Seeing is knowing? Visual word recognition in non-dyslexic and dyslexic readers: an ERP study

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Seeing is knowing? Visual word recognition in non-dyslexic and dyslexic readers - an ERP study

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Abstract

The aim of the current study was to investigate whether phonological/semantic processing of the word takes place simultaneously with, or following, the early processing of its visual features. Event related potentials (ERPs) were recorded in thirteen dyslexic (4 female) and fourteen non-dyslexic (6 female) native English speaking young adults in two lexical decision tasks. In Task 1 participants had to make an orthographic lexical decision to distinguish frequently used words (W) from pseudohomophones (PH1) focusing on visual properties of stimuli. In Task 2 they had to make a phonological lexical decision - to pseudohomophones (PH2) and pseudowords (PW) and decide whether stimuli sounded like real words – focusing on non-visual higher order, i.e., phonological and semantic, processing of the stimuli. The behavioural performance was less good and the ERP peaks' latency longer in dyslexics compared to controls. Similarly to Twomey, Kawabata Duncan, Price & Devlin (2011), the reaction times (RTs) and the number of errors (reversed for the controls in Task 2) increased across four conditions for both groups in the following order: W< PH1< PH2< PW. The ERPs were larger in Task 2 compared to Task 1 starting at 100 ms (P1) for the controls and from about 220 ms (P2) for the dyslexics. The latency of N2 peak in left occipito-temporal sites was larger (as was the number of errors) in PH2 compared to PW condition in controls only, which indicates phonological/semantic specific processing at a time latency of 250-260 ms. Thus, the visual task required less effort than the phonological task, dyslexics' behavioural performance was less good and the brain activation delayed compared to controls. Combined behavioural and ERP results of this study indicated that phonological/semantic processing of the word took place 150 ms after processing of its visual features in controls and possibly later in dyslexics.

Keywords: ERP, dyslexia, visual word recognition, phonology, semantics

1. Introduction

Reading or visual word recognition involves several cognitive operations, such as visual encoding of letters, translation of letter shapes into graphemes and orthographic patterns, and activation of lexical/phonological structures and their meaning (Bentin et al., 1999). There is much debate in the current literature regarding the activation and time course of these operations and whether they are performed in a stage wise or a parallel manner. According to the influential dual-route cascaded (DRC) model of reading (Coltheart et al., 2001), in visual word recognition there are essentially two pathways from printed word to semantic access: direct and indirect. The direct (lexical) route suggests that meaning is directly accessed through orthography-to-semantics bypassing phonology, when high-frequency words are processed (Coltheart, 1978). According to the indirect (sub-lexical) route, the meaning is accessed from print to semantics via phonology, when low-frequency words are used. This model highlights discrete stages of word recognition processed in a cascaded flow dynamic (e.g., Schrifiers et al. 1990; Hauk et al., 2006; Schurz et al., 2010). However, this view is currently challenged with neuroimaging studies suggesting parallel processing of all operations and simultaneous feed-forward and top-down functional linkage of the brain areas involved in reading (e.g., Price & Devlin, 2011; Devlin et al., 2006). Thus, according to a recent fMRI study by Twomey et al. (2011), ventral occipito-temporal cortex (vOTC) that corresponds to location of so called ‘visual word form area’ (VWFA, Cohen et al., 2000, see in Cohen and Dehaene, 2004) may serve as an interface linking visual word form information with non-visual properties of the stimuli. The authors suggest that the higher order phonological and semantic properties of the stimulus may influence the processing of words in vOTC, so that the activation in vOTC reflects not only bottom-up but also top-down influences.

While the time course of visual word recognition is currently hotly debated in the literature (e.g., Kronbichler et al., 2007; Twomey et al., 2011), less research has been carried out to elucidate these stages of processes and their deviations in dyslexia. Developmental dyslexia is a specific learning disability that is neurological in origin and is characterised by difficulties in reading, writing and spelling that cannot be explained by any kinds of deficits in general intelligence, socioeconomic disadvantage, general motivation or sensory acuity (World Health Organisation, 1993). Recent neuroimaging studies converge in showing underactivations and fewer connections between the key neural network structures involved in visual word recognition among individuals with dyslexia (e.g., Goswami, 2009; Price and Devlin, 2011). It is not clear, however, whether all or some of the processes underlying rapid word recognition are affected (e.g., Schulz et al., 2008). Some behavioural and neuroimaging research carried out with dyslexic children highlights deviations already in early stages of processing (van der Mark et al., 2009; Schulz et al., 2008). However, the dynamics of higher order functions, such as recognition of phonological and semantic features in visual word form is not very clear in dyslexic readers (e.g., Wimmer et al., 2010; Kherif et al., 2011).

Establishing precise time-course of these activations would help highlight whether the processing of single words is performed in sequential or parallel fashion. However, the neuroimaging techniques, such as fMRI, lack crucial information on time course of the observed neural activity and cannot answer questions such as ‘how early is semantics’ and ‘in what order do these cognitive operations occur in’ (Editorial, Biological Psychology, 2009). Electrophysiological methods like electroencephalogram (EEG) and event related potentials (ERPs), on the other hand, provide high temporal resolution with a potential of resolving these questions by providing crucial timing information. In a recent review of ERP literature and neurocognitive basis of reading single words (Dien, 2009), it was suggested that reading may be comprised of two phases: an initial fast cascaded sequence of activations (Estimation phase), followed by seeking a more accurate solution by coordinating information across the entire network (Resonance stage). Generally, ERP components are considered to index visual features and letter analysis (P100), orthographic familiarity (P150) and lexicality (N170), phonological (P2/N2) and semantic (N300) processing. However, the distinction between these processes and their time course is not always clear and sometimes indistinguishable. Thus, according to Wheat et al. (2010), phonological influences during visual word recognition were observed in an MEG study as early as 100 ms, whereas semantic task effect was reported in P1 component in an ERP study of category priming (Segalowitz & Zheng, 2009). However, these two studies did not control for visual familiarity effect, i.e., in both studies visually familiar letter combinations were used that could have facilitated the phonological and semantic processing. In another recent ERP study a phonological lexical decision task was used (‘does this sound like a real word’) in order to observe the dynamics of visual word recognition at different levels of processing (van der Mark et al., 2009). However, in this study as well the initial visual familiarity affects word recognition process and the lexical status (word or not) is confounded with the phonological status (sounds like a word or not).

Here, I aimed to separate the visual and non-visual features of the word recognition process, in a design similar to Twomey et al.'s (2011), in which meaning could be accessed only based on phonological and semantic features of unfamiliar letter strings. To accomplish this, Twomey et al. (2011) separated the tasks to be visual only and phonological/semantic only. Thus, Twomey et al. (2011) used visual or orthographic and non-visual or phonological lexical decision tasks. In the first task participants had to decide whether the presented stimuli, words (W) and pseudohomophones (PH1) 'looked like' real words. In the second task, pseudohomophones (a different set, PH2) and pseudowords (PW) were presented and participants had to decide whether the stimuli ‘sounded’ like words or not. Thus, in the second (phonological) task there was no visual information (both types of stimuli were visually unfamiliar non-words) available to make a decision. This paradigm is very well suited to use in an ERP study since in every trial of Experiment 1 a decision had to be made based on visual familiarity of the words, whereas in Experiment 2 in every trial a phonological/semantic decision had to be made that was not made on the basis of visual familiarity. Different sets of PH (PH1 and PH2) were used in these two tasks to ensure no repetition or response conflict (‘no’ in the first, and ‘yes’ in the second) occurred across the tasks. Thus, these stimuli could be compared across the tasks as well as with the other experimental condition in each task, i.e., PH1/W and PH2/PW. The results of this study showed greater activation to PH2 than to PW in vOTC and the authors concluded that the phonological/semantic information is possibly accessed by top-down interaction from higher level areas to the ventral occipito-temporal area. Thus, it really may be the case that these higher level features are indeed processed quite early, but the temporal pattern of these processes has not been dealt with in conditions where these low and higher level processes are disentangled, either in dyslexic or non-dyslexic individuals.

Thus, the aim of the current study was to use high density ERPs to investigate further the pattern of brain activation involved in initial visual and non-visual (higher order) cognitive processing during silent reading. The ERPs and behavioural measures were recorded to frequently used words (W) and pseudohomophones (PH1) in the visual task, and to PH2 and pseudowords (PW) in the phonological task, in dyslexics and controls. Based on Twomey et al.'s (2011) results, particularly the PH2/PW fMRI signal difference in vOTC, simultaneous orthographic and phonological processing was expected in the ERP activation, possibly as early as 100-150 ms from the stimulus onset (e.g., Wheat et al., 2010; Braun et al., 2009). My second aim was to observe whether a similar pattern of behavioural results and brain activation could be recorded in dyslexic adult readers. Particularly, I was interested to see whether, in terms of behavioural performance, the accuracy (number of correct answers) and the speed (reaction times) of processing would be in a similar range of performance compared to controls. It was also of interest to observe whether the pattern of brain activation found in controls would be altered in individuals with dyslexia both in visual (orthographic) and non-visual (phonological/semantic) lexical decision tasks. Based on previous findings (e.g., Taroyan et al., 2009; Mahe et al., 2013), I expected less lateralised and delayed activation among dyslexic participants when compared to the controls, both in visual and phonological lexical decision tasks.

2. Methods

2.1. Participants

Thirteen dyslexic (4 females) and fourteen age-matched control (6 females) monolingual native English speakers were tested in this study. All participants were students at Sheffield Hallam University, right-handed, with normal or corrected-to-normal vision and no history of brain injuries or neurological problems. Dyslexic participants were assessed for dyslexia previously in schools or at the entry to the University by qualified psychologists and had no comorbid conditions. They were also tested prior to the study for word reading efficiency (TOWRE; Torgeson et al., 1999). Mean values of age, IQ (WASI subset of performance IQ; Wechsler, 1999) and TOWRE scores for both groups are shown in Table 1. There were no significant differences between the dyslexic and control groups in chronological age or IQ scores (one factor ANOVAs, $p>.6$), but as expected dyslexics had significantly lower TOWRE ($p<.001$) scores compared to controls. The participants were offered course credit as part of the course assessment or paid for their participation. The study was approved by the local ethics committee (Faculty of Development and Society, Sheffield Hallam University), and written informed consent was obtained from all participants prior to the testing.

--------- Insert Table 1 about here ------

2.2. Tasks and stimuli

The same design as in Twomey et al. (2011) was employed in this experiment. The participants were tested in two lexical decision tasks: visual (orthographic) and non-visual (phonological or semantic). In the first task frequent regular English words (W) and corresponding pseudohomophones (PH1) were used and the participants had to decide whether they saw a real word or not. In the second task a different set of pseudohomophones (PH2) and pseudowords (PW) were used and the participants had to decide whether the stimulus they saw sounded like a real word or not. The pseudohomophones (PH1 and PH2) were created by replacing the vowel or the sequence of letters in the corresponding real word, e.g., ‘blown’ to ‘bloan’. The PWs were created in a similar way but with the result being unrepresentative of a real language item, e.g., ‘green’ to ‘drean’, ‘least’ to ‘lerst’, etc. All stimuli were monosyllabic words of 4-6 letters (*M*=4.5, *SD*=.59) and 2-5 phonemes (*M*=3.36, *SD*=.54). All conditions were balanced for bigram frequency (*M*=1447.94, *SD*=1016.8, *F*(3,328)=2.64, *p*=.05), trigram frequency (*M*=232.63, *SD*=350.41, *F*(3,324)=2.36, *p*=.072), and orthographic neighbourhood (*M*=5.55, *SD*=4.84, *F*(3,328)=1.00, *p*=.395), based on N-Watch (Davis, 2005). Additionally, real words and source words for pseudohomophones (PH1 and PH2, respectively) were matched for frequency per million words (*M*=86.79, *SD*=153.23, *F*(2,245)=.24, *p*=.784), based on Celex database (Baayen & Pipenbrook, 1995), and imageability (*M*=483.31, *SD*=111.7, *F*(2, 217)=.07, *p*=.932), calculated from the MRC Psycholinguistic Database (Coltheart, 1981). All stimuli were 1-1.5 cm high, lower case, presented in black on a light grey background. They were displayed on a 22 inch PC monitor, and the viewing distance to the screen was 60 cm. The experiment was designed and run using E-prime V2.0 (Psychology Software Tools Inc).

2.3. Procedure

There were total of 160 trials in each task, 80 W and 80 PH1 in the visual task, 80 PH2 and 80 PW in the second task, each lasting about 4.5 sec, and each task lasting about 12 min. Participants were instructed to press one button on the response pad if the string of letters looked or sounded like a word (W or PH2, in the first or second task respectively), and the other button if it did not look or sound like a real word (PH1 or PW accordingly).

Each trial started with a fixation period (a small black fixation cross in the centre of the screen) of 1000 ms, followed by the main stimulus (W, PH1, PH2 or PW) displayed for 2000 ms (optimal minimal duration based on pilot tests with dyslexic participants to allow them enough time for the response), and followed by a blank screen (1500 ms) to allow for the motor response and in order to provide a rest to eyes from fixation of the stimuli.

Participants were seated in a comfortable chair in an acoustically shielded, dimly lit room. They were asked to fixate the small fixation cross displayed in the centre of the monitor at eye level that was followed by the stimulus. They were also required to refrain from eye movements, head or other body movements during stimulus presentation. Short training sessions were provided in order to familiarise the participants with the task. The recording was monitored and controlled by the experimenter in the adjacent room.

2.4. Data acquisition

The EEG was recorded via a 64 channel WaveGuard cap of ANT BV (www.ant-neuro.com, Enschede, Netherlands). TheWaveGuard cap consists of 64 shielded Ag/AgCl sintered pin electrodes plus GND ('Patient Ground') arranged according to 10-10 International System in a shielded connector cable attached to a 64 channel EEG/ERP ASA-Lab system (ANT Neuro BV, www.ant-neuro.com, Enschede, Netherlands). Individual sensors were prepared such that impedances were below 10 KOhm. The EEG was recorded with common average reference, without filters (full-band DC EEG), with a sampling frequency of 512 Hz. The EEG data was recorded and analysed using ASA Advanced Source Analysis (ANT Neuro BV, www.ant-neuro.com, Enschede, Netherlands) software version 4.7.8. Simultaneously all trial specific information, such as condition type (W, PH1, PH2, PW), accuracy of responses, and mean reaction times (RTs) to correct responses, was recorded through E-prime and ASA and stored for the further analysis of EEG and behavioural performance data.

2.5. Data Filtering and Artefact removal

The EEG data were digitally bandpass filtered in the range of 1- 40 Hz. The high-pass filter was set at 1Hz to make sure that slow direct current (DC) shift was excluded from trials, whereas the low-pass filter was set at 40 Hz to remove the 50-60Hz noise from electrical sources. Next a segmentation of the continuous EEG into epochs or trials was performed starting 100ms before the stimulus onset and lasting 1000ms after the stimulus onset for each of the four experimental conditions, each recording site, and each participant. Artefacts were detected automatically based on -90 to +90 μV amplitude thresholds, as well as the threshold for eye movements (70 μV) in channels near to the eyes, e.g., Fp1, Fp2, Fpz. Artefact correction procedures were next performed using ASA software and PCA Matlab-based methods (Ille et al., 2002).

2.6 Data analysis

The EEG and behavioural data were further processed and analysed off-line using ASA 4.7.8 and Eprime 2.0. Mean RTs from the whole experiment, the number of false alarms (commission errors) and misses (omission errors) were determined for each participant.

Following the artefact removal, ERPs were computed by averaging all remaining trials accompanied with a correct response (about 60-70 for each condition), time-locked to stimuli, lasting 1100ms including 100 ms pre-stimulus baseline. We performed baseline-correction of all potentials next, by subtracting the averaged 100 ms of pre-stimulus recording from the entire wave.

The group average ERPs were computed separately for the dyslexic and control participants in each experimental condition and are displayed in Figs. 1 & 2 respectively. The following ERP components were identified by visual inspection of group average and individual participant data: P1 (~100-120ms), N1 (~160-170 ms), P2 (~200-220ms), N2 (250-260 ms) and P3 (350-370 ms). These ERP peaks were best defined and with maximal amplitude in occipital and occipito-temporal areas. We also focused on these occipito-temporal channels based on their sensitivity to visual word recognition (Taroyan & Nicolson, 2009; Twomey et al., 2011; Dujardin et al., 2011) and the approximate location of the visual word form area over the left hemisphere. Electrophysiological methods, such as ERPs, do not usually provide a reliable spatial resolution, however, as in previous research (e.g., Taroyan & Nicolson, 2009), visual inspection of group average ERPs showed task and condition (PH2/PW) specific effects in this area, with amplitude to PW being larger than to PH2 in the left hemisphere (see Fig. 1).

2.7. Statistical analysis

The mean RTs to correct responses for each participant were subjected to a two factor mixed measures analysis of variance (ANOVA) with the between-subjects factor Group (dyslexics versus controls) and the within-subjects factor Condition (W, PH1, PH2, PW). The same analysis was undertaken on the numbers of commission and (very few) omission errors.

The amplitude and latency of the ERP components from the respective regions of interest were analysed with the amplitude of the peaks in each individual participant's ERPs found in the time windows defined by the peaks in the group average ERPs (see above in section *2.6*) and automatically measured at the peak maximum. The latency of the peaks was computed relative to the stimulus onset. The average amplitude and latency values of ERP components from each channel and for each participant were submitted to ANOVA with 1 between-subjects factor Group (dyslexics versus controls) and 3 within-subjects factors Condition (W, PH1, PH2, PW), Area (O, OP) and Hemisphere (left and right).

Similarly to Twomey et al. (2011), when there was a main effect of Condition or main effects interaction, planned paired t-tests were conducted to evaluate differences between the stimuli within each task (W/PH1, PH1/PH2), or between two tasks (PH1/PH2) within each group. When Mauchly's test indicated significant non-sphericity in the data, a Greenhouse-Geisser correction was applied. The criterion for statistical significance was $p < 0.05$. The statistical analysis was performed using Statistical Package for Social sciences (IBM SPSS Statistics, Inc., Chicago, Illinois) version 20.

3. Results

3.1. Behavioural data

As can be seen in Figs. 1a&b, the RTs were overall longer [$F(1,25) = 3.5$, $p=.07$] and the number of errors significantly larger [$F(1,25) = 13.3$, $p<.005$] in Dyslexics compared to Controls. There was also a significant main effect of the Condition both for the RTs [F(1,25) = 99.5, p<.001] and the number of errors [$F(1,25) = 16.1$, $p<.001$], as well as Condition by Group interaction effect for the errors. Further analysis showed that the RTs were significantly faster in Word compared to PH1 condition in Task 1 for Controls [680 vs 779 ms, $t(13) = 8.9$, $p < .001$] and for the Dyslexics [767 vs 947 ms, $t(12) = 5.0$, $p < .001$], as well as in the PH2 compared to PW condition in Task 2 for Controls [921 vs 1133 ms, $t(13) =$

6.6, $p < .001$] and Dyslexics [988 vs 1209 ms, $t(12) = 4.4$, $p < .001$]. It can also be seen in Fig. 1, that the RTs were faster in the PH1 (Task 1) compared to the PH2 (Task2) condition in Controls [779 vs 921 ms, $t(13) = 5.6$, $p < .001$] but not significantly in Dyslexics [947 vs 988 ms, $t(12) = .9$, $p = .4$]. Similar pattern of results was found for the number of the errors in Dyslexics (see Fig. 1b), i.e., W<PH1<PH2<PW, with significant effects found for W/PH1 [5.6 vs 9.5, $t(12) = 2.5$, $p = .03$] and PH1/PH2 [9.5 vs 18.2, $t(12) = 3.1$, $p = .009$] comparisons. However, in controls this pattern was slightly different, hence the Group by Condition interaction effect, i.e., W<PH1<PW<PH2, with PH1/PH2 being the only significant effect [5.6 vs 11.4, $t(13) = 3.1$, $p = .009$]. Thus, the pattern of the behavioural results was the same in both groups with the RTs and errors increasing from Task1 to Task 2 W<PH1<PH2<PW, but in controls this pattern reversed for the number of errors in Task 2 (PW<PH2).

--- Insert Figure 1 about here ---

3.2. ERP data

The group average waveforms for the Controls and Dyslexics displayed in Fig. 2 show characteristic ERP components, i.e., P1, N1, P2, N2 and P3 in left and right occipital (O1, O2) and occipito-temporal (PO5, PO6) sites selected for further analysis. The ERP peaks were measured in the individual participants' waveforms, however, the later P2/N2/P3 complex was more consistently found in Task 2. The latter could be related to the more effortful processing of visually unfamiliar semantic/phonological information compared to the easier orthographic task. This was also reflected in the amplitude of the ERP components. As can be seen in waveforms in Fig. 2 and topographic maps in Figs. 3 & 4, the amplitude of the ERPs was larger in Task 2 compared to Task 1, especially in Controls. It can also be seen in the topographic maps of Figs. 3&4 that the overall brain electrical activation was larger in Controls than in Dyslexics. These observations were supported by the results from ANOVA with only significant differences reported below and shown in Figs 3&4 for the most prominent peaks P1, N1 and N2.

--- Insert Figures 2- 4 about here ---

Thus, the statistical analysis showed that the Condition effect was significant for the amplitude of the early peaks P1 [$F(3,39) = 4.7$, $p = .036$] and N1 [$F(3, 39) = 6.6$, $p = .01$] for the controls only, and as a main effect for the later peaks P2 [*F*(3,72) =5.6, *p*=.01] and N2 [*F*(3,75) =11.9, *p*<.001]. As can be also be seen in Fig. 2, these effects were due to the larger amplitude of the ERP peaks in Task 2 compared to Task 1 in controls mainly (see Fig. 2) which was also supported by significant Condition by Group interactions for P3 ERP peak [*F*(3,75) =2.8, *p*=.04]. Thus, there was a task dependent effect reflected in the amplitude of all ERP peaks for the controls, however, for the dyslexics this effect was present only in later ERP peaks P2 and N2.

There were no amplitude related significant Group effects, however, the peak latency was significantly longer in Dyslexics compared to Controls for P1 [*F*(1,25) =9.7, *p*=.005], N1 [*F*(1,25) =10.2, *p*=.004] and P2 [*F*(1,25) =6.0, *p*<.001] components. A significant Condition by Side by Group interaction effect was found for the latency of N2 peak [*F*(3,75) =4.6, *p*=.005]. Paired samples t-tests showed that the latency of N2 was longer in the left occipital and occipito-temporal areas in PH2 compared to PW condition for the Controls only [*t*(13) =2.4, *p*=.03] similarly to larger number of errors in PH2 compared to PW condition in Controls (see Figs. 1 &2). However, the RTs showed the responses were faster in PH2 compared to PW condition, both in controls and dyslexics (Fig. 1).

4. Discussion

In the current study I aimed to investigate the time course of electrical brain activation related to visual word recognition in dyslexic and control native English speaking young adults. My main objective was to establish whether higher order cognitive processes such as access to the meaning of the written word happens simultaneously or after (and with how much delay) the initial visual familiarity recognition stage. Overall, the behavioural performance was faster and more accurate in orthographic Task1 compared to phonological/semantic Task 2. It was also found that the amplitude of the early ERP peaks (P1 and N1) was larger for the controls in Task 2 than in Task 1 and for the later peaks (P2 and N2) across both groups. The performance was better in the W compared to the PH1condition in Task 1, as well as in PH2 compared to PW condition in Task 2. However, this effect reversed in controls for the number of errors being slightly larger in PH2 condition compared to PW. Additionally, the latency of the N2 peak was delayed in PH2 compared to PW condition in the left occipital and occipito-temporal recording sites for the controls only.

The behavioural measures also indicated that the dyslexics were significantly slower and significantly less accurate than the controls. The pattern of the brain activation showed similar results, with the latency of the peaks P1, N1 and P2 longer for the dyslexics than for the controls.

Thus, the main Condition and between-task effects indicated that phonological processing required greater efforts across both groups as evidenced by worse behavioural performance and larger amplitude of the ERP peaks in Task 2. Interestingly, this task-dependent effect was present in Controls in all peaks, both early and late, whereas in dyslexics it was only found in the later peaks, P2 and N2. This may indicate that for the controls the difference in the task had an effect at an earlier time of 100 ms, whereas for the dyslexics this did not happen until 220 ms from the stimulus onset. This task-dependent effect was also found in fMRI results reported by Twomey et al. (2011) for the left vOTC. The authors suggested that it could be caused by larger phonological demands placed on the second task, e.g., phonological decoding and assembly. This finding was interpreted as further support for the account of an integration of the low level visual and higher level cognitive processing, in this case orthographic and phonological/semantic, rather than cascaded flow sequential processing taking place in this region. Although this modulation in response to the task requirements/ instructions (orthographic/phonological) was recorded as early as 100 ms in the control participants there were no within-task effects to indicate more specific phonological processing, e.g., a greater or delayed activation to PH2 compared to PW, at this stage in time. According to Dien (2009) and others (e.g., Brem et al., 2009), early components of ERPs, such as P1 and N1, most probably reflect the fast or transient estimation stage, such as coarse evaluation of the incoming information, followed by more detailed or sustained processing of higher level features of the word. Thus, some sort of initial interaction or top-down prediction (Price & Devlin, 2011) and surface assessment possibly takes place at this early stage (later combined with higher level processing, e.g., Hauk et al., 2006) that is reflected in greater P1/N1 amplitude in Task 2. A delay in this task-effect among the dyslexic participants could be caused by reported reduced activation and reduced functional connectivity between vOTC and other language areas (van der Mark et al., 2011; Price and Devlin, 2011). Thus, this work provides further insight into whether 'seeing is knowing' with the controls 'knowing' the difference between the two tasks once they 'see' (indexed by P1 ERP component) but not the dyslexics possibly due to impaired early activation already shown in previous research (e.g., Taroyan & Nicolson, 2009; Mahe et al., 2013).

In terms of within-task effects, similarly to Twomey et al. (2011), in Task 1 behavioural performance was faster in W compared to PH1 condition both for the dyslexics and controls; however, unlike Twomey et al. (2011), accuracy also increased in W compared to PH1 condition for both participant groups. Thus, our participants found lexical decisions easier to be made for real words than for PH1 although there were no supporting ERP correlates found (e.g., larger amplitude to PH1). In Task 2 the performance was faster in PH2 compared to PW condition for both groups; it was also more accurate in PH2 compared to PW condition for the dyslexics. However, as already reported here and similarly to the results of Twomey et al. (2011), for the controls this (non-significant) effect was reversed for the number of errors, whereas the accuracy was lower in PH2 compared to PW condition. This pattern of behavioural results mirrors those reported in Twomey et al. (2011). They also reported shorter RTs and more errors made in PH2 condition in Task 2, and the result was interpreted as a speed-accuracy trade off. And it seems a similar situation applies to our control participants, where it may have been more difficult to accept a PH2 as a word (sounds as a word) than to reject a PW as a word, hence more mistakes were made in PH2 condition but at the expense of accelerated RTs.

This effect was also supported by the longer latency of the N2 component in left occipital and occipito-temporal recording sites for the PH2 compared to PW condition in the controls only. It was not found in the right hemisphere of the controls and generally not present in the dyslexics. It is interesting that this finding again mirrors the fMRI data in Twomey et al.'s (2011) study where the signal was more pronounced to PH2 compared to PW condition. In our control participants' ERPs the delayed latency of the N2 component in the left hemisphere and particularly occipito-temporal sites indicates that: a) larger effort is applied and more time is required for the decision that PH2 sounds as does a real word; b) recorded in the area that is consistently reported to be specialised in visual word recognition and recently also responsible for integration of higher level phonological and low level visual information. Thus, another aim of our study was achieved: the stimulus driven fMRI effect of Twomey et al. (2011) was also found in the current ERP study with a clearer time indication for more detailed phonological or semantic specific processing at about 250 ms and not earlier as reported in previous studies (e.g., Braun et al. 2009; Wheat et al., 2010). It could be caused by increased difficulty in our experiment, as the orthographic familiarity effect (van der Mark et al., 2009) was completely removed in the current design. This effect was found only in control participants but not in dyslexics, which also indicates that difficulties they have with phonological processing are reflected in the absence of differences between phonologically correct and incorrect letter sequences early in processing. A presence of such effect in our control participants indicates that semantic processing does happen in the occipital-temporal sites that possibly correspond to vOTC location in Twomey et al. (2011). It is also possible that orthographic and these more detailed phonological processes in visual word recognition may not happen simultaneously but with some time delay in-between possibly caused by top-down modulations and feedback to vOTC, as suggested by Twomey et al. (2011). Thus, the task and stimulus driven effects in this study suggest that visual or orthographic word recognition and some initial phonological related estimation was present in controls as early as 100 ms but the more detailed phonological/semantic processing reflected in PH2/PW difference was recorded at later time of 250 ms in N2 peak latency. Unlike Twomey et al (2011), the results of this study show evidence for sequential rather than parallel processing of early orthographic and later phonological/semantic stages in visual word recognition. According to Schurz et al. (2010), a 'global recognition mode' usually precedes a serial analytical mode and success of the former can determine the start of the latter. This may also be the case for the present study, where a fast initial coarse estimate and lexical decision is made very early (100ms) and is followed by higher level and more detailed processing slightly later (250ms).

This stimulus driven effect was not found in ERP results of dyslexics. The slower and less accurate behavioural performance of the dyslexic participants, as well as the longer latency of their ERP peaks compared to controls were generally expected and often reported in previous research (e.g., van der Mark, 2011; Dujardin et al., 2011; Taroyan et al., 2007). This prolonged brain electrical activation in both visual and non-visual phonological/semantic tasks could be related to greater difficulties dyslexics have with lexical decision tasks in general and consequently greater efforts applied to compensate for these difficulties (e.g., Taroyan & Nicolson, 2009). However, the difference may also be due to a greater variance in the ERP data of the dyslexics suggesting asynchrony and processing speed differences. Thus, according to Breznitz (2002), speed of processing may be slower generally among the dyslexic individuals but even slower in the auditory-phonological as compared to the visual-orthographic domain. This gap in speed of processing (SOP) was found in latencies of P200 and P300 ERP components (Breznitz, 2002). In the current study too between-group differences were found in the behavioural data for both tasks but were much larger in the second phonological/semantic lexical decision task due to larger number of errors made by dyslexic participants. The latter directly indicates that the second task was particularly difficult for them when not supported by familiar orthographic information and based only on phonological and semantic processing. Abnormalities in left occipito-temporal areas of dyslexics to print tuning reflected in impaired N170 were reported often recently (e.g., Mahe et al., 2013; Hasko et al., 2013) and attributed to their core phonological deficits. Thus, it seems that in addition to general delays and deviations in the amplitude of the dyslexic participants that were reported in similar studies before, there were also between-task group differences where the task-dependent effect happened at approximately 100 ms in controls and at a slightly later time of approximately 220 ms in dyslexics. As discussed earlier, this electrophysiological indicator of the initial estimate of orthographic/phonological task requirements seems to be delayed in dyslexics that also indicates phonological processing difficulties in this participant group related either to general under-activation in vOTC (e.g., Wimmer et al., 2010) and/or lack of phonological knowledge and failure/delay in establishing top-down interactions and predictions (e.g., Price & Devlin, 2011) or the SOP gap between orthographic and phonological processing aspects (e.g., Breznitz, 2002).

In conclusion, this study showed once more that high temporal resolution ERPs are very sensitive indicators of visual word recognition both in control and dyslexic readers. The separation of the tasks into orthographic and phonological did help to extract stage specific processing and enriched the fMRI results found in Twomey et al. (2011). According to the ERP results, an initial coarse estimation of the task happened at 100 ms and a more specific detailed semantic/phonological processing - at a slightly later time of 250 ms in the left occipital and occipito-temporal sites in controls, emphasising once more the sensitivity of this region in reading related processing. These results, unlike those of Twomey et al. (2011), support sequential or stage-wise processing of orthographic and phonological information. As for the dyslexic participants, such stimulus driven ERP effects were not found indicating specific difficulties in phonological processing further supported by deficient and delayed behavioural performance. Overall, the delayed latency of the ERP peaks in dyslexics followed by a reduced performance in the behavioural results further supports previous findings of impaired activation and possibly reduced functional connectivity between vOTc and other language areas. Further research with more vigorous control of the stimuli needs to be carried out to confirm the current results and to find out whether phonological and semantic processing occur at the same time or at different stages in similar and other ERP experimental designs.

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Figure Legends

Figure 1. Behavioural data for control and dyslexic groups (mean ± SE) for: a) Reaction times and b) performance accuracy.

Figure 2. Group average ERPs for Control and Dyslexic participants in Word, PH1, PH2 and PW conditions in Tasks 1 and 2. The green vertical lines on the waveforms indicate the stimulus onset at 0 ms. The channel locations are specified at the start of the waveforms and the ERP peaks indicated on Controls' and Dyslexics' average ERPs.

Figure 3. Topographic ERP maps for the P1 (at 100 ms), N1 (at 160 ms) and N2 (at 260 ms) peaks in both tasks and all 4 conditions for the Controls' group. The distribution of brain electrical activation is captured at peak latencies of P1, N1, N2 ERP components. The black symbols on the maps represent the individual channels in 64 channel ANT WaveGuard cap.

Figure 4.Topographic ERP map for the P1, N1 and N2 peaks in both tasks and all 4 conditions for the Dyslexics' group. All other symbols are the same as in Figure 3.