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Print-Tuning Lateralization and Handedness:

An ERP Study in Dyslexic Higher Education Students

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Abstract

Despite their ample reading experience higher-education students with dyslexia still show deficits in reading and reading-related skills. Lateralized print-tuning, the early sensitivity to print of the left parietal cortex signalled by the N1 event-related potential (ERP) component, differs between beginning dyslexic readers and controls. For adults the findings are mixed. The present study aims to investigate whether print-tuning, as indexed by the N1 component, differs between 24 students with dyslexia and 15 non-dyslexic controls. Since handedness has been linked to lateralization, first a separate analysis was conducted including only right-handed participants (n = 12 in both groups), like in most previous studies. ERPs were measured during a judgement task, requiring visual, phonological, or semantic judgments. In both groups the N1 was earlier and stronger in the left then in the right hemisphere. However, when only strongly right-handed participants were evaluated, the N1 was less left-lateralized for participants with dyslexia as compared to controls. Participants with dyslexia had longer reaction times during the ERP-experiment, and performed worse on many reading (-related) tasks. These findings suggest that abnormal print-tuning can still be found among higher-education students with dyslexia, and that handedness should be regarded in the study of print-tuning.

Keywords: Dyslexia, Adults, Neuroimaging, Lateralization, Print-Tuning

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According to the International Dyslexia Association (IDA), developmental dyslexia is a specific learning disability of neurological origin characterized by “difficulties with accurate and/or fluent word recognition and by poor spelling and decoding abilities” (Lyon, Shaywitz, & Shaywitz, 2003, p. 2). Dyslexia has often been linked to phonological processing difficulties (e.g. Ramus et al., 2003), and is not the result of low cognitive abilities and/ or the lack of appropriate instruction (Lyon et al., 2003). The prevalence of dyslexia generally varies between 3 - 10 %, depending among others on the language and diagnostic criteria (Miles, 2004). Even though most individuals with dyslexia choose a vocational education, the number of dyslexic students in higher education is still significant. Richardson and Wydell (2003) report that 0.42% of all UK higher education students have dyslexia. Dyslexia is also the most frequently reported disability among students in higher education, and the number is increasing according to figures of the Higher Education Statistics Agency (as cited in Mortimore & Crozier, 2006).

Far less attention has been paid to dyslexia in individuals with advanced reading skills than to dyslexia in children (but see e.g. Felton, Naylor, & Wood, 1990; Miller-Shaul, 2005; Rüsseler, Becker, Johannes, & Münte, 2007), and most studies that have been done were conducted in English. For Dutch, which has a more transparent orthography than English, only very few systematic studies of dyslexia in higher education students have been carried out. According to Callens, Tops, and Brysbaert (2012), the cognitive profile of Belgian (Dutch-speaking) dyslexic students includes poorer scores on a wide range of linguistic processes including (but not limited to) word, pseudo-word and text reading, digit span, and rapid naming of verbal information. Similar to studies in English (See Swanson & Hsieh, 2009), the main results indicate that students with dyslexia had even more trouble writing than reading, and that reading deficiencies were more prominent in speed and not in accuracy indexes.

The slower reading by students with dyslexia may be a result of deficient letter string processing as demonstrated by Hawelka, Huber and Wimmer (2006). Deficient letter string processing could be caused by deficits in visual processing and visual attention (e.g. Buchholz & McKone, 2004; Lobier, Zoubrinetzky, & Valdois, 2012). The present paper aims to investigate if there is a difference in brain activity between Dutch students in higher education with and without dyslexia using Event Related Potentials (ERP). More specifically we focus on early visual processing as indexed by the N1 component.

Lateralized Print-Tuning

The N1 is an early negative ERP component around 150 ms that, despite its wide distribution, manifests earlier and stronger in the left than in the right parietal-occipital region during visual/orthographic tasks (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999). It is thought to originate from the Visual Word Form Area (VWFA) in the fusiform gyrus as a response to a written stimulus, and is associated with perceptual expertise for print processing (Dehaene, Clec'H, Poline, Bihan, & Cohen, 2002; Moscoso del Prado Martín, Hauk, & Pulvermüller, 2006; Nobre, Allison, & McCarthy, 1994), for which we will here use the term print-tuning. Lateralized print-tuning develops with age; Helenius, Tarkiainen, Cornelissen, Hansen and Samelin (1999) found evidence of N1 lateralization in a magnetoencephalography (MEG) study conducted in adults; no such N1 lateralization was found by Maurer, Brem, Bucher and Brandeis (2005) in an electroencephalography (EEG) study in pre-reading children. Both studies used a similar method for data collection, a repetition detection task, and contrasted symbol strings against letter strings or words.

Maurer et al. (2007) found that, by Grade 2, lateralized print tuning is already observable in children with normal reading development, but not in children with dyslexia. However, in Grade 5, N1 lateralization differences between dyslexic and control children had almost completely disappeared (Maurer et al., 2011), suggesting that some normalization of print-tuning had taken place. It is worth noting that there were still clearly observable differences in brain activation in the VWFA in the accompanying functional Magnetic Resonance Imaging (fMRI) study. Furthermore, differences in the N1 component have been found between adults with and without dyslexia using MEG (Helenius et al., 1999). Spironelli and Angrilli (2009) also found reduced N1 lateralization in 10 year old normal-reading children in contrast to both students and older adults. Contrary to Helenius et al. (1999) and Maurer et al. (2005, 2007, 2011) they used a word reading task rather than a repetition detection task, which may be more adequate to measure N1 lateralization in the EEG of older participants. A similar methodology to Spironelli and Angrilli (2009) is therefore adopted in the present study.

Handedness and Dyslexia

Thus far, we focused on N1 lateralization effects in individuals with and without dyslexia. While the processing of language (including auditory and visual comprehension and expressive skills) is typically left-lateralized, the right-lateralization of language occurs in 15% of the ambidextrous, and 27% of the strongly left-handed individuals, in contrast to only 4% of the strongly right-handed individuals (Knecht et al., 2000). As a consequence, handedness emerges as an important factor, especially since individuals with and without dyslexia have been traditionally assumed to differ in this respect (e.g. Geschwind & Behan, 1982). The incidence of left-handedness among the population with dyslexia has been widely debated (Locke & Macaruso, 1999; Scerri et al., 2010; Vlachos, Andreou, Delliou, & Agapitou, 2013). Much is yet unclear about how hemispheric lateralization is related to language and literacy problems; while atypical lateralization is often reported among people with these problems, many people with an atypical cerebral lateralization in the general population do not have language or literacy difficulties (Bishop, 2013).

Despite some regional variation, 70-90% of the world's population is right-handed or has a strong tendency towards right-handedness, indicating left brain-dominance for motor function (Gilbert & Wysocki, 1992; Raymond & Pontier, 2004; Scerri et al., 2010). Left-handedness has been found to prevail in 10% of the population and mixed-handedness can be identifiable in up to 30% of individuals (Annett, 2002; Hardyck & Petrinovich, 1977). How handedness affects the lateralization of print-tuning is unclear. This is mainly due to the lack of exhaustive reports on handedness, the tendency to exclude left handers from neuroimaging studies (e.g. Bentin et al., 1999; Spironelli & Angrilli, 2006, 2009; among many others), and their underrepresentation when they are included (e.g. Helenius et al., 1999; Maurer et al., 2005; for a discussion see also Willems, Van der Haegen, Fisher, & Francks, 2014). That early visual processing can differ between left- and right-handers becomes clear from a study by Willems, Peelen and Hagoort (2010); they found that the visual processing of human faces is typically right-lateralized, in the fusiform gyrus, in right-handers, but that this lateralization was absent among left-handers.

The Present Study

We here investigate whether lateralized print-tuning differs between students with and without dyslexia. Although the results of previous studies are mixed, we expect to be able to find less left-lateralized N1 in students with dyslexia, since the method by Spironelli and Angrilli (2009) may be more sensitive than the letter-symbol contrast employed in other studies (e.g. Helenius et al., 1999; Maurer et al., 2005). Because handedness may influence language lateralization and most previous studies have only included right-handed participants, we first analysed the data of strongly right-handed participants only, and then included the whole sample in our analyses. With this analysis we also aim to investigate to what extent our results can be generalized to the whole population, or whether they are valid for right-handers only. We expect that the N1 lateralization difference between students with and without dyslexia will be stronger when only right-handed participants are included because language is generally more often left-lateralized in right-handers. Behavioural tests were also conducted to assess current reading fluency and reading related skills. We expect that especially stronger activity in the left posterior area will be related to better reading and reading-related skills.

Methods

Participants

Fifty Dutch higher-education students or recent-graduates, between 18 and 28 years old, were included. Thirty participants had a clinical diagnosis of dyslexia by an educational psychologist, for which they provided written proof, while the other 20 participants reported no reading difficulties. Serious neurological, linguistic or psychiatric deficits and developmental disorders other than dyslexia, like Attention Deficit Disorder (ADD), Autism Spectrum Disorders (ASD) or dyscalculia, were exclusion criteria for participation in the study. Participants were recruited with the help of posters, mouth to mouth advertisement and announcements by study advisors. Two participants that were tested were excluded from further analysis; one student with dyslexia because the behavioural test was invalid so the diagnosis of dyslexia could not be confirmed, and the other, without dyslexia, because of the presence of ADD, which was initially not reported. All participants were native speakers of Dutch and spoke English as a second language. Other languages that were spoken by some of the participants included French, German, Frisian, Spanish and Chinese. All participants had normal or corrected to normal vision and none had hearing impairments, which wereinclusion criteria, and was verified in the intake questionnaire. They participated in the study in exchange for course credits or a gift-voucher. All participants gave written informed consent after having received written and verbal information about the study.

The forty-eight remaining participants were categorized into two groups, a group with dyslexia and a non-dyslexic control group. As we did not have any control about how dyslexia was diagnosed, and because in most cases the diagnosis was made years ago, word and pseudo-word reading fluency tests, which will be discussed below, were administered at the beginning of our study. Of the 29 participants with a clinical diagnosis of dyslexia, only the 25 that showed poor performance on these tests, were included in the Dyslexia group. Reading was judged to be poor when the student's reading score belonged to the lowest two deciles on at least one test and to the lowest four deciles on the other test, according to the norms provided by Kuijpers et al. (2003). Fifteen students without a diagnosis of dyslexia, and performing above average on both word and pseudo-word reading, were included as the Control group. The five students with dyslexia who read above the norms and the four students without dyslexia who performed below average on at least one reading test were excluded from further analyses.

Of the remaining 40 students, 32 were female (19 dyslexic) and 8 were male (6 dyslexic). The mean age was 22;3 (years; months), *SD* = 2;7. Thirteen participants with dyslexia, and 12 control participants were strongly right-handed (handedness score > 8, see below for an explanation). Only in the Dyslexic not-strongly right handed group there were people with a left-hand preference (m = 3.92, sd = 6.25), the three not-strongly right-handed participants in the control group all scored 8 on the handedness questionnaire. In the sub-sample with strongly right handed participants, five were male (3 dyslexic) and 20 were female (10 dyslexic).

Experimental Design

Similar to the procedure by Spironelli and Angrilli (2009), participants had to perform three tasks with the same word-pairs: a visual control task and two linguistic judgement tasks. During the first task, participants had to indicate whether both words of the pair were written in capitals (visual judgement), during the second task they had to indicate whether the words rhymed (phonological judgment), and during the third task they had to indicate whether the word meanings were related (semantic judgement). When there was a match, the participant had to press a button with a green happy smiley, when there was no match the participant had to press a red sad smiley. The match percentage was 25% during each task. Whether the match or no-match button was on the left or right side of the keyboard was balanced across participants. Differences across tasks are mainly important for the analysis of the reaction times and accuracy, but not so much for the EEG analysis since we focus on early orthographic processing, which we expect to be similar in all three tasks.

The stimuli consisted of 100 word-pairs that were kept constant in all tasks. The first word was always written in capitals; if the second word was also written in capitals this was a visual match. If the words rhymed this was a phonological match, and if the meanings of the words were related, this was a semantic match. There were 25 matches of each type, and word-pairs only matched in one task. The 25 remaining word-pairs did not match in any of the tasks. All words were mono- or bi-syllabic nouns, between 3 and 8 letters in length. Words with a frequency above 10 per million were selected from the CELEX database (Baayen, Piepenbrock, & Gulikers, 1995). Only words with one listing were included to avoid words with multiple meanings. The final set of word-pairs was selected from a larger set of 120 word-pairs that was piloted among 3 children between 10 and 12 years old, and 3 adults, such that ambiguous items were eliminated.

For all three tasks, the word-pairs were presented successively in the centre of the screen. The words were written in white on a black background in font Courier New, size 18. At the start of each trial, the first word appeared for 1.5 s. This word was followed by an inter stimulus interval (ISI) of 1 s during which a fixation cross was presented. Next, the second word appeared until the participant responded, with a maximum duration of 5 s. When the second word disappeared, the screen turned black for half a second. Finally, during the inter trial interval (ITI), a fixation cross appeared that announced the start of a new trial. The ITI length varied between 1.5-2.5 seconds. The timing of the experiment is illustrated in Fig.1. The stimuli were presented using E-prime 2.0.8.90 (Psychology Software Tools, Pittsburgh, PA, USA).

<<<<< INSERT FIGURE 1 ABOUT HERE >>>>>

Tasks were split into two blocks of 50 trials, which were presented separately. After performing all tasks once, the tasks were repeated in the same order as during the first half of the experiment. The order of the tasks was counterbalanced across participants. After 25 trials there was a short break, which could be ended by the participant. After each block, there was a longer break, where a short entertaining movie was played for 1.5-3 minutes such that the participants were forced to take a break and could switch more easily between tasks. In the middle of the experiment, there was a longer break during which participants were offered a drink. During the experiment, the participant sat in a dimly lit electrically shielded and sound attenuated room at an approximate distance of 50 cm from a 16 inch computer screen. Depending on the number of letters the stimuli were approximately 2 – 5.5 cm wide, resulting in a visual angle between 1.15 and 3.15 degrees.

Behavioural Tests

Before the EEG recording, a short background questionnaire and several behavioural tests were administered. Participants were asked questions about their reading behaviour, language knowledge, and handedness. The latter was measured with an adapted version of the Dutch handedness inventory (van Strien, 1992), which is similar to the Edinburgh Handedness Inventory (Oldfield, 1971). Participants had to indicate which hand(s) they used for 10 actions. The final handedness score ranged from -10, completely left-handed to + 10, completely right-handed. Below the behavioural tests are described in more detail.

Word reading fluency. Word reading fluency was assessed with the Dutch version of the one-minute-test (“Eén-minuut-test”; Brus & Voeten, 1973). Participants had to read correctly as many words of increasing length and difficulty as possible within one minute.

Pseudo-word reading fluency. Pseudo-word reading fluency was assessed with the “Klepel” test (van den Bos, Lutje Spelberg, Scheepstra, & de Vries, 1994). Participants had to read correctly as many pronounceable non-words as possible within two minutes.

Digit-span. Verbal working memory capacity was assessed with the digit-span (DS) subtest of the fourth edition of the Dutch Wechsler Adult Intelligence Scale (WAIS-IV-NL; Wechsler, 2012). During the test participants had to verbally report series of digits orally presented by the experimenter. The test contains two parts consisting of 16 items each: forwards, where the digits have to be reported in the same order as they were presented, and backwards, where the digits have to be reported in the reversed order, starting with the last digit and ending with the first. Each part was terminated after two consecutive incorrect responses to series of the same length.

Similarities. The similarities test of the WAIS-IV-NL (Wechsler, 2012) was used to measure participants’ verbal intelligence. During this task, which includes 18 items of increasing difficulty, participants had to verbally explain the similarity between two words. The maximum score is 36 points and after four incorrect answers, the test is terminated.

Visual attention span. The Visual Attention Span (VAS), the span of letters that can be processed in parallel, was measured with a task described by Valdois et al. (2003). During this task participants saw letter strings for 200 ms on a computer screen. The strings consisted of 5 letters, selected from the following capitals: B, D, F, H, L, M, P, R, S, and T. Participants had to verbally report the letters they had seen in the order in which they were presented. There were 20 trials in total, and the score is the total number of letters reported correctly.

Rapid automatized naming. A Rapid Automatized Naming (RAN) test (van den Bos & Lutje Spelberg, 2007) was used to measure the ability to retrieve verbal information quickly from memory. Participants had to name 50 digits presented on a card as fast and accurately as possible.

EEG Recording and Analysis

The EEG was recorded using an elastic electro-cap with 64 tin electrodes that were organized according to the international 10-20 system (Sharbrough et al., 1991). A Refa 8-64 average reference amplifier (TMSi, Oldenzaal, the Netherlands) was used to record the EEG at a sampling rate of 500 HZ. No online filters were used. The horizontal and vertical ElectroOculogram (EOG) was recorded using 4 tin electrodes, two near the outer canthi of each eye, and two above and below the left eye. In addition, two electrodes were attached to the left and right mastoid and a ground electrode was attached to the sternum. Brain Vision Recorder 1.10 (Brain Products GmbH, Munich, Germany) was used to acquire the data.

The data were analysed using Brain Vision Analyzer 2.0.1.3931 (Brain Products GmbH, Munich, Germany). During pre-processing the data were first filtered with a high pass filter of 0.5 Hz and a low pass filter of 30 Hz, both with a slope of 24 dB/Oct. Next, large artefacts and EEG recorded during the breaks were manually removed after visual inspection, because they could interfere with the Independent Component Analysis (ICA) ocular correction that was used to correct for blinks and saccades. One right-handed participant with dyslexia had to be excluded from the EEG analyses because there were too many large artefacts that disturbed the ICA; therefore the EEG analysis was performed for 39 participants. After ICA the data was re-referenced to an average reference excluding the eye electrodes, mastoid electrodes, T7 and T8, which were often noisy because of bad contact, and any other electrodes exhibiting too much noise. The latter was determined during automatic artefact rejection with the following criteria: a difference of 200 µV within 200 ms, absolute amplitude larger than 100 µV or a gradient larger than 50 µV/ms. If more than 10% of the usable EEG was rejected, a channel would be excluded from the average and from the analysis; this applied to one participant. If it was a channel of interest, a stricter criterion of 5 % rejection was used; this applied to another participant for whom channel P6 had to be removed. The epoch length used for the analysis was 1200 ms, starting 200 ms before the onset of the first word. The baseline correction was performed using these first 200 ms before word onset. The number of trials kept in the analysis varied between 74 and 100 per participant per task, with the mean number of trials varying between 95.41, in the orthographic task, and 96.23, in the semantic task (*sd* between 2.77 – 4.38). The number of trials left in the analysis, as tested by a repeated measures analysis, did not differ significantly between groups or tasks, nor was there a group*task interaction.

After pre-processing, two clusters of electrodes were created by averaging the channel amplitudes: Posterior Left, consisting of P3, P5, P7, PO3 and PO7, and Posterior Right, consisting of P4, P6, P8, PO4 and PO8. For the participant for whom channels of interest had to be removed, the posterior right cluster contained only 4 electrodes. Similar to Spironelli and Angrilli (2009), we analysed the N1 response to the first word. The latency of the N1 was first determined in the grand average of all participants across all tasks, for the left and right posterior clusters, separately. A 100 ms search window, symmetrically around the mean N1 latency, was then used to detect the N1 semi-automatically for each participant, separately for each task and cluster. Finally, the peak latency and the mean amplitude averaged over 10 ms symmetrically around the peak were exported for statistical analysis.

Statistical Analysis

First, we analysed whether the Groups (Dyslexia vs. Control) differed on the behavioural measures using both parametric and non-parametric tests depending on the distribution of the variables, which was in all analyses assessed with the Kolmogorov-Smirnov test for normality. Two 2 x 3 repeated measures ANOVAs were used to analyse Group differences in reaction times and accuracy during the different Tasks (Visual vs. Phonological vs. Semantic). The reaction times were log transformed such that they were normally distributed. The accuracy data was not transformed, because this did not improve the normality of the distribution which was skewed due to a ceiling effect. These analyses were performed for left and right-handed people together to have more power, but if results differed from the analysis with only right-handed participants, the latter results are reported as well.

For the EEG analysis of both the N1 latency and N1 amplitude a 2 x 2 x 3 repeated measures ANOVA was performed with Hemisphere (Left vs. Right) and Task (Visual vs. Phonological vs. Semantic) as within subject factors, and Group (Dyslexia vs. Control) as between-subject factor. Correlations between reading (-related) skills and the N1 were also investigated. Depending on the normality of the involved variables, Pearson or Spearman correlations were used. These analyses were initially performed with strongly right-handed people only, with a handedness score > 8, since EEG studies usually include only right-handed participants. However, we repeated the analysis with all participants to investigate whether we could generalize our results to a larger population. Finally, a correlation analysis was performed to investigate in what way handedness is related to the behavioural and EEG measures in the study. Because handedness was not normally distributed, Spearman-correlations were used. Since the participants with dyslexia in this study were more left-handed compared to controls, this was done separately within the groups, to avoid confounding effects of dyslexia.

Results

Behavioural Tests

Participant characteristics and the scores on the behavioural tests are presented in Table 1, including effect sizes and t or U values of the statistical analyses. The groups did not only differ on the word and pseudo-word reading fluency tests, which was expected since it was part of the grouping criteria, but also on reading related skills. Dyslexic students performed worse on RAN, VAS and forward and backward DS. They performed similarly to the control group on the similarities task. There was no difference between the groups in the time that participants spent on reading. The dyslexic group was more left-handed than the control group, but they did not differ in age. The same analysis with strongly right-handed participants (with 13 dyslexic and 12 control participants) yielded similar results as the analysis with all participants. Only the DS scores did no longer differ significantly between groups (DS-forward: $U = 46.5$, $p = .086$, $r = .346$; DS-backwards: $U = 54.0$, $p = .181$, $r = .267$).

<<< INSERT TABLE 1 ABOUT HERE >>>

Reaction Times and Accuracy

Mean reaction times and accuracy obtained from the judgement tasks are presented in Table 2. There was a significant main effect of Group: dyslexic participants responded slower than controls (F (1, 38) = 14.113, $p = .001$, $\eta_p^2 = .271$). There was also a significant main effect of Task (F (2, 76) = 79.909, p < .001, η_p^2 = .678). Pairwise comparisons revealed that responses were fastest during the visual task compared to the other two tasks (p < .001), and that responses during the phonological task were faster than those during the semantic task, (p < .001). There was no significant interaction between Task and Group (F (2, 76) = 1.603, p = .208, η_p^2= .040). The assumptions of sphericity and homogeneity of (error) variance were not violated, and the log transformed reaction times were also normally distributed. When the analysis was repeated with only strongly right-handed participants the results for Task were similar, but the main effect of Group was no longer significant (F (1, 23) = 3.760, p = .065, η_p^2= .141).

For accuracy, there was a marginally significant main effect of Task, (F (2, 76) = 2.758, p = .070, η_p^2 = .067). Pairwise comparisons revealed that participants performed slightly better during the phonological task compared to the semantic task (p=.033). There was no main effect of Group, (F (1, 38) = .385; p = .539, η_p^2 = .010), nor an interaction between Group and Task (F (2, 76) = .968 p =.385, η_p^2 = .025). However, it has to be noted that the overall accuracy was very high, with a mean above 97% for all tasks and groups and a range between 86 and 100% correct. This suggests a ceiling effect, resulting in highly skewed data. In the analysis with only strongly right-handed participants, there were no (marginally) significant effects regarding accuracy.

<<< INSERT TABLE 2 ABOUT HERE >>>

EEG Analysis for Right-Handed Participants Only

In the first EEG analyses, 24 participants with a handedness-score above 8 were included, 12 with dyslexia and 12 controls. The EEG analyses of both N1 latency and amplitude included Hemisphere (left vs. right) and Task (visual vs. phonological vs. semantic) as within-subject factors, and Group (dyslexia vs. control) as between-subject factor. The assumption of sphericity was met in both analyses. All within-subject variables were normally distributed, and there was homogeneity of (error) variances across groups with the exception of amplitude in the left hemisphere during the phonological task and latency in the right hemisphere during the semantic task.

A significant effect of Hemisphere was found for N1 latency; the N1 peaked earlier in the left hemisphere (M = 171.028, SE = 5.209) compared to the right hemisphere (M = 192.194, SE = 4.928, F (1, 22) = 9.772, p = .005, η_p^2= .308). No significant main-effects of Group or Task, or interactions between Group and Task, were found.

Means and standard deviations for N1 amplitude are presented in Table 3. The N1 amplitude was more negative in the left than in the right hemisphere (F (1, 22) = 9.072, p = .006, η_p^2= .292). In addition, there was a significant interaction between Group and Hemisphere (F (1, 22) = 4.429, p = .047, η_p^2= .168). The right-handed participants with dyslexia showed less left-lateralization of the N1 than the right-handed control group, as illustrated in Figs. 2 and 3. Finally, there was a marginally significant main effect of Group, (F (1, 22) = 3.263, p = .085, η_p^2 = .129), the overall N1 amplitude was slightly larger for controls. No (marginally) significant main-effects of Task or interactions with Tasks were found.

<<< INSERT FIGURE 2 & 3 & TABLE 3 AROUND HERE >>>

Finally, correlations were calculated between the reading related scores and the N1 latency and amplitude in the left and right hemisphere. Because the N1 latency and amplitude did not differ significantly between tasks, the average N1 across tasks was used. Pearson correlations are reported, since N1 amplitude and the raw reading scores were normally distributed within the groups. The correlations between left N1 amplitude and reading fluency were marginally significant for both word, (r = -.373, p =.073), and pseudo-word reading (r = -.365, p = .080). The correlations between right N1 amplitude and reading scores were not significant, for word reading (r = .103, p = .634), nor for pseudo-word reading (r = .022, p = .918). Correlations with reading related skills were not significant except for the VAS and DS-backward scores. Here, a non-parametric test was used because the VAS and DS-Backward scores were not normally distributed. There was a marginally significant Spearman-correlation between VAS and left N1 amplitude (r_s = -.373, p = .072), and significant Spearman-correlations between DS-Backwards and both left N1 amplitude (r_s = - 4.26, p = .038) and right N1 amplitude (r_s = - .406, p = .049), There were no significant correlations between N1 latency in either hemisphere and reading (related) skills.

EEG Analyses All Participants

For the EEG analysis with all participants 24 participants with dyslexia and 15 participants without dyslexia were included. For the latency analysis the assumption of sphericity was met, for amplitude this was not the case for Task. Most within-subject variables were normally distributed within groups; only for the N1 amplitude in the right hemisphere during the semantic task this was not the case. The assumption of homogeneity of (error) variances was violated for latency in the right hemisphere during the semantic task, and for amplitude in the right hemisphere during the visual task.

Similar results were obtained for N1 latency for all participants as in the analysis with only strongly right-handed participants. N1 latency was shorter in the left hemisphere (M = 175.222, SE = 4.031) compared to the right hemisphere (M = 188.592, SE= 4.192, F (1, 37) = 6.075, p = .018, η_p^2= .141). No significant main effect of Group or Task or interaction effects between Group and Task were found. N1 amplitude was significantly more negative in the left hemisphere (M = -2.883, SE = .335) compared to the right hemisphere (M = -1.823, SE = .256, F

(1, 37) = 8.463, p = .006, η_p^2=.186). In contrast to the results for strongly right-handed participants, no effect of Group or interactions with Group were found, possibly due to a reduced N1 lateralization in the control group (Left N1: M = -3.305, SE = .526, Right N1: M = -1.691, SE = .401) and an overall stronger N1 in the dyslexic group (Left N1: M = -2.462, SE = .416, Right N1: M = -1.955, SE = .317). Effects of Task were again not significant. Of all correlations between N1 and reading and reading-related skills, only a marginally significant Spearman-correlation was found between the DS-backward and N1 amplitude in the right hemisphere (r_s= -.272, p = .094), and the DS-forward and N1 latency in the left hemisphere (r_s= -.279, p = .086).

Correlation Analysis Handedness

To investigate the effect of handedness, independent of the effect of dyslexia, a Spearman-correlation analysis was performed between handedness and the other study measures, separately per group. There was a marginally significant correlation for dyslexic students (n = 25) between handedness and word reading fluency (r_s = .364, p = .073), as well as between handedness and reaction times during the phonological task (r_s = -.338, p = .098) and the semantic task (r_s = -.357, p = .080). For the 24 dyslexic students included in the EEG analysis there was also a marginally significant correlation between handedness and the N1 voltage in the left hemisphere (r_s = -.373, p = .066). For controls (n = 15), there were no significant correlations between handedness and study measures, possibly due to the low variance in handedness scores among controls.

Discussion

The main research question was whether lateralization of print-tuning differs between students with and without dyslexia. A clear print-tuning effect was found: both dyslexic and control participants showed a clearly identifiable N1, which was significantly earlier and stronger in the left than in the right hemisphere, independent of which task was executed. In addition, the strongly right-handed dyslexic participants showed the expected weaker print-tuning, in that the N1 amplitude was less left-lateralized than in the controls. Therefore, this study shows the importance of handedness as a factor in the analysis of print-tuning deficits in students with dyslexia.

Our finding that the N1 was left-lateralized, both in amplitude and latency, is similar to other studies (e.g. Bentin et al., 1999; Spironelli & Angrilli, 2009). The fact that no task-related effects were found is probably due to N1 being an early component, reflecting early automatic processing. A modification of N1 amplitude lateralization by dyslexia has been found in previous EEG studies with young children (Maurer et al., 2007), and in a MEG study with adults (Helenius et al., 1999), but not in children in Grade 5 (Maurer et al., 2011). Since similar deficits in orthographic processing signalled by the N1 have been reported for young readers with dyslexia, it is unlikely that the N1 differences in our study are a consequence of the reading disorder, e.g. reflecting compensation, rather than a manifestation of the underlying reading deficit.

Remarkably, despite the lower power in the analysis, significant lateralization differences between dyslexic and control participants were only observed for strongly right handed participants. As most EEG studies only include (strongly) right-handed participants, this is a very important finding, as it suggests that the results of those studies are only valid for a subset of the population. Since 10% percent of the people are left handed and 30% percent have a mixed handedness (Annett, 2002; Hardyck & Petrinovich, 1977), this is a noteworthy group. In the dyslexic group, a marginally significant negative association was found between handedness and the left N1 amplitude; the left N1 amplitude was larger in right-handed dyslexic participants. In the present study, right-handedness was also related to better reading skills within the dyslexic group. Although this result was also only marginally significant, and needs to be verified in a larger study, it suggests that even for the better reading dyslexic students a print-tuning impairment can be found.

The behavioural tests revealed that students with dyslexia performed worse, relatively to the controls, on the (pseudo-)word reading fluency tasks, as well as on the RAN, DS and VAS tasks. However, their general verbal intelligence was similar to the control students. Interestingly, students with dyslexia did not spend more time reading per week than students in the control group. During the EEG experiment, students with dyslexia performed significantly slower than students without dyslexia during all tasks. Reaction times were fastest during the visual task followed by the phonological task, and slowest during the semantic task. Overall accuracy was very high and no significant group differences were found.

Our behavioural results are in line with previous studies. Callens et al. (2012) found similar differences in RAN and DS between higher education students with and without dyslexia. Lower performance on the VAS task, requiring fast visual processing of letter strings, has also been reported among adult dyslexic readers (Hawelka et al., 2006). Verbal intelligence, measured with the similarities task, did not differ between groups, which confirms that the students with dyslexia had a specific reading difficulty, and that the dyslexic and control group were effectively matched on verbal intelligence, probably due to the recruitment of higher education students. Although more subtle language deficits cannot be ruled out, as Callens et al. (2012) did report significant differences between students with and without dyslexia on morphological and syntactic indexes, these were not assessed in our study.

With respect to reaction times, our results are also in line with those by Callens et al. (2012), who found that differences between students with and without dyslexia were most pronounced on speed measures compared to accuracy measures. We expected to find that the phonological task in particular would be more difficult for the group with dyslexia, because a phonological processing deficit is often considered to be a core deficit of dyslexia (e.g. Ramus et al., 2003; Shaywitz & Shaywitz, 2005). Instead, we found that the students with dyslexia performed slower on all tasks. This could be a result of a deficit in early automatic print processing which took place during all tasks, including the visual task. Deficits in linguistic domains other than phonology have often been reported. For example, a previous ERP study also found processing differences between adults with and without dyslexia in syntax and semantics (Rüsseler et al., 2007). Furthermore, the dyslexic readers in our study may have compensated for their phonological deficit or developed better phonological skills as a result of their ample reading experience.

Handedness did not only have an effect on the results of the EEG analyses. Some behavioural differences were no longer significant when only right-handed participants were included. A possible cause is the lower power in these analyses. In addition, for dyslexic students, who had most variance in handedness-scores, there was a trend in the data that suggested that right-handedness was related to better word reading fluency and shorter reaction times during the phonological and semantic tasks, the two tasks that involved reading. This could explain the disappearance of the group effect in the analysis of the reaction times when only right-handed participants were included.

An important issue addressed in this study is the relationship between print tuning and behavioral measures of reading and reading-related skills. We found that better reading scores and a better VAS-score were associated with a more negative, thus larger, left N1 amplitude for right-handed participants. Better performance on the DS-Backward was also associated with more negative N1 amplitudes in both hemispheres for right-handed participants, and a slightly more negative right N1 amplitude for all participants. Furthermore, DS-Forward tended to be better if the left N1 was earlier. A link between reading scores and the left N1 amplitude could be expected since we found a reduced left N1 amplitude for dyslexic students. The link between the left N1 amplitude and the VAS performance is very interesting, even though the effect was only marginally significant and should be replicated in future studies. The fast orthographic processing of letters that is required during the VAS task seems intuitively related to N1 amplitude, which reflects the early automatic processing of print. It is unclear what the underlying mechanism of the relationship between DS and the N1 is, especially since this relationship was more pronounced for DS-Backward. Perhaps participants used a visual strategy to store the digits, which was especially helpful when they had to be reversed; this would be an interesting topic for further research.

To our knowledge, this study is the first to combine behavioural and EEG measures in a sample of (Dutch) higher-education students with dyslexia. Since this group still has reading difficulties despite extensive reading experience, primary processing deficits that are still found in this group are likely to be fundamental to the developmental disorder. Relating behavioural and EEG results is important for investigating this assumption, because EEG can provide further insights in the underlying mechanisms of behavioural deficits.

Limitations of this study include the small sample size, especially in the analysis with only right-handed participants. However, the parametric assumptions were still met during most analyses, and if possible a non-parametric test was used when this was not the case. Furthermore, the effects that were found are in line with the literature and the 300 trials per participant make our estimate of the N1 reliable. To generalize our results, future studies should balance handedness and gender more equally across groups than in this investigation. Given the sample size, we did not investigate the effect of interventions that participants with dyslexia received in the past, nor if they used assistive technology during their everyday reading, which could perhaps explain some individual differences in the group with dyslexia. In the current study, participants with vision problems were excluded based on self-report; therefore, we cannot rule out that some participants may have had subtle vision problems that they were unaware of. Future studies could include an examination of the participants' vision.

In the future, it would also be worthwhile to look at other EEG components. In the present study, we did not expect any task effects because we focused on an early ERP component evoked by the first word, however, it would be interesting to see whether there are task related differences between the groups in later components such as the P300 and N400 during the presentation of the second word. Another issue may be the influence of the visual characteristics of the stimuli. It would be interesting to know how factors like font, font size and font colour, influence the experimental outcomes for students with and without dyslexia. Since the N1, originating from the VWFA, is assumed to be a response to the abstract stimulus-independent properties of letter strings (McCandliss, Cohen, & Dehaene, 2003), we do not expect that they would have a large influence on the N1 response. However, these stimulus characteristics could perhaps influence later components and reaction times.

In conclusion, this study provided evidence for a difference in N1 lateralization between students with and without dyslexia. Better reading scores were associated with a larger N1 amplitude in the left hemisphere. However, these effects were limited to strongly right-handed participants. We have thus confirmed that handedness modulates the relationship between dyslexia, behaviour, and brain processes. If we want to draw conclusions that can be generalized to the whole population, it is crucial to include left-handed participants in future studies.

References

Annett, M. (2002). *Handedness and brain asymmetry: The right shift theory*. Hove, UK: Psychology Press.

Baayen, R. H., Piepenbrock, R., & Gulikers, L. (1995). *The CELEX Lexical Database (CD-ROM), Release 2, Dutch Version 3.1*. Philadelphia, PA: Linguistic Data Consortium, University of Pennsylvania.

Bentin, S., Mouchetant-Rostaing, Y., Giard, M., Echallier, J., & Pernier, J. (1999). ERP manifestations of processing printed words at different psycholinguistic levels: Time course and scalp distribution. *Journal of Cognitive Neuroscience, 11*(3), 235–260.

Bishop, D. V. M. (2013). Cerebral asymmetry and language development: Cause, correlate, or consequence? *Science*, *340*(6138), 1230531.

Brus, B. T., & Voeten, M. J. M. (1973). *Een minuut test, vorm A en B. Verantwoording en handleiding*. Nijmegen: Berkhout.

Buchholz, J., & McKone, E. (2004). Adults with dyslexia show deficits on spatial frequency doubling and visual attention tasks. *Dyslexia*, *10*(1), 24–43.

Callens, M., Tops, W., & Brysbaert, M. (2012). Cognitive profile of students who enter higher education with an indication of dyslexia. *PLoS ONE*, *7*(6), e38081.

Dehaene, S., Clec'H, G. L., Poline, J.-B., Bihan, D. L., & Cohen, L. D. (2002). The visual word form area: A prelexical representation of visual words in the fusiform gyrus. *NeuroReport*, *13*(3), 321–5.

Felton, R. H., Naylor, C. E., & Wood, F. B. (1990). Neuropsychological profile of adult dyslexics. *Brain and Language*, *39*(4), 485–497.

Geschwind, N., & Behan, P. (1982). Left-handedness: Association with immune disease, migraine, and developmental learning disorder. *Proceedings of the National Academy of Sciences of the United States of America*, *79*(16), 5097–5100.

Gilbert, A. N., & Wysocki, C. J. (1992). Hand preference and age in the United States. *Neuropsychologia*, *30*(7), 601–608.

Hardyck, C., & Petrinovich, L. F. (1977). Left-Handedness. *Psychological Bulletin*, *84*(3), 385–404.

Hawelka, S., Huber, C., & Wimmer, H. (2006). Impaired visual processing of letter and digit strings in adult dyslexic readers. *Vision Research*, *46*(5), 718–723.

Helenius, P., Tarkiainen, A., Cornelissen, P., Hansen, P. C., & Salmelin, R. (1999). Dissociation of normal feature analysis and deficient processing of letter-strings in dyslexic adults. *Cerebral Cortex*, *9*(5), 476–483.

Knecht, S., Dräger, B., Deppe, M., Bobe, L., Lohmann, H., Flöel, A., … Henningsen, H. (2000). Handedness and hemispheric language dominance in healthy humans. *Brain*, *123*(12), 2512–2518.

Kuijpers, C., van der Leij, A., Been, P., van Leeuwen, T., Keurs, M. ter, Schreuder, R., & van den Bos, K. P. (2003). Leesproblemen in de bovenbouw van het voortgezet onderwijs en de volwassenheid: Normering van een aantal tests. *Pedagogische Studiën*, *80*, 272–287.

Lobier, M., Zoubrinetzky, R., & Valdois, S. (2012). The visual attention span deficit in dyslexia is visual and not verbal. *Cortex*, *48*(6), 768–773.

Locke, J. L., & Macaruso, P. (1999). Handedness in developmental dyslexia: Direct observation of a large sample. *Journal of Neurolinguistics*, *12*(2), 147–156.

Lyon, G. R., Shaywitz, S. E., & Shaywitz, B. A. (2003). A definition of dyslexia. *Annals of Dyslexia*, *53*(1), 1–14.

Maurer, U., Brem, S., Bucher, K., & Brandeis, D. (2005). Emerging neurophysiological specialization for letter strings. *Journal of Cognitive Neuroscience*, *17*(10), 1532–1552.

Maurer, U., Brem, S., Bucher, K., Kranz, F., Benz, R., Steinhausen, H.-C., & Brandeis, D. (2007). Impaired tuning of a fast occipito-temporal response for print in dyslexic children learning to read. *Brain*, *130*(12), 3200–3210.

Maurer, U., Schulz, E., Brem, S., van der Mark, S., Bucher, K., Martin, E., & Brandeis, D. (2011). The development of print tuning in children with dyslexia: Evidence from longitudinal ERP data supported by fMRI. *NeuroImage*, *57*(3), 714–722.

McCandliss, B. D., Cohen, L., & Dehaene, S. (2003). The visual word form area: Expertise for reading in the fusiform gyrus. *Trends in Cognitive Sciences*, *7*(7), 293–299.

Miles, T. R. (2004). Some problems in determining the prevalence of dyslexia. *Electronic Journal of Research in Educational Psychology*, *2*(2), 5–12.

Miller-Shaul, S. (2005). The characteristics of young and adult dyslexics readers on reading and reading related cognitive tasks as compared to normal readers. *Dyslexia*, *11*(2), 132–151.

Mortimore, T., & Crozier, W. R. (2006). Dyslexia and difficulties with study skills in higher education. *Studies in Higher Education*, *31*(2), 235–251.

Moscoso del Prado Martín, F., Hauk, O., & Pulvermüller, F. (2006). Category specificity in the processing of color-related and form-related words: An ERP study. *NeuroImage*, *29*(1), 29–37. http://doi.org/10.1016/j.neuroimage.2005.07.055

Nobre, A. C., Allison, T., & McCarthy, G. (1994). Word recognition in the human inferior temporal lobe. *Nature*, *372*(6503), 260–263.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*(1), 97–113.

Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., & Frith, U. (2003). Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. *Brain*, *126*(4), 841–865.

Raymond, M., & Pontier, D. (2004). Is there geographical variation in human handedness? *Laterality: Asymmetries of Body, Brain and Cognition*, *9*(1), 35–51.

Richardson, J. T. E., & Wydell, T. N. (2003). The representation and attainment of students with dyslexia in UK higher education. *Reading and Writing*, *16*(5), 475–503.

Rüsseler, J., Becker, P., Johannes, S., & Münte, T. F. (2007). Semantic, syntactic, and phonological processing of written words in adult developmental dyslexic readers: An event-related brain potential study. *BMC Neuroscience*, *8*(1), 52.

Scerri, T. S., Brandler, W. M., Paracchini, S., Morris, A. P., Ring, S. M., Talcott, J. B., … Monaco, A. P. (2010). PCSK6 is associated with handedness in individuals with dyslexia. *Human Molecular Genetics*, ddq475.

Sharbrough, F., Chatrian, G.-E., Lesser, R. P., Lüders, H., Nuwer, M., & Picton, T. W. (1991). American Electroencephalographic Society guidelines for standard electrode position nomenclature. *Journal of Clinical Neurophysiology*, *8*(2), 200–202.

Shaywitz, S. E., & Shaywitz, B. A. (2005). Dyslexia (specific reading disability). *Biological Psychiatry*, *57*(11), 1301–1309.

Spironelli, C., & Angrilli, A. (2006). Language lateralization in phonological, semantic and orthographic tasks: A slow evoked potential study. *Behavioural Brain Research*, *175*(2), 296–304.

Spironelli, C., & Angrilli, A. (2009). Developmental aspects of automatic word processing: Language lateralization of early ERP components in children, young adults and middle-aged subjects. *Biological Psychology*, *80*(1), 35–45.

Swanson, H. L., & Hsieh, C.-J. (2009). Reading disabilities in adults: A selective meta-analysis of the literature. *Review of Educational Research*, *79*(4), 1362–1390.

Valdois, S., Bosse, M.-L., Ans, B., Carbonnel, S., Zorman, M., David, D., & Pellat, J. (2003). Phonological and visual processing deficits can dissociate in developmental dyslexia: Evidence from two case studies. *Reading and Writing, 16*(6), 541–572.

van den Bos, K. P., & Lutje Spelberg, H. C. (2007). *Continu Benoemen & Woorden Lezen. Een test voor het diagnosticeren van taal- en leesstoornissen. Handleiding.* Amsterdam: Boom Testuitgevers.

van den Bos, K. P., Lutje Spelberg, H. C., Scheepstra, A. J. M., & de Vries, J. R. (1994). *De Klepel vorm A en B. Een test voor de leesvaardigheid van pseudowoorden. Verantwoording, handleiding, diagnostiek en behandeling.* Nijmegen: Berkhout.

van Strien, J. W. (1992). Classificatie van links- en rechtshandige proefpersonen. *Nederlands Tijdschrift Voor de Psychologie*, *47*, 88–92.

Vlachos, F., Andreou, E., Delliou, A., & Agapitou, P. (2013). Dyslexia and hand preference in secondary school students. *Psychology & Neuroscience*, *6*(1), 67–72.

Wechsler, D. (2012). *Wechsler Adult Intelligence Scale - Fourth Edition. Dutch version.* Amsterdam: Pearson.

Willems, R. M., Peelen, M. V., & Hagoort, P. (2010). Cerebral lateralization of face-selective and body-selective visual areas depends on handedness. *Cerebral Cortex*, *20*(7), 1719–1725.

Willems, R. M., Van der Haegen, L., Fisher, S. E., & Francks, C. (2014). On the other hand: Including left-handers in cognitive neuroscience and neurogenetics. *Nature Reviews Neuroscience*, *15*(3), 193–201.

Table 1.

Participant Characteristics and Behavioural Test Results for All Dyslexic and Control Participants.

Variable	Control[a] *M*	Control[a] *SD*	Dyslexia[b] *M*	Dyslexia[b] *SD*	Test Statistic *U / t*	Effect Size *r*
Demographics						
Age in Months	273.5	21.8	262.5	35.0	1.1	0.176
Handedness Score	9.5	0.8	6.9	5.3	112.0*	0.355
Reading						
Word reading fluency	108.0	8.5	73.1	8.9	12.2**	0.890
Nonword reading fluency	111.3	9.6	63.4	8.2	16.8**	0.939
Minutes Spent on Reading per Week	1121.7	532.2	1199.5	918.4	171.0	0.073
Reading Related Skills						
Rapid Automatized Naming (item/min.)	182.5	21.7	134.3	21.6	30.0**	0.699
Digit span – Forwards	10.4	1.8	8.9	1.6	100.5*	0.391
Digit span – Backwards	9.7	1.8	8.2	1.5	96.5*	0.413
Similarities	24.3	2.7	23.6	3.5	0.6	0.118
Visual Attention Span	89.5	14.4	78.1	9.8	60.0**	0.593

Note. An independent t-test was used to compare the raw reading fluency scores, age in months, and the similarities test between groups. For all other variables Mann-Whitney *U* tests were used because the data were not normally distributed within groups. In all cases a two-sided probability criterion was used.

[a]n = 15. [b]n = 25.

* $p < .05$. ** $p < .01$.

Table 2.

Means and Standard Deviations of the Untransformed Reaction Times and Accuracy per Task for All Dyslexic and Control Participants.

	Reaction Times				Accuracy			
	Control[a]		Dyslexia[b]		Control[a]		Dyslexia[b]	
Task	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Visual	562	140	693	150	98.6	1.4	97.9	2.5
Phonological	600	112	810	186	98.2	1.4	98.8	1.3
Semantic	731	194	948	225	97.7	1.3	97.1	3.0

[a]n = 15. [b]n = 25.

Table 3.

Means and Standard Deviations of the N1 Amplitude per Group, Task and Hemisphere for Strongly Right-Handed Participants.

	Control[a]		Dyslexia[b]	
Hemisphere and Task	Mean	SD	Mean	SD
Left Hemisphere				
Visual	-3.781	2.486	-2.037	1.282
Phonological	-3.475	2.261	-1.805	1.233
Semantic	-3.688	2.487	-1.879	1.744
Right Hemisphere				
Visual	-1.860	1.031	-1.470	1.690
Phonological	-1.710	1.293	-1.738	1.481
Semantic	-1.659	0.735	-1.499	1.465

[a]n = 12. [b]n = 12.

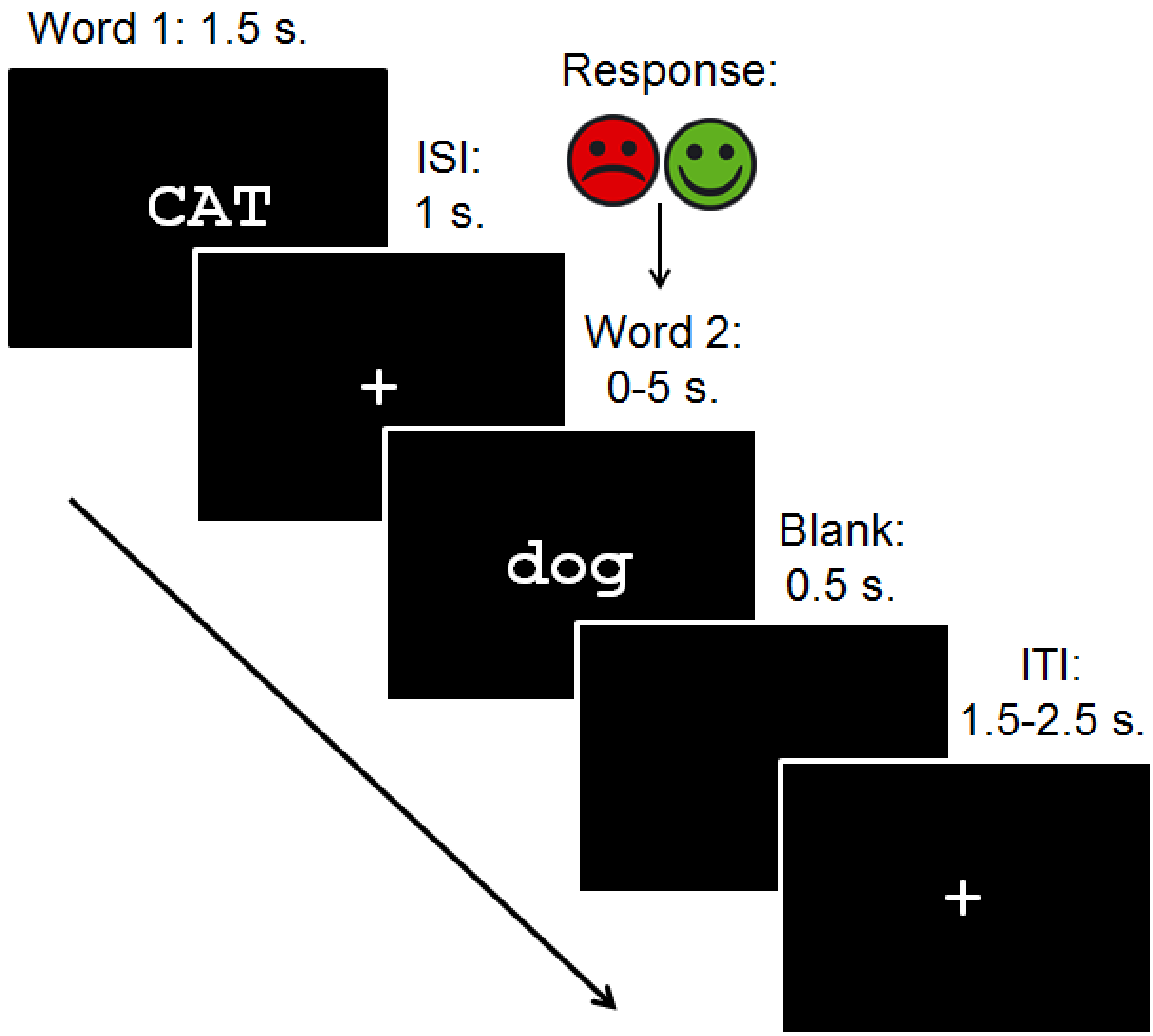

Figure 1

Timing of the EEG experiment. Words were presented consecutively in white on a black screen. Participants had to respond within 5 seconds to word 2, after which the word disappeared. The length of the ITI was jittered. ITI = Inter Trial Interval. ISI = Inter Stimulus Interval.

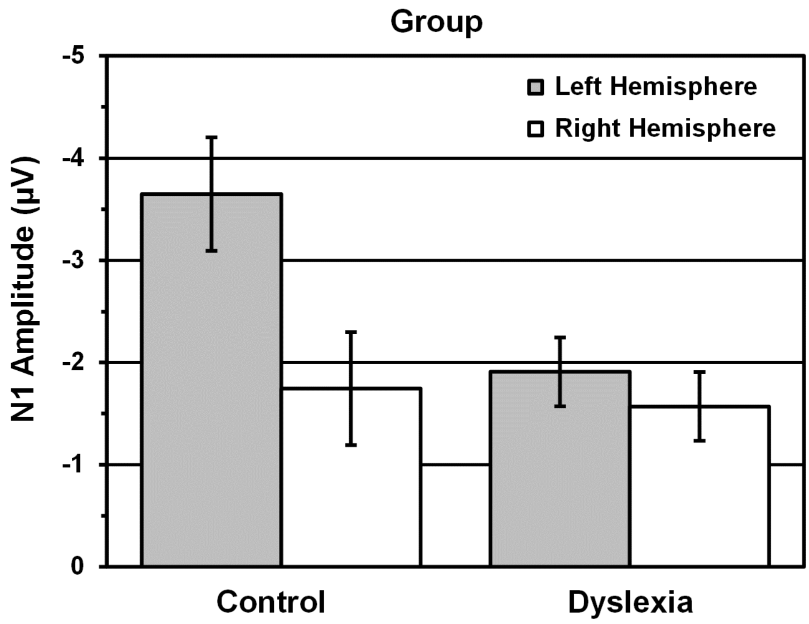

Figure 2.

Mean N1 Amplitude per Group and Hemisphere for strongly right-handed participants. Error bars indicate Standard Errors.

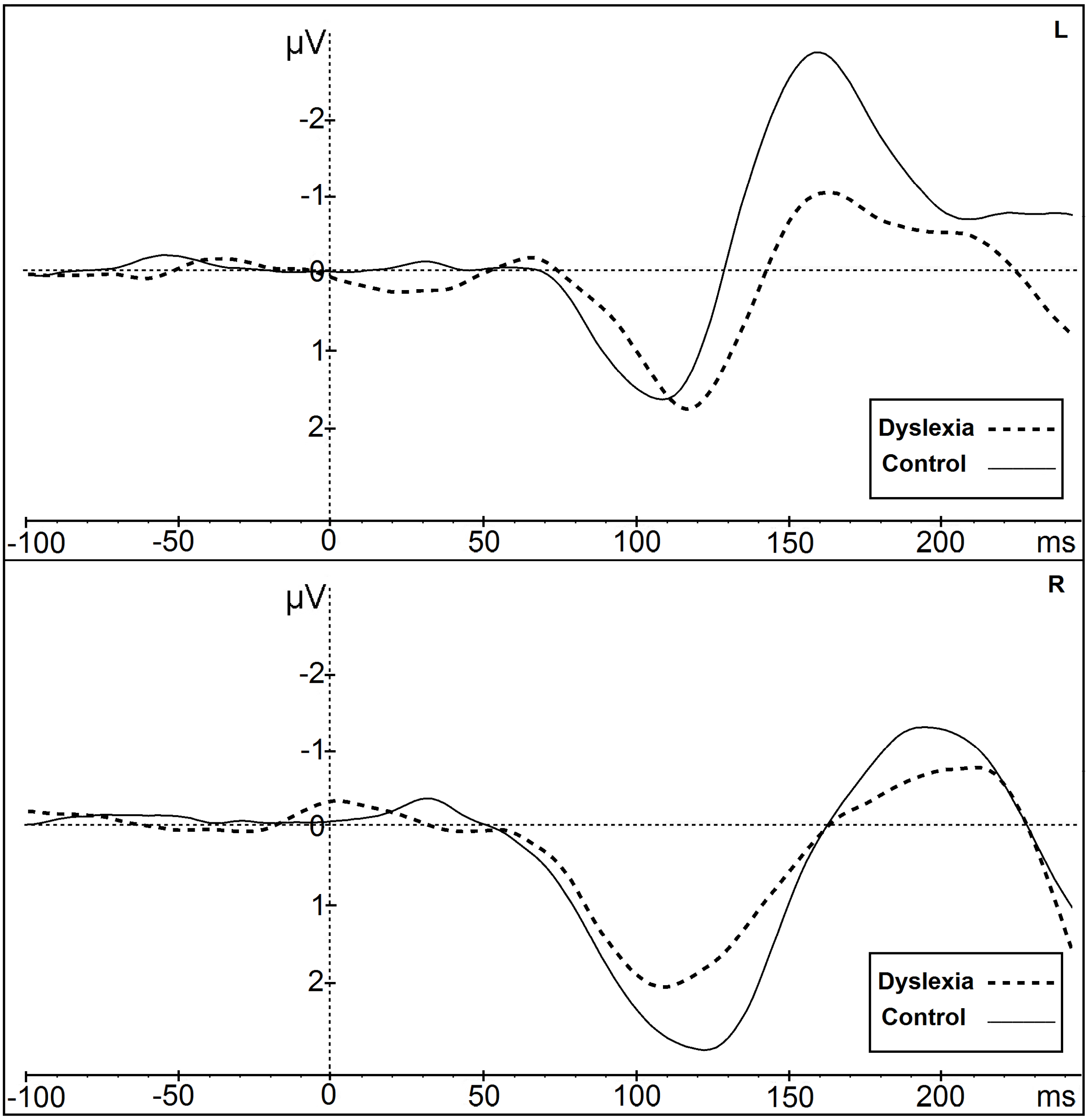

Figure 3.

The grand average N1 for strongly right-handed participants per Group in the left and right posterior area.