to top-down inhibitory modulations (feedback; see also Klimesch et al., 2007, 2011; Klimesch, 2012). Decreased contralateral alpha as observed at the end of the cue-target interval for controls might therefore imply increased contralateral gamma activity after onset of a subsequently presented stimulus and vice versa, and for dyslexic individuals it might mean that the lack of this contralateral decrease is accompanied with less gamma activity after stimulus onset, in line with the idea of Vidyasager (2013). The experimental setup employed in the current study is not optimal to properly analyze gamma activity, but future studies employing MEG

(magnetoencephalographic) measures may test the proposed changes in gamma in relation to alpha for dyslexic individuals.

Results as observed in the current study might motivate interventions that enhance attentional selection processes. Several recent studies revealed that a specific intervention with action video games (AVG) may improve attentional processes and reduce reading problems in dyslexic children (Franceschini et al., 2013, 2017; Franceschini and Bertoni, 2018; Gori et al., 2016). For example, AVG training for dyslexic children improved phonological decoding (Franceschini et al., 2013, 2017; Franceschini and Bertoni, 2018), visuo-spatial attention (Franceschini et al., 2013, 2017), and crossmodal attention shifting (Franceschini et al., 2017). A recent paper by Łuniewska et al. (2018), however, indicated that the effects of the AVG intervention with Italian- and English-speaking children were not observed for Polish-speaking children, indicating that the effectiveness of the AVG intervention is still a point of discussion.

In sum, our data revealed the following results. First, no clear reduction in contralateral power in the upper alpha band at the end of the cue-target interval in the Posner task was observed for dyslexic participants while this reduction was present for controls. These findings suggest that dyslexic participants were not able to sustain attention. Secondly, we observed a contralateral reduction in both groups in the lower alpha band halfway the cue-target interval, which suggests a comparable and actually even faster initial orienting effect for dyslexic individuals, which does not confirm the SAS hypothesis. Third, dyslexic individuals had problems with identifying invalidly cued HSF targets in the left visual field, which partly supports the *mini-neglect* hypothesis. Fourth, the delay observed for dyslexic individuals seems related to a diminished orienting effect in the cue-target interval. Fifth, performance on the neuropsychological tests did not point to a problem at the level of executive functioning, while absence search was actually improved for dyslexic individuals, suggesting that these tests are sensitive to different aspects than the employed endogenous orienting task. Together, these observations support the view that developmental dyslexia can be characterized by different attentional deficits, and foremost an inability to sustain spatial attention.

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