Visual naming deficits in dyslexia: An ERP investigation of different processing domains

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ABSTRACT

Naming speed deficits are well documented in developmental dyslexia, expressed by slower naming times and more errors in response to familiar items. Here we used event-related potentials (ERPs) to examine at what processing level the deficits in dyslexia emerge during a discrete-naming task. Dyslexic and skilled adult control readers performed a primed object-naming task, in which the relationship between the prime and the target was manipulated along perceptual, semantic and phonological dimensions. A 3×2 design that crossed Relationship Type (Visual, Phonemic Onset, and Semantic) with Relatedness (Related and Unrelated) was used. An attenuated N/P190 – indexing early visual processing – and N300 – which index late visual processing – was observed to pictures preceded by perceptually related (vs. unrelated) primes in the control but not in the dyslexic group. These findings suggest sub-optimal processing in early stages of object processing in dyslexia, when integration and mapping of perceptual information to a more form-specific percept in memory take place. On the other hand, both groups showed an N400 effect associated with semantically related pictures (vs. unrelated), taken to reflect intact integration of semantic similarities in both dyslexic and control readers. We also found an electrophysiological effect of phonological priming in the N400 range – that is, an attenuated N400 to objects preceded by phonemic related primes vs. unrelated – while it showed a more widespread distributed and more pronounced over the right hemisphere in the dyslexics. Topographic differences between groups might have originated from a word form encoding process with different characteristics in dyslexics compared to control readers.

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1. Introduction

Picture naming is one of the earliest milestones in linguistic development, and is thought to represent a "precursor" of the child's developing visual word recognition system. Cognitive processes involved in it include (a) visual recognition and conceptual preparation (*How do I want to refer to this object?*), (b) selection of the corresponding semantic-syntactic representation from the mental lexicon, (c) phonological code retrieval, and (d) phonetic/articulatory processing (Glaser, 1992; Gordon, 1997; see also Levelt (2001), for an influential model of language production). These processing stages unfold at a millisecond time-scale and recruit widespread cortical regions, with activation spreading from posterior visual areas through parietal and temporal regions and into frontal areas (Indefrey and Levelt, 2004; Levelt et al., 1998; Vihla et al., 2006).

However, individuals with *developmental dyslexia,* a persistent reading disorder despite adequate intelligence and no general learning problem (for a review see Vellutino et al. (2004)), differ from chronological age- and reading-matched controls in their ability to name visually presented items. Readers with dyslexia show longer naming latencies and also tend to commit more errors in response to *familiar* items, including objects, letters and digits (for an overview, see Wolf et al. (2000)). Furthermore, the naming deficit persists into adulthood (e.g., Jones et al., 2009, 2016). Evidence show that dyslexic readers are maximally impaired in serial naming tasks – with matrix presentation of items – that require simultaneous activation/access of multiple visual and phonological representations that compete for output, as in the so-called rapid automatized naming tasks, RAN (Araújo et al., 2011b; Jones et al., 2010, 2008; Wolf and Bowers, 1999; Wolf et al., 2002).

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However, individual stimulus presentation (i.e., discrete/confrontation naming tasks) also incurs a significant, albeit smaller, naming speed cost (e.g., Araújo et al., 2011a; Bowers and Swanson, 1991; Truman and Hennessey, 2006; see Jones et al. (2009) for a direct contrast between discrete- and multiple-naming formats). Yet, it is still an open question which underlying processing stages are involved and contribute to impaired naming performance by dyslexic readers, which we investigate in the present study.

A set of behavioral studies viewed visual naming impairments as symptoms of a deficit within the phonological processing system, in particular, the naming delay occurs at the level of phonological encoding – the on-line process of activating/accessing phonological information during spoken word production – and/or in the formation of (specified) phonological representations (discrete naming: Faust and Sharfstein-Friedman (2003), Nation et al. (2001), Swan and Goswami (1997a) and Truman and Hennessey (2006); serial naming: Clarke et al. (2005) and Pennington et al. (2001)). In support of this view, naming performance by dyslexic children is more sensitive to lexical variables that affect the complexity of phonological encoding, such as the word length, compared to controls (Nation et al., 2001; Swan and Goswami, 1997a). Moreover, dyslexics produced far more phonological errors than controls (Swan and Goswami, 1997b).

Despite these findings, a straightforward relationship between the speed of name retrieval and phonological ability has not always been found. In the case of RAN tasks, naming speed is found to predict unique variance in reading beyond the effect of other measures of phonological processing (Kirby et al., 2003; Landerl and Wimmer, 2008; Manis et al., 2000). However, the relationship between RAN and reading competence is a complex one, and factors such as the script transparency of a writing system (i.e. the transparency of its letter-sound mappings) might impact the cognitive dynamics of reading and its core predictors (for recent cross-language studies see Caravolas et al. (2013), Georgiou et al. (2008), Vaessen et al. (2010) and Ziegler et al. (2010)). Moreover, in at least a subgroup of dyslexics, phonological processing (assessed by phonological awareness and verbal short-term memory tasks) is close to the normal range, while rapid naming performance is significantly affected (Araújo et al., 2010; King et al., 2007; Nelson, 2015; O'Brien et al., 2012; Papadopoulos et al., 2009; Wolf et al., 2002). Therefore, the interest in exploring the role of other (extra-phonological) cognitive processing stages has seen a revival, in particular those related to early stages of visual information processing (e.g., Araújo et al., 2011a; Jones et al., 2010, 2008). Although there is a substantial literature documenting dissociations between dyslexic and non-dyslexic readers' naming performance, until now only a few studies have been conducted that directly compare the performance on experimentally manipulated versions of the naming tasks and have tried to disentangle the contribution of visual, semantic and phonological aspects during visual naming. In one exception, Jones et al. (2008) demonstrated in an eye-movement study that when naming sequences of letters, the performance of dyslexics is particularly poor under conditions of increased visual-orthographic confusability between adjacent letters. The authors proposed that inefficiencies at early stages prior to phonological access may also constrain dyslexics' naming performance. More recently, using a boundary paradigm, Jones et al. (2013) found similar results. Taken together, these findings suggest that, at least for RAN tasks, dysfluency in dyslexia reflects a more complex problem than just the retrieval of phonological codes. In the same vein, Pan and colleagues, combining a RAN paradigm with eye-movements, found smaller group differences for symbolic (dice surfaces) stimuli than for alphanumeric (digits) stimuli requiring identical phonological representations. It was argued then that phonological output processing per se may not fully account for the link between naming speed and reading skill,

and the authors proposed that the degree of automaticity in translation from visual symbols to phonological codes is also critical in dyslexia (Pan et al., 2013).

One of the obvious difficulties in interpreting naming latencies in dyslexia is that RTs are end-state measures, thus making it hard to tease apart the different subprocesses involved in visual naming performance. At the functional level, only a few PET and fMRI studies have focused on the neural basis of visual naming in dyslexia. In McCrory and colleagues' work, both word reading and (discrete) picture naming tasks elicited reduced activation in the left occipitotemporal region in participants with dyslexia relative to the control group. This result, not specific to orthographic decoding, was interpreted in the context of a general impairment in integrating phonology and visual information in dyslexia (McCrory et al., 2005). But one limitation of these brain imaging techniques is that they do not provide the temporal resolution needed for a temporal window analysis. Electrophysiological recording has a high temporal precision that these measures lack, thereby providing very useful in any attempt to decompose the distinct cognitive processing stages required for production. Somewhat surprisingly, however, very few studies have taken advantage of these measures in the study of impaired visual naming in dyslexia (for an exception see Breznitz (2005) and Mayseless and Breznitz (2011)). As an example, using a silent object- and letter-naming task, Breznitz (2005) observed that dyslexics' slowness in naming is manifested already at the early stage of stimulus identification and classification (N1-P2-N2 complex), which persists when processing the information in memory (P300) and into the output stage. Maylseless and Breznitz (2011), in turn, found differences between groups when viewing objects and pseudo-objects in an object decision task, corresponding to the P1 and N1 components, i.e., shorter peak latencies were exhibited by the dyslexics, which is interpreted as due to the greater cognitive demands of the task on this group. In the current study we use ERPs as a promising avenue to measure online activity during visual naming[1] in skilled readers and adults with dyslexia, extending prior work by using a task designed to selectively emphasize the different component processes involved in naming, from perceptual analysis to semantic and phonological access/activation, and analyzing neural correlates of these processes.

1.1. Electrophysiological markers of perceptual, semantic and phonological processing

Research has identified a set of ERP components that occur between approximately 100 and 600 ms as being related to the core processing stages underlying visual object processing. The earliest of these ERP components, the N/P190, is characterized as an early anterior negativity that inverses in polarity in posterior regions, arising between 100 and 250 ms post-stimulus onset. The N/P190 component reflects activation of a picture's perceptual features in visual cortex, and has been observed in priming paradigms where related or repeated pictures (versus unrelated) evoked smaller amplitudes (Eddy and Holcomb, 2010; Eddy et al., 2006). Once initial processing of visual features occurs, a more form-specific representation is activated, reflected by a frontally-

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[1] Substantial evidence shows that naming deficits in dyslexia generalize across tasks (e.g., discrete- and multiple-naming tasks), meaning that deviances in dyslexics' naming performance might reflect (in part) a common mechanism underlying these distinct formats of naming. In this study, we use "visual naming" as a broad term to refer to the visual naming deficits that co-occur in dyslexia across task formats, so we decided against entering into a lengthy discussion about the processing requirements that are specific to each task and how these requirements impact dyslexia; others have addressed this topic specifically; e.g., Jones et al., 2009).

distributed negativity at about 300 ms after stimulus presentation (N300). The N300 appears to reflect processing of object-specific representations, because a similar response has not been reported for words (Barrett and Rugg, 1990; Eddy and Holcomb, 2010; Eddy et al., 2006; McPherson and Holcomb, 1999). It is the first marker of successful object categorization, with an increased amplitude (i.e., more negative) for unidentified objects compared to correctly categorized stimuli (McPherson and Holcomb, 1999; Schendan and Kutas, 2002, 2007). Eddy and Holcomb (2010) described the N300 as still reliant upon the physical form of the object rather than higher level abstract conceptual and semantic features of the objects, which likely reflect the mapping of perceptual information to a more form-specific percept in memory.

The N300 is followed by the N400 component, which is a negative deflection over centro-parietal sites peaking at approximately 400 ms post-stimulus onset (for a review, see Kutas and Federmeier (2011)). Since the 80's, an impressive number of research studies investigated this ERP component with written and spoken words and sentences, while there are fewer studies using line drawings, photos or pictures. The N400 has been widely used as an index of semantic processing, with an increase in amplitude for semantically unrelated compared to semantically and/or associatively related material (e.g., using a semantic-priming paradigm: 'coffee–tea' vs. 'chair–tea') or when information mismatches from expectation (e.g., using a semantic-anomaly paradigm: 'I like my coffee with cream and sugar/socks') (e.g., Deacon et al., 2000; Hamm et al., 2002; Kutas and Hillyard, 1980a, 1980b). But there remains a lack of consensus on the interpretation of the N400 processing nature (Kutas and Federmeier, 2011; and Lau et al., 2008 for extensive overviews on the topic). On most accounts, word level priming as reflected in the attenuation of the N400 component is interpreted as resulting from automatic spreading of activation via the semantic network, so N400 indexes facilitation of lexical access (e.g., Collins and Loftus, 1975; Kiefer, 2002). An alternative interpretation of the N400 effect is that it reflects in large part post-access semantic integration processes. These processes are concerned with entering the spoken or written word into a higher-order meaning representation of the entire discourse; in the case of isolated words, the priming word is considered the 'context' into which the target word must be integrated (e.g., Brown and Hagoort, 1993; Holcomb, 1993; Sereno et al., 1998). An influential ERP study supporting a post-lexical account was conducted by Brown and Hagoort (1993): using a masked-priming paradigm, the authors failed to show any change in the N400 amplitude when the prime was masked below conscious perception, that is, when priming depends exclusively on automatic spread of activation, unlike in the unmasked presentation condition.

Pictures elicit a similar but more frontally distributed N400 than the N400 for words (Ganis et al., 1996; McPherson and Holcomb, 1999). N400 effects for pictures have also been observed in priming paradigms, for example, in object decision (Holcomb and McPherson, 1994), relatedness judgment (Barrett and Rugg, 1990; McPherson and Holcomb, 1999), and overt naming tasks (Blackford et al., 2012; Chauncey et al., 2009). Typically, less negative-going ERPs are elicited when prime words/pictures and targets are either full repetitions or semantically related (compared to non-related pairs). This attenuation of the N400 evoked by pictures may in part reflect activation at a stage of word-level semantic processing (Eddy et al., 2006); but see below for evidence showing that the N400 is also modulated by phonological factors.

On the other hand, it is somewhat unclear when we would see a signature of phonological access in the ERP waveform; there has been no systematic exploration of how phonological relations modulate ERPs during the performance of object visual naming tasks. Yet, there is some indication that at least some phonological

information can become available between approximately 300–500 ms after picture onset. For example, in a magnetoencephalography (MEG) study, Vihla et al. (2006) observed stronger fronto-temporal activity after 300 ms when participants named or made phonological decisions about pictures (both tasks require phonological code retrieval), compared with visual and semantic judgment tasks. These activations were interpreted as reflecting enhanced phonological and covert phonetic/articulatory processing in the former tasks. In another study, Dell'Acqua et al. (2010) using a picture-word interference paradigm, found a less negative waveform at around 320 ms for picture targets with a superimposed distractor word sharing the first two-to-three phonemes of their names (compared to unrelated), likely driven by overlap of phonological word-form representations. Moreover, at least for words, the N400 component is also sensitive to phonological factors, including to word-initial phonological overlap and alliteration priming (e.g., Connolly and Phillips, 1994; Jescheniak et al., 2002, O'Rourke and Holcomb, 2002; Praamstra et al., 1994), and also to rhyme similarity (Rugg, 1984a, 1984b; Rugg and Barrett, 1987). Likewise, Chauncey et al. (2009) reported a modulation around 550 ms to pictures preceded by identity than non-identity words, which the authors interpreted as driven by phonological and/or articulatory representations required to produce the picture name. However, with a word-picture priming paradigm, Blackford et al. (2012) found no significant difference between ERP waveforms evoked by phonemic related and unrelated pictures within the first 600 ms after picture onset. Because in this study there was no overlap between the prime and target name past the first phoneme, the authors concluded that the retrieval of individual phoneme representations occurs quite late in production, during the preparation of an articulatory response. Other authors have suggested that some activation/access to a word's phonological information can occur as early as 200 ms after stimulus onset (Strijkers et al., 2011). Yet, for the purpose of the present study we will consider phonological priming effects on the N400 epoch, as previous studies have predominantly shown effects of phonological manipulations in the N400 range (Jescheniak et al., 2002; Rugg, 1984a, 1984b; Rugg and Barrett, 1987).

1.2. The current study

In this study we used recordings of event-related potentials (ERPs) to examine at what processing level the dyslexic naming deficit emerges. The relationship between visual naming and (poor) reading fluency is dependent on the format of the naming task, discrete- or multiple-naming (e.g., de Jong, 2011; Gasperini et al., 2014). But there is substantial evidence that, even at the discrete level, dyslexic readers' naming fluency/accuracy is impaired. Due to methodological constraints using EEG, in this study we decided then to use a discrete-naming task to study naming problems in dyslexia instead of the more typical rapid naming paradigm.

Dyslexic and skilled adult readers were asked to perform an object-naming task in a priming paradigm, in each the relationship between the prime and the target was manipulated along the perceptual, semantic, and phonological dimensions, and modulations of the ERPs were analyzed. An innovative aspect of the present study is that it thus allow us to tease apart the role of perceptual, semantic and phonological component processes more directly by experimental contrasts, and how these impact on naming performance. Crucially, specific priming effects should be bounded to distinct neural correlates, and (deviant) ERP responses in readers with dyslexia can be allocated to the processing steps of visual naming models.

The differences between related and unrelated object pairs (i.e., the priming effect) were investigated with respect to three time

epochs of interest: (1) the N/P190 component indexing early perceptual processing; (2) the N300 component which reflect later stages of visual processing; and (3) the N400 component which is related to semantic processing and is also sensitive to phonological variables. Based on previous behavioral (e.g., Jones et al., 2010) and ERP studies (Eddy and Holcomb, 2010; Eddy et al., 2006), we expected shorter response latencies and also attenuated (less negative) amplitudes of the N/P190 and N300 visual components for those target pictures that were preceded by a picture prime relating on the perceptual dimension (compared to unrelated prime-target pairs), while perceptual priming effects on the N400 ERP component are not strongly predicted. We note here that previous behavioral reports had already alluded to the contribution of early stages of processing on the naming performance in dyslexia (i.e., prior to higher level of linguistic processing; e.g., Araújo et al., 2011a; Jones et al., 2008, 2010), and one of the exciting aspects of using ERPs is that we can tackle the specific processes alluded to in this assumption (early versus late visual processing stages).

Further, a semantic priming effect (the difference between semantically primed vs. unprimed objects) is highly predicted. The retrieval of semantic information from the stimulus may be bolstered by the "privileged access" of visual descriptions to semantic features during object naming, and so the availability of semantic processing can bootstrap the naming process (Glaser, 1992; Gordon, 1997). Following previous semantic priming studies using pairs of pictures (Barrett and Rugg, 1990; Holcomb and McPherson, 1994; McPherson and Holcomb, 1999), we were primarily interested to see modulations in the N400 epoch, expecting that those pictures that were semantically related with a preceding prime would elicit smaller N400 than unrelated pairs. This would corroborate the vast electrophysiological literature in favor of a semantic interpretation of the N400 (Kutas and Federmeier, 2011).

Finally, with respect to phonological-onset overlap, it is harder to predict what the effect of phonological priming will be. In contrast to the spoken-word recognition literature, the conditions that lead to phonological facilitation and inhibition during speech production are less clear. Evidence supports the hypothesis that phonologically similar words compete with each other during the retrieval of a phonological word form in speech production (Bock, 1987; Sevald and Dell, 1994; Wheeldon, 2003), as well as the hypothesis that formally similar words facilitate speech production (Jescheniak and Schriefers, 2001; Schriefers et al., 1990). In terms of ERPs, we anticipated that matching of phonological information between prime and target's name would induce reduced N400 amplitudes but not impact the waveforms encompassing the N/P190 and N300 (Blackford et al., 2012).

2. Material and methods

2.1. Participants

Seventeen adults with developmental dyslexia (6 males and 11 females; mean age [$\pm$ SD]=23.3 [$\pm$ 4.9] years) and 18 age-matched controls (7 males and 11 females; mean age [$\pm$ SD]=23.1 [$\pm$ 3.3] years) were tested. All were native speakers of Portuguese and, apart from two participants, were undergraduate students; none of them reported neurological diseases or psychiatric disorders. The dyslexic participants volunteered to take part in the study through advertisement on the University's student e-mail services, and campus posters. All had received a formal dyslexia diagnosis by a specialized therapist during their childhood/adolescence, and still consider their reading speed and spelling inadequate. Control participants had no history of reading and/or spelling problems. Both groups completed a battery of cognitive and literacy measures, described below. In addition, participants

completed a self-report measure on reading history, The Adult Reading History Questionnaire (ARHQ; Lefly and Pennington, 2000; Portuguese version: Alves and Castro, 2004). Written informed consent was provided for each participant.

The individual's reading achievement was assessed through the time-limited reading aloud test, adapted for the Portuguese population from the Differential Diagnosis Dyslexia Battery (3DM; Blomert and Vaessen, 2009). The reading test contained three subtasks of high- and low-frequency words and pseudowords (half a minute for each); reading speed was taken as the number of correct items read per second. Because appropriate age norms were not available, reading scores were converted into z-scores with reference to normative data collected in a preliminary study with 177 adults (mean age 21.1 $\pm$ 3.5). Dyslexic participants' word reading scores diverge from the mean level of the normative sample for at least 1.5 standard deviation (SD), while participants assigned to the control group have word reading scores in the range of $\pm$ 1 SD. A further inclusion criterion for all the participants was a nonverbal IQ score in the normal range (> 85), that was estimated based on four non-verbal competence tests from the Wechsler Adult Intelligence Scale, WAIS-III (Block Design, Matrix Reasoning, Picture Completion, and Coding); scores were converted into standardized scores and the global non-verbal IQ was then estimated following the WAIS-III manual procedure (Wechsler, 1996).

In order to get a detailed description of our sample, in addition to the Performance Scale subtests, two subtests (Vocabulary and Digit Span) of the WAIS-III Verbal Scale were also performed. Finally, phonological processing was assessed with a Phoneme deletion and Spoonerism task (Francisco and Faísca, 2012), and a Rapid automatized naming task with letters and digits (Phonological Assessment Battery; Alves et al., 2007).

As can be seen in Table 1 non-verbal IQ did not differentiate the groups, but the mean performance of the dyslexics was reliably lower than that of the controls for the digit span subtest, and, as expected, for all reading and phonological processing tasks.

2.2. Stimuli and design

Stimuli were black-and-white line drawings of common

Table 1
Average performance on cognitive tasks and mean age of dyslexic and control participants, and group differences (*t*-tests).

	Dyslexics		Controls			
	M	SD	M	SD	*t*-value	Cohen's *d*
Age (years)	23.9	4.9	23.7	4.3	−.08	.04
Non-verbal IQ	104.5	9.9	105.9	7.7	.45	.16
Vocabulary	9.9	2.5	11.2	2.2	1.57	.55
Digit span	9.1	2.8	11.6	1.9	3.04[*]	1.05
Reading speed (items/sec)						
Words	1.2	.31	1.9	.18	8.37[**]	2.76
Pseudowords	.82	.22	1.5	.21	8.32[**]	3.16
Phoneme deletion (máx.18)	12.8	2.8	16.4	2.2	4.16[**]	1.43
Spoonerism (máx.38)	20.5	12.4	32.1	5.2	3.38[*]	1.22
RAN (sec/50 items)						
RAN letters	26.5	4.5	17.5	2.3	−7.53[**]	2.52
RAN digits	25.8	4.0	17.1	3.5	−6.73[**]	2.32
QHL (máx.100)	67.6	9.0	25.4	7.8	−13.98[**]	5.01

Note. RAN, Rapid automatized naming; QHL, Adult Reading History Questionnaire. Standardized scores: Non-verbal IQ expressed in IQ scores (mean =100, SD =15); performance on the vocabulary and digit span tasks expressed in standardized scores (mean =10, SD =3).

[*] *p* < .01.
[**] p < .001.

Fig. 1. Example of object-pairs. Stimuli consisted of an object prime matched to a target object on one of three types of relationships: Visual, Semantic, or Phonological (e.g., 'chave' [key],/ˈSav6/, and 'chávena' [cup],/ˈSav6nA/). For each Relationship Type, an Unrelated item was paired with the same target object.

objects, mostly selected from the set by Cycowicz et al. (1997) and Snodgrass and Vanderwart (1980). Seventy related prime-target pairs of objects were constructed for each Relationship Type: Visual, Semantic, and Phonological. To test for stimulus suitability, two independent groups of participants rated the degree of visual and semantic relatedness of each of these pre-selected object pairs in two preliminary norming studies (see Section 2.2.1), while this was not needed in choosing the objects to represent the phonological category (as in this case the evaluation of relatedness between prime and target can be directly estimated through the computations of the number of phonemes that overlap between the objects' names). Following the analysis of the visual and semantic rating scores and of the degree of phonemic overlap, and to maximize the chance of detecting priming effects, those 53 object pairs, for each condition, that corresponded to the highest scores of relatedness in the dimension of interest (while keeping the other dimensions low-rated) were deliberately chosen for using in the main experiment (an example is given in Fig. 1); there was no overlap/re-use of the target objects between 'Relatedness' conditions.

Visually related pairs consisted of pictures that were similar in shape but unrelated in phonology and semantics. These pairs were largely selected from items used in prior line drawing shape similarity studies (e.g., Huettig and McQueen, 2007). Semantically related pairs consisted of objects that were related by virtue of their similarity in meaning rather than on the basis of the associative links that lies in their frequent co-occurrence in language use, so that priming effects resulted from activation within the semantic system rather than from associative links. This is important because associative relations are not necessarily based on the semantic properties of the lexical items (see also e.g. Alario et al. (2000) for a differential role of semantic and verbal association information during picture-naming). As for the other categories, all object pairs had low association strength (mean =.021), as measured by free association norms (Marques, 2002). With respect to phonological priming, the related pairs were

constructed in such a way that the prime shares, at least, the first two phonemes with the target picture name (phonological onset overlap; the range of phonological overlap was 2-to-5 phonemes; on average 2.8 phonemes), but both are unrelated in shape and semantics. Phonemic overlap among items could also occur in other positions within the word (i.e., beyond the first two phonemes; e.g. 'cadeira' [chair],/kAˈDAjrA/, and 'caderno' [notebook],/kAˈDErnu/), but they never rhyme with each other. The length of the target picture names varied from 3 to 9 phonemes and consisted of 2–4 syllables. For each Relationship Type, an unrelated prime was also paired with the same target object; so for each participant, the same target picture for a given Relationship Type was seen in both the related and the unrelated condition. Unrelated pairs comprised two successive items that were unrelated on all dimensions; these pairs were created by pseudo-randomly pairing the targets with primes from another condition. This resulted in a 3x2 design that crossed Relationship Type between the prime picture and the target picture (Visual, Semantic, and Phonological) by Relatedness (Related and Unrelated). There was no significant difference in frequency ($F(2,158)=.27$, $p=.76$), phonological neighborhood density ($F(2,158)=.96$, $p=.39$), number of phonemes ($F(2,158)=.78$, $p=.46$), number of letters ($F(2,158)=.49$, $p=.61$), or number of syllables ($F(2,158)=2.2$, $p=.12$) of the names of target objects across the three Relationship Types (values taken from the Corlex frequency database, Bacelar do Nascimento (2007)). The target objects were also matched on familiarity, visual ambiguity, and visual complexity (all $Fs < 1$; values based on the Portuguese normative data; Ventura, 2005).

The 318 stimuli pairs (53 Visually related, 53 Phonologically related, 53 Semantically related, and 3 x 53 Unrelated pairs) were presented in two pseudorandomized lists that were balanced among the participants in each group; each list was divided into 10 blocks. Within each list, each target object appeared twice, once paired with a related prime object and once with an unrelated prime object. This way, priming effects could be measured on exactly the same target objects while ensuring that no incidental differences rather than the manipulated properties contributed to the observed effects. The sequence of these two presentations was counterbalanced across participants, so that every object pair appeared in every position within the list the same number of times: In List 1 the related pair was presented before the corresponding unrelated pair in half of the cases and the opposite for the other half. In List 2 the order was reversed. In addition, in creating these lists, the following general criteria were applied: (1) the minimum lag between repeated target pictures was 30 intervening trials, and this was constant across all conditions; (2) no target picture was preceded by a visually, phonologically, or semantically related picture from the previous trial; (3) no more than two trials of the same relationship type followed in succession.

2.2.1. Norming studies

Fourteen undergraduate students provided shape-similarity ratings and 14 new volunteers provided semantic-similarity ratings; none took part in the main experiment. In each study, participants were presented with the 420 pictures organized into pairs (i.e., seventy related pairs for each relationship). In the visual norming study, participants were instructed to ignore the semantic content of the pictures and the sound structure of the picture's name and to exclusively judge how similar the physical shape of the target picture was to the physical shape of the prime. In the semantic norming study, participants rated the semantic relatedness of pairs of pictures while ignoring any other similarity. Judgments were made on a seven-point scale (1 representing 'absolutely no similarity in physical shape/meaning' and 7 representing 'extremely similar'. The visually related picture-pairs were judged to be physically more similar, and the semantically

related items were considered to be more similar in meaning, than any of the other items in these sets ($p < .001$ for all comparisons).

2.3. Experimental procedures

Prior to the ERP recording, participants were familiarized with the set of experimental prime pictures in order to ensure that they would in fact use the intended name. This was a two-step process: In a first practice block, participants were familiarized with the names of the objects by seeing the corresponding names printed below each picture. In a second training block, the object pictures were presented again but without their names, and participants were asked to name each one aloud; labels other than the ones expected were corrected. We decided not to familiarize participants with the names of the target pictures used in the experiment to avoid potential repetition priming and episodic memory effects that can influence ERPs, namely the N400 (e.g., Bentin and McCarthy, 1994; see also Luck (2014)).

For the experimental blocks participants were informed that they would view two sequential pictures of objects, and that they should name the first picture covertly (prime) and to name aloud the second one (target) as quickly and accurately as possible. Presentation 0.7 software (nbs.neuro-bs.com/presentation) was used to display the stimuli on a computer CRT screen with a 85-Hz refresh rate[2] (size: 19 in.; spatial resolution: 1280×960; color resolution: 24 bits). At a viewing distance of ~ 120 cm, pictures subtended about 5º (height) by 7º (width) of visual angle. Voice detection equipment was used to register response times between the onset of the stimulus display and that of the response. Each trial had the following structure: a fixation cross ($+$) appeared at the center of the screen for 500 ms, followed by presentation of the first picture (prime) of the pair (500×362 pixels) for 150 ms. Next, a white screen was presented for 40 ms, followed by presentation of the second picture (target) for 2000 ms. The length of stimulus onset asynchrony (SOA) was based on previous work exploring the relationship between SOA and prime duration (e.g., Eddy and Holcomb, 2010) and the series of effects (N/P190, N300, N400) reflecting a cascade of processes involved in object recognition. The subjects were instructed to avoid eye blinks and body movements during the presentation of the stimuli. Before the task, subjects practiced 10 trials in order to be adequately familiarized with the experimental tasks.

2.4. ERP recordings

Continuous electroencephalogram (EEG) was acquired through the ActiveTwo Biosemi electrode system from 64 Ag/AgCl active scalp electrodes that were mounted in an elastic cap. These electrodes were located at standard left and right hemisphere positions over the frontal, parietal, occipital, and temporal areas. They were also positioned according to the International 10–20 system guidelines. The electrode montage included 10 midline sites and 27 sites over each hemisphere. Two additional electrodes (CMS/DRL nearby Pz) were used as an online reference (for a complete description, see biosemi.com; Schutter et al., 2006). Three other electrodes were attached over the right and left mastoids (for

offline mastoid reference montage), and below the right eye (to monitor eye-movements and blinks). Vertical eye-movements were monitored by the right eye electrode and the Fp2 electrode from the cap, and horizontal eye movements were monitored using the F7 and the F8 electrode from the cap. Bioelectrical signals were amplified using an ActiveTwo Biosemi amplifier (DC-67 Hz bandpass, 3 dB/octave) and were continuously sampled (24 bit sampling) at a rate of 512 Hz throughout the experiment.

2.5. ERP data analysis

The EEG data were analyzed using the FieldTrip open source toolbox (Oostenveld et al., 2009; documentation and algorithms available at ru.nl/fcdonders/fieldtrip). ERP data were computed from 125 ms prior to the onset of the prime to until 600 ms following the target presentation and were time-locked to the onset of the prime stimuli. Note that, across all participants, the lowest value in the range of median naming times was 870 ms and so, to avoid speech-related artifact, we only analyzed and show ERP activity up until 600 ms post-target onset. Because a very short time window is provided on the ERPs immediately preceding the target presentation, we used a baseline in the -125 to 0 ms interval before prime onset rather than prior to the target (which in the last case would encompass the period when the prime was being observed and presumably processed); a similar methodological approach was already used in previous language production studies with priming (e.g., Redmann et al., 2014). Before averaging, epochs for each subject that contained ocular and/or muscle movement artifacts, or electric noise were manually eliminated from the analysis, as well as any trials where subjects gave incorrect responses. Data were visually artifact rejected on a trial-by-trial basis for eyeblink and on a channel-by-channel basis for drift, blocking and excessive alpha wave. The mean (SD) number of the accepted epochs in the grand averages is given in Table 2. One control subject and one dyslexic subject were not included in the ERP analysis due to a high percentage of artifacts (more than 30% of the trials per condition). Corrected trials were filtered offline (30 Hz low-pass) and re-referenced to the mean of the two mastoids. ERP data were analyzed by computing the mean amplitudes of the waveforms during specific time windows, relative to the 125 ms pre-stimulus baseline (i.e., -125 ms preprime). In this study we used mean amplitude (i.e. the average over a time window that contains the component of interest) rather than the peak amplitude because the mean amplitude is considered a more reliable measure. Also, ERP components can often have a relatively flat or heterogeneous morphology, providing no definitive point at which to measure peak amplitude. In this case, it may be preferable to take a mean amplitude measure that spans the temporal width of the components (see Handy (2005) and Luck (2014)). Whenever an ERP effect was absent for the dyslexic group as compared to the controls, we proceed to test the individual peak latency measured at the maximum peak amplitude within predefined time-windows, in order to clarify whether it is just the case that priming effect was delayed in dyslexics. Peak latencies were determined per subject for each condition and for

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[2] We acknowledge here that due to the refresh rate, it is possible that our inter-stimulus interval duration (see below) is actually 35 or 47 ms (rather than the 40 ms as intended), and one can therefore wonder whether this might have an impact on ERPs during the processing of the target. In principle, any effect will be random and affect all conditions, in other words, it is unlikely that this uncertainty makes a systematic difference. Moreover, in Presentation software the trigger associated with a stimulus event is bound to the onset of the stimulus (i.e., the trigger is sent only when the stimulus is actually presented), which means that any uncertainty caused by the refresh rate will not affect the epoch used for the EEG analysis of the target.

Table 2
The average number of trials used in individual ERPs per group.

	Control readers	Dyslexic readers
Visually related trials	39.8 (2.7)	40.0 (3.7)
Visually unrelated trials	40.5 (3.5)	40.1 (3.6)
Phonologically related trials	41.6 (2.7)	40.1 (2.6)
Phonologically unrelated trials	41.8 (2.4)	41.0 (2.6)
Semantically related trials	41.6 (3.1)	41.4 (2.9)
Semantically unrelated trials	42.5 (2.3)	41.4 (2.7)

the clusters of channels of interest. We note here that the same pattern of results was observed when we re-analyzed the data after adjusting the time window centered on each peak for the dyslexic group.

Individual ERPs were averaged within each experimental condition and for each group. For the analyses, and to restrict the number of statistical comparisons, electrodes were selected a priori in regions of interest according to theoretical considerations and visual inspection of the waveforms.

To analyze the priming effects, we compared ERPs elicited by pictures preceded by Related primes with those elicited by pictures preceded by Unrelated primes for each Relationship Type, during the time windows from 100 to 200 ms (N/P190 component), from 250 to 350 ms (N300 component), and from 350 to 550 ms (N400 component). Previous work with pictures has used similar latency ranges to assess activity of these ERP components (e.g., Barrett and Rugg, 1990; Eddy and Holcomb, 2009, 2010). Mean voltages were computed for each time window and for selected electrodes in three scalp regions where the effects were found to be maximal: frontal (F7/F8, AF7/AF8, AF3/AF4, F1/F2, F3/F4), centro-parietal (C3/C4, C5/C6, CP5/CP6) and parieto-occipital (P7/P8, PO7/PO8, PO3/PO4). Responses in the N/P190 time window were analyzed at parieto-occipital and also at anterior, frontal sites, because early perceptual effects on ERPs are expected in this region (Eddy and Holcomb, 2009, 2010). The priming effects on the N300 were restricted to the frontal electrodes, because the N300 component is maximal over these sites when a mastoid reference is used (Holcomb and McPherson, 1994; McPherson and Holcomb, 1999). The N400 was assessed at all three regions; although the N400 has a typical centro-parietal topography, nonlinguistic material as pictures tend to evoke a more widespread N400-like effect (Kutas and Federmeier, 2011).

We first performed an overall analysis of variance on the mean amplitude of the N/P190, N300, and N400 components from the representative electrodes with Relationship Type (Visual vs. Semantic vs. Phonologic), Relatedness (Related vs. Unrelated), Hemisphere (right vs. left) and – where applicable – Electrode Site (frontal vs. centro-parietal vs. parieto-occipital) as within-subject factors and Group as a between-subject factor. Note that we have no reason to expect that the factor Relatedness interacts with Hemisphere in a particular way. The main reason for including laterality as a within-factor in our analysis was because some previous studies showed that the ERP effects in the two groups (dyslexics and nondyslexics) may indeed differ in topography, independently of any difference in their mean amplitudes (e.g. Araújo et al., 2012; for a review of functional studies, see Richlan et al. (2009)) and, so, hemispheric asymmetry might be informative on its own. The overall analysis was done before testing the specific contrasts of interest in order to protect against Type I Error. Whenever three- and four-way interactions involving the Relationship Type and Relatedness factors were found to be significant, we proceed to test our hypotheses and the effect of Relatedness was examined separately for each of the three Relationship Types an at each Reading Group in a mixed-design ANOVA, during the three time windows of interest. If necessary the Greenhouse-Geisser adjustments were employed to correct for violations of sphericity. Post-hoc analyses (Tukey HSD) were conducted to investigate significant interactions.

Note: Mean number of trials with standard deviations in parentheses. The number of trials did not differ significantly between groups for each comparison of interest (Mixed ANOVA: all $Ps > .3$).).

3. Results

3.1. Behavioral data

The data were analyzed using a repeated measures ANOVA, with Relationship Type (Visual, Semantic, and Phonological) and Relatedness (Related, Unrelated) as within-subject factors, and the Group as a between-subject factor. For brevity, all of the inferential statistics are not reported here for non-significant interactions; the same logic was applied to the ERP analysis of mean amplitudes. We refer the interested reader to Supplementary material for full information.

3.1.1. Response time analysis

Response times (RTs) from the incorrect answers and implausibly long or short RTs (i.e., 2 SD below or above the subject and condition means) were excluded from the analysis. Mean RTs were calculated for each subject and each condition. The main effect of Group was not statistically significant, $F(1,33)=2.4$, $p=.13$, $\eta_p^2=.07$ (CA: Mean RT [$\pm$ std]=1009 [$\pm$140] ms, DYS: Mean RT [$\pm$ std]=1095 [$\pm$180] ms). There was a main effect of Relationship Type, $F(1.64, 52.57)=3.8$, $p=.04$, $\eta_p^2=.11$, as well as a significant interaction between Relationship Type and Relatedness, $F(2,66)=3.7$, $p=.03$, $\eta_p^2=.10$. Follow up paired t-tests at each level of Relationship Type showed significantly shorter naming times on Related than on Unrelated targets in the Semantic condition, $t(34)=2.4$, $p=.02$ (Related: Mean RT [$\pm$ std]=1045 [$\pm$174] ms, Unrelated: Mean RT [$\pm$ std]=1067 [$\pm$174] ms), but not in the Visual condition, $t(34)=.7$, $p=.44$ (Related: Mean RT [$\pm$ std]= 1064 [$\pm$162] ms, Unrelated: Mean RT [$\pm$ std]=1056 [$\pm$177] ms), or in the Phonological condition, $t(34)=1.3$, $p=.21$ (Related: Mean RT [$\pm$ std]=1046 [$\pm$163] ms, Unrelated: Mean RT [$\pm$ std]=1035 [$\pm$165] ms). Neither the interaction between Group and Relationship nor the interactions between Group and Relatedness and between Group, Relatedness and Relationship were significant ($Fs < 1$).

3.1.2. Accuracy analysis

A significant main effect of Group was observed, $F(1,33)=11.0$, $p < .01$, $\eta_p^2=.25$. The subjects with dyslexia made relatively more errors and also "non-responses" in comparison with their respective controls, for all conditions (6% and 4.6% errors, and 6.9% and 2.7% non-responses, respectively). Error analysis for the dyslexic participants showed a tendency to produce semantically related associations (e.g., "Xilofone" [xylophone] instead of "Flauta" [flute]) and semantically plus visually related associations (e.g., "Burro" [donkey] instead of "Cavalo" [horse]). Occasionally, semantically plus visually plus phonologically related associations were rather produced (e.g., "Escada" [ladder] instead of "Escadote" [stepladder]), while pure phonological or perceptual confusions were extremely rare. Across all participants, only one dyslexic participant reported the prime instead of the target, and only once. The same pattern of errors was observed for the control readers.

The main effect of Relatedness did not reach significance, $F(1,33)=1.8$, $p=.18$, $\eta_p^2=.05$, although we found a significant effect of Relationship Type, $F(2,66)=6.9$, $p < .01$, $\eta_p^2=.17$, due to significantly more errors in the Visual (about 12%) than in the other conditions (approximately 9% for both Semantic and Phonological conditions). We note that this result is unlikely to be due to linguistic variables of the targets' names, or to differences in the familiarity, visual ambiguity, or visual complexity of the pictures, which were matched across the three Relationship types (see Section 2). One possibility is that the picture targets that we used in the Visual condition were inherently more difficult to name. Still, the interaction between Relationship Type and Relatedness was non-significant ($F < 1$).

3.2. Electrophysiological data

Because some properties of the prime could potentially influence the period of the target (i.e., carry over effects to the period when the target is being observed and processed), we first checked whether the properties of the prime (Related or Unrelated prime) led to differences in the ERP waveform. An omnibus ANOVA was then carried out over the mean ERP amplitudes time-locked to the onset of the prime to until 190 ms (i.e. during the time interval encompassing the prime plus the white screen that precedes the target), using the same mixed-design ANOVA as we used in the analysis time-locked to the onset of the target (see above). This analysis showed neither a significant main effect of Relatedness nor any interaction with Relatedness ($p > .2$ for all contrasts). Therefore, it is unlikely that any priming effects that were found are spurious and caused by carry over from the prime.

We then proceeded to the analysis of the EEG responses time-locked to the onset of the target. Mean voltages are presented in Supplementary table.

3.2.1. The N/P190: 100–200 ms

Analysis of the mean amplitude across the N/P190 time window through an omnibus ANOVA including all stimulus categories together revealed a significant three-way interaction between Relationship Type, Relatedness and Electrode site, $F(2,62)=9.3$, $p < .001$, $\eta_p^2=.231$, as well as a significant four-way interaction Relationship Type by Electrode site by Hemisphere by Group, $F(2,62)=5.4$, $p=.007$, $\eta_p^2=.149$. The four-way interaction between Relationship Type, Relatedness, Electrode Site and Group did not reach statistical significance, while the result was actually not completely null, $F(2,62)=2.4$, $p=.095$, $\eta_p^2=.073$, a moderate effect size. These interactions were then followed up by examining the effect of Relatedness through 2 (Relatedness) x 2 (Electrode site) x 2 (Hemisphere) ANOVAs separately for each of the three Relationship Types – Visual, Phonemic Onset and Semantic – at each Group.

Restricting the analysis to each condition, for the control readers we found a significant interaction between Electrode site and Relatedness for visual priming, $F(1,16)=14.5$, $p < .005$, $\eta_p^2=.475$, and for semantic priming, $F(1,16)=4.9$, $p=.042$, $\eta_p^2=.234$, while no interaction with relatedness was observed in comparing the Phonologically related and Unrelated pairs during the N/P190 time window. As expected, target pictures preceded by perceptually similar primes evoked a smaller N/P190 in anterior regions ($p=.018$) that inverse in polarity in the posterior regions ($p=.014$), compared to target pictures preceded by Unrelated primes. Moreover, pictures preceded by semantically related primes evoked smaller amplitudes than those preceded by semantically unrelated primes, but this effect was primarily frontally distributed ($p=.049$). We note here that the differing visual similarity between related and unrelated picture pairs may have been responsible for the (unexpected) semantic priming effects found in this early visual component. Although we have tried as far as possible to match the Semantically related and Unrelated pairs, there is still a difference in mean visual similarity between these picture pairs, with Semantically related pairs being also more similar in shape than Unrelated pairs ($p=.012$, based on the pre-test rating scores). In the dyslexic group we found no early divergences in the waveforms between 100 and 200 ms for each of the three Relationship Types. This was reflected by the absence of any main effects of Relatedness or interactions of interest; only a close to significance interaction Electrode site by Relatedness was observed for semantic priming, $F(1,15)=3.7$, $p=.073$, $\eta_p^2=.199$ (Figs. 2, 3 and 4).

One could still wonder whether visual priming effect might be just delayed in the dyslexic participants. This is not the case, however, as when we perform a repeated measures ANOVA on the peak latency of the N/P190, we found no significant main effect of Group, $F < 1$, or interaction involving Group and Relatedness, $F(1,31)=1.2$, $p=.29$.

3.2.2. The N300: 250–350 ms

The omnibus ANOVA revealed an interaction between Relationship Type and Hemisphere, $F(2,62)=19.3$, $p < .001$, $\eta_p^2=.383$, and also a four-way interaction between Relationship Type, Relatedness, Hemisphere and Group, $F(2,62)=3.1$, $p=.04$, $\eta_p^2=.092$. We thus proceeded to examining the effect of Relatedness through 2 (Relatedness) x 2 (Hemisphere) ANOVA separately for each of the three Relationship Types and at each Group.

Restricting the analysis to each condition, for control readers, only the perceptually similar versus Unrelated stimulus pairs differentiated on the N300 mean amplitude, as indicated by a significant interaction between Relatedness and Hemisphere, $F(1,16)=5.1$, $p=.037$, $\eta_p^2=.243$. Over right frontal sites, significantly larger negativities were elicited for pictures preceded by Unrelated primes compared to those preceded by perceptually similar primes ($p=.017$) (Figs. 2 and 4). No main effects of Relatedness or interactions of interest were observed at the most anterior sites when restricting the analysis to the Semantic or the Phonological priming (all $Fs < 1$) (Figs. 3 and 4). For dyslexic readers, all contrasts failed significance in the N300 time window, as reflected by the absence of any main effects of Relatedness or interactions with Relatedness (all $Ps > .2$). When the same analysis was repeated using the average peak latencies, the main effect of Group or the interactions between Group and Relatedness were still non-significant (all $Ps > .2$).

3.2.3. The N400: 350–550 ms

During the N400 time window, the omnibus ANOVA revealed a significant three-way interaction Relationship type by Relatedness by Hemisphere, $F(2,62)=6.6$, $p=.002$, $\eta_p^2=.176$, as well as a four-way interaction Relationship type by Relatedness by Electrode site by Group, $F(4,124)=2.5$, $p=.047$, $\eta_p^2=.074$. We next proceeded to the separate ANOVAs.

In comparing the Visually related and Unrelated pairs during the N400 time window, for both groups, pictures preceded by perceptually similar primes evoked a smaller N400 than pictures preceded by Unrelated primes. The visual priming effect was modulated by the factor Hemisphere for control readers, $F(1,16)=9.6$, $p=.009$, $\eta_p^2=.359$, because the effect of Relatedness was restricted to the right hemisphere ($p=.014$). The same interaction was marginally significant for the dyslexic group, $F(1,15)=4.2$, $p=.058$, $\eta_p^2=.220$. Effects of visual priming were of equal magnitude across the scalp, as no interaction between Relatedness and Electrode site was observed for this contrast (Figs. 2 and 4). In comparing the Semantically related and Unrelated pairs, a two-way interaction between Relatedness and Hemisphere was found for the controls, $F(1, 16)=7.0$, $p=.017$, $\eta_p^2=.305$, indicating that stimuli differentiate at right hemisphere ($p < .005$) but not at the left hemisphere. For dyslexic readers, the semantic priming effect was modulated by the factor Electrode site, $F(2, 30)=4.0$, $p=.028$, $\eta_p^2=.212$. Post-hoc analyses showed that, for this group, the semantic priming effect was restricted to the frontal regions ($p < .05$), with pictures preceded by Unrelated primes being associated with less negative-going amplitudes than pictures preceded by Semantically related primes. To test the possibility that, due to the lack of effect for visual features, the semantic priming might be delayed in dyslexia, we next performed a repeated measures ANOVA on the N400 peak latency. No main effect of Group or interaction between Group and Relatedness was observed (all $Fs < 1$).
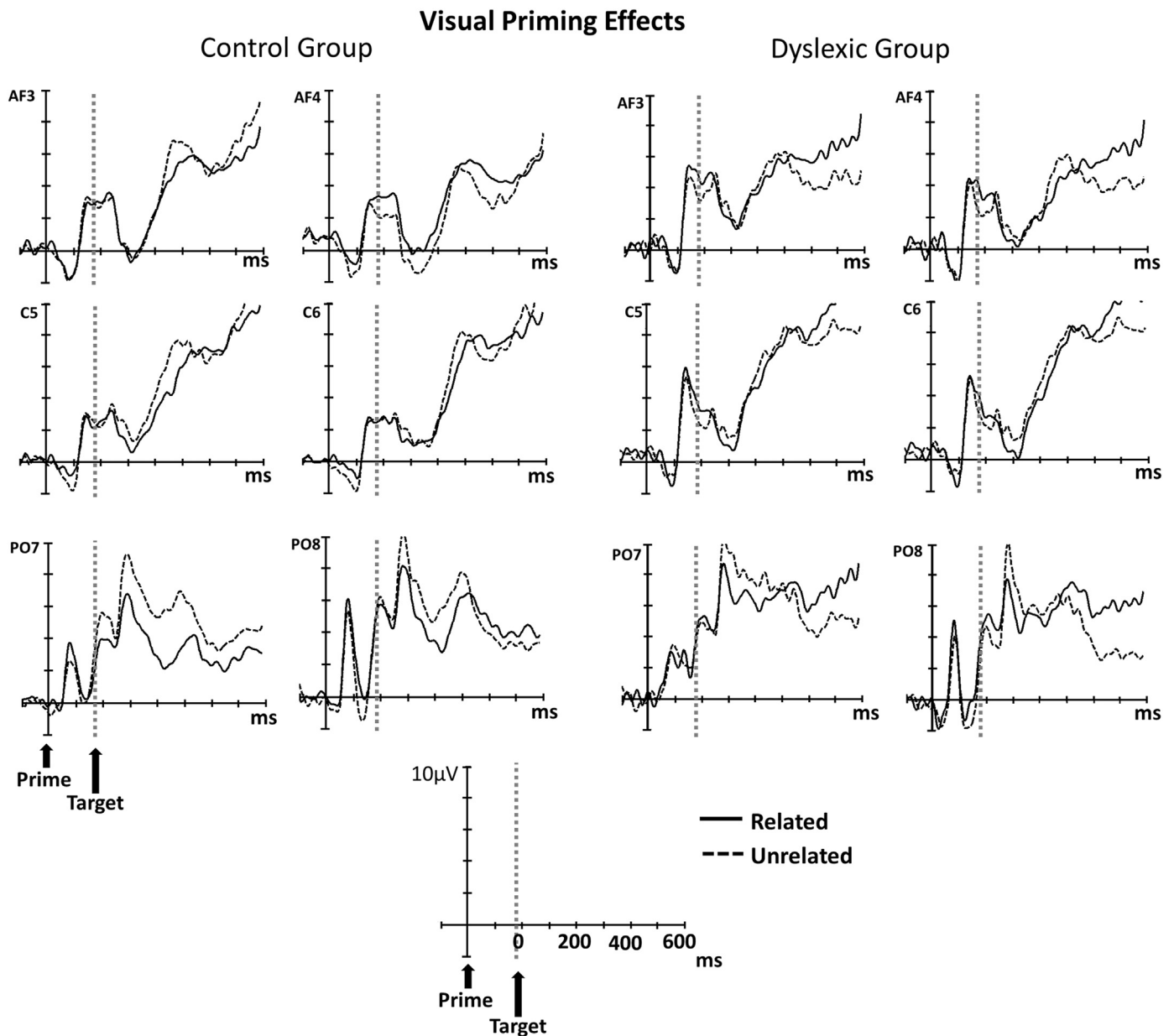
Visual Priming Effects

Control Group   ### Dyslexic Group

Fig. 2. Average ERP waveforms from representative electrodes for the Visual Manipulation, time-locked to prime onset (primed conditions are represented by solid lines, unprimed conditions by dotted lines; baseline between − 125 and 0 ms before prime onset). Waveforms averaged separately for normal readers and dyslexic readers.

Lastly, the contrast Phonologically related versus Unrelated pictures revealed that for both groups Unrelated pictures evoked enhanced negative-going amplitudes than Phonologically related pictures. A significant interaction between Relatedness and Electrode site was found for the controls, $F(2, 32)=4.0$, $p=.030$, $\eta_p^2=.209$, because differences between waveforms evoked by Unrelated vs. Phonologically related pictures were significant at the centro-parietal and parieto-occipital sites (both $Ps<.05$) but not at frontal electrode sites. For dyslexic readers, phonologically related primes evoked a widespread N400-like effect in the ERPs but restricted to the right hemisphere ($p=.032$), as indicated by a significant interaction between Relatedness and Hemisphere $F(1, 15)=5.0$, $p=.040$, $\eta_p^2=.251$ (Figs. 3 and 4).

3.2.4. Additional analyses

Lastly, it could be asked how representative the mean effects tested above are of the individuals in the group. We thereby computed the number of dyslexic readers falling outside de

normal range of the control group; normal range was defined here as thresholds 1 SD below the control mean. For the visual priming effect, more than half of the dyslexic sample performed below the control normal range during the N/P190 time window (56% for the frontal electrode clusters and 63% for the parieto-ocipital electrode clusters), while about 44% of the dyslexic participants scored below this cut-off during the N300 time window (for both right and left frontal electrode clusters). For the semantic contrast, less than 20% of the dyslexics registered overall scores < 1 SD below the control normal range during the N400, while for the phonological priming effect it was generally around 40% that performed below the cut-off on the time window encompassing the N400 (38% for the frontal, 44% for the parieto-occipital, and 50% for the centro-parietal electrode clusters). It thus means that at least for the visual and phonological contrasts a substantial amount of readers with dyslexia did fall beyond the normal range of the control reference group.
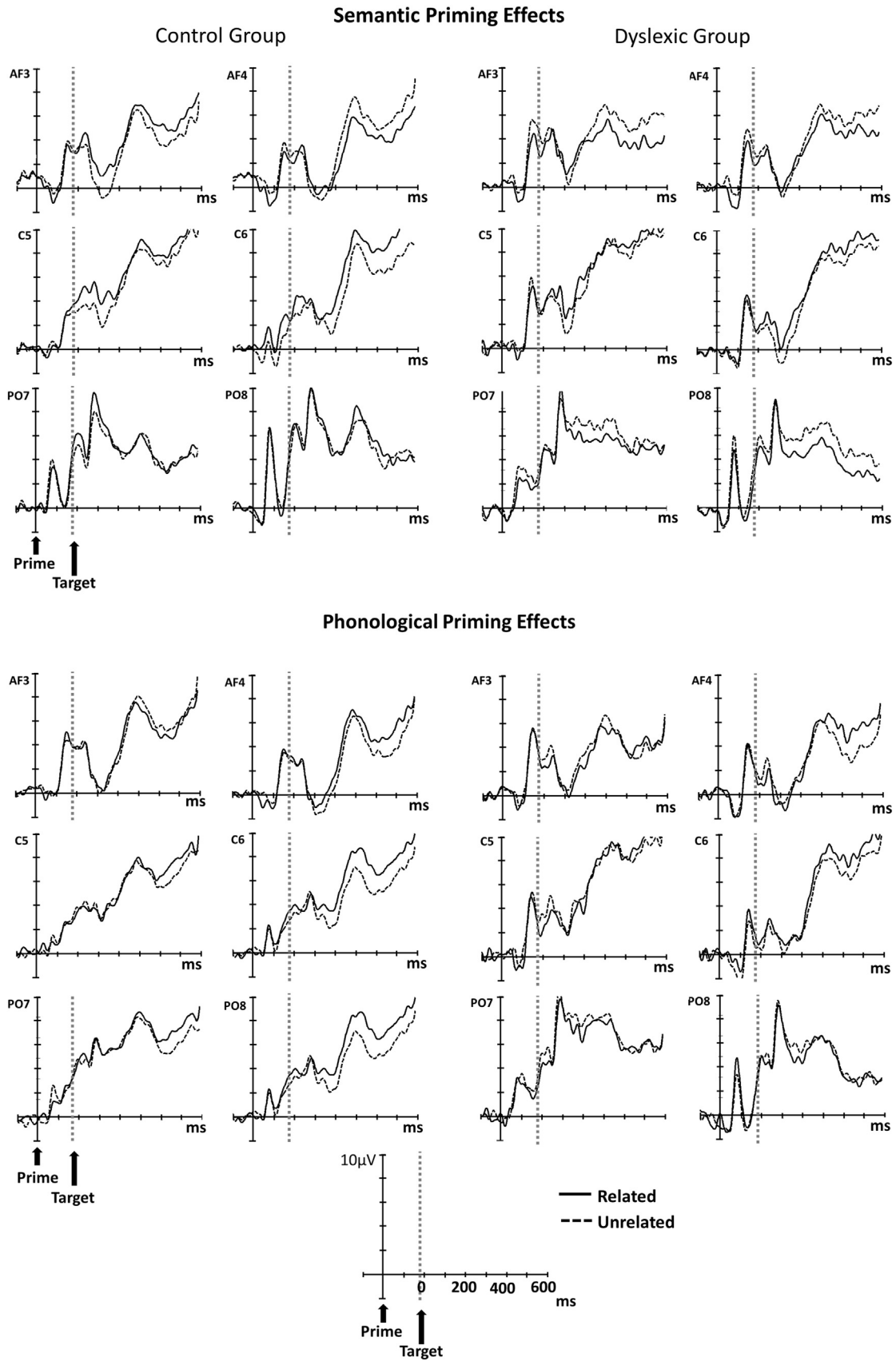
Fig. 3. Average ERP waveforms from representative electrodes for the Semantic and Phonological manipulations, time-locked to prime onset (primed conditions are re-presented by solid lines, unprimed conditions by dotted lines; baseline between −125 and 0 ms before prime onset). Waveforms averaged separately for normal readers and dyslexic readers.
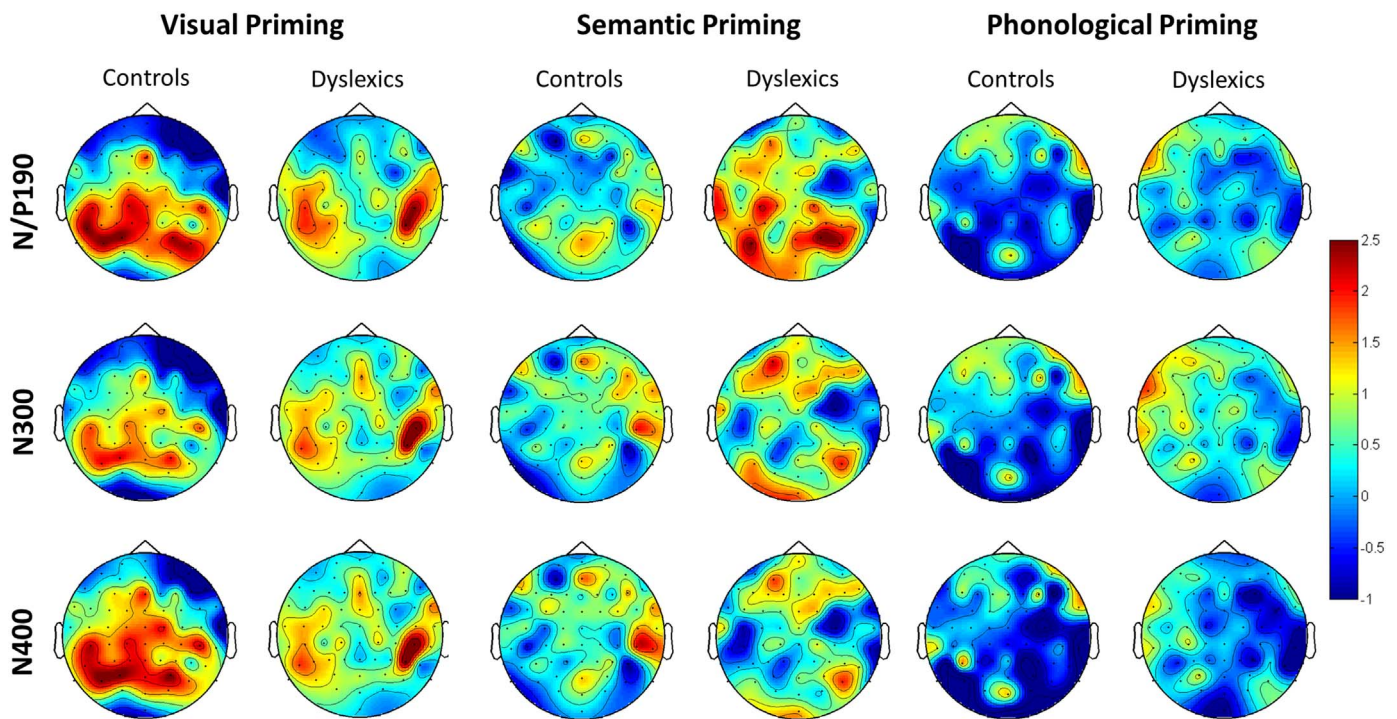
Visual Priming   **Semantic Priming**   **Phonological Priming**

Fig. 4. Topographic distribution of the priming effects in control and dyslexic readers. Voltage maps show unrelated minus related voltage differences.

4. Discussion

This study aimed to contribute to the debate over which processing stage(s) contributes to the visual naming deficits in dyslexia. A promising avenue for providing a fine-grained analysis of the time course of visual and linguistic processing in visual naming is the recording of ERPs, which were used here. ERPs were recorded while dyslexic adults and age-matched controls performed an object-naming task in a priming paradigm, in which perceptual, semantic category, and phonological onset overlap between pairs of pictures was manipulated.

Behaviorally, our dyslexic sample committed more errors in naming pictures of objects than controls did, thus confirming a performance deficit. It is quite surprising that adults would fail to be able to name an object that was displayed for 2 s. A possible explanation for the results may be that dyslexics' performance reflects impaired ability to disengage with the (already-named) prime in order to focus on processing the target; the target followed the prime after a very short interval of 40 ms, which involves accurate and rapid engagement and disengagement of processing resources in each stimulus. This explanation fits well with a substantial literature on atypical attentional deployment (in the visual modality) in dyslexia, probably linked to a parietal lobe dysfunction (e.g., Facoetti et al., 2008; Hari et al., 1999; Ruffino et al., 2010; see Hari and Renvall (2001) for a review). According to Hari and Renvall's (2001) proposal, dyslexic readers exhibit 'Sluggish Attentional Shifting' (SAS) that impairs their ability to rapidly disengage from processing one item in order to engage with another item. However, our finer-grained analysis of errors showed no dominant type of error and it was also not the case that dyslexics have just reported the prime more than the target, which we would have expected from a SAS-based interpretation. But we note here that dyslexics differed from control readers both in terms of the proportion of errors they committed and of the non-responses. At the same time, response latencies did not differ significantly between groups in this study. To some extent, this result is consistent with prior work suggesting that dyslexics'

impairments in visual naming as reflected in the longer latencies persist into adulthood but at a more subtle level, that is, slower naming is apparent when naming proceeds in rapid succession (e.g., Felton et al., 1990; McCrory et al., 2005) as opposed to confrontation naming with no time constraints. It is possible that our sample of adult dyslexics are compensated to some extent, and some deficits at this behavioral level only becomes visible when using more demanding or complex tasks. Indeed, longer naming latencies characterized our dyslexic sample when performing more sensitive rapid automatized naming tasks (see Table 1).

In addition, our results showed that the priming effects in object-naming become manifest mostly at the electrophysiological level and not at the behavioral level, in both groups. Only the semantic relatedness manipulation reached statistical significance in the RT analysis: faster naming times were observed when target pictures were preceded by a picture from the same semantic category compared to unrelated ones. A similar facilitatory effect is sometimes observed in studies with picture naming (e.g., Jones et al., 2010), although the degree to which semantic facilitation (or interference) occurs during the processing of non-orthographic stimuli will depend on the experimental parameters of the task (e.g., with longer vs. shorter SOAs; Alario et al., 2000; Schriefers et al., 1990). Yet, when pictures were preceded by other perceptually similar or overlapping phonologically with the onset of the target name, no behavioral effects were obtained in our study; apparently, our priming manipulation lacks robustness to be captured by traditional behavioral measures. The lack of behavioral priming effects which were however reflected in the ERP waveform is not an uncommon finding in the literature, at least with line drawings (e.g., Holcomb and McPherson, 1994; McPherson and Holcomb, 1999). Perhaps a task involving attentive processing of the specific relationships would have elicited overt effects.

4.1. Perceptual relationship

The N/P190 component presents itself as a posterior positivity/anterior negativity occurring at about 100–250 ms post stimulus

onset, and has been suggested to reflect early perceptual processing of visual features of the objects in visual cortex (Eddy and Holcomb, 2009; Eddy and Holcomb, 2010; Eddy et al., 2006). Accordingly, control subjects in our study showed an attenuation of the early N/P190 component to target pictures preceded by a perceptually similar prime picture as compared to the unrelated trials, in agreement with previous studies (Eddy and Holcomb, 2010). We interpret this early priming effect as most likely reflecting greater benefit in perceptual processing from the visual-structural information available from the (related) prime and, consequently, less demanding neural processing of the perceptually primed target picture.

Regarding dyslexic readers, we found no perceptual priming suppression on the N/P190 time window; there was a tendency for a perceptual priming modulation restricted to the posterior sites in these individuals, but this did not reach statistical significance. It thus seems that some perceptual characteristics were processed in the target stimulus by dyslexics' brain, but eventually in a sub-optimal way. However, we acknowledge here that, given the statistical weakness of the omnibus ANOVA analysis ($p = .095$, partial-$\eta^2 = .073$, a moderate effect size), our results of a differential N/P190 to perceptually related versus unrelated pictures need to be interpreted cautiously. Recent work with words and non-ortho-graphic symbol-strings have already detected reduced neural activation for individuals with dyslexia during time segments related to perceptual processing (P1 response, an effect presumably related to the N/P190 for pictures; e.g., Araújo et al., 2012; Brandeis et al., 1994; Maurer et al., 2007; Maurer et al., 2011) which may have originated from involvement of a smaller or less synchronous neural population in visual recognition. Using an object decision task, Mayseless and Breznitz (2011) also obtained evidence of different brain activation among dyslexic readers from the very early stages of processing. From a perspective of individual subtypes within the dyslexia profile, other types of difficulties have been ascribed to a deficit occurring as early as the orthographic-visual analysis stage (prior to (non)lexical processing during reading), including between- or within-word migration errors in attentional or letter position dyslexia (e.g., Friedmann et al., 2010; Kohnen et al., 2012); but we note that a discussion about the existence of subtypes of developmental dyslexia is beyond the scope of this manuscript.

In this study we were also interested in another important effect observed in object recognition, a later negative-going effect – the N300. This effect most likely reflects object-specific processing that is sensitive to the activation of a specific percept in memory, but prior to higher level semantic processing (Eddy et al., 2006; McPherson and Holcomb, 1999). In this study, an increased frontal negativity occurring at about 250–350 ms was observed for control readers in response to unrelated target pictures compared to perceptually related pictures, as predicted from previous work with picture priming and picture naming (while no such effect has been reported for words; Chauncey et al., 2009; Holcomb and McPherson, 1994; McPherson and Holcomb, 1999). Yet, of most interest here, no differential N300 modulation in the ERP waveform by visual priming was observed in the dyslexic participants. This is a quite interesting result as it suggests for the first time that individuals with dyslexia may fail to activate an intermediate representation that relies on a "more complex" integration of perceptual features onto form-specific representations in memory, reflected in the N300 neural marker. Some previous behavioral studies had already explored for the possible involvement of early stages prior to higher level linguistic processing in dyslexia, by using a manipulated version of a naming task (e.g., Araújo et al., 2011a; Jones et al., 2008, 2010). For example, Araújo and colleagues manipulated various surface attributes that should affect stimulus discriminability and visual feature analysis (such as the amount of detail/complexity and color), fundamental to successful recognition. Dyslexics' performance differed qualitatively from controls as a function of the surface object information that was available, namely they take less advantage of this information during object-naming when compared to the typical readers. However, one obvious inherent limitation of this study is that it does not allow a fine-grained dissociation between early visual feature analysis versus integration of information deficits. As this respect, the present findings on the N300 range add new insights to the literature: late rather than early visual processing stages seem to contribute most to naming performance in dyslexia.

In sum, in this study we confirmed that when overall shape and/or internal features of the prime and target overlap, lower demands are imposed on early perceptual processing and visual recognition of target pictures is then facilitated (perceptual priming on N/P190 and N300, extending also to the later N400 epoch). More crucially, taken together our results also suggest that early stages prior to higher level of linguistic processing, occurring in the N/P190 and in particular the N300 time window, might be at play in the visual naming impairments by dyslexics, at least in part. Ultimately this would potentially result in less optimal information transfer between the visual and language systems during access and retrieval of picture names, and thus slow down the naming response.

4.2. Semantic relationship

In picture naming tasks, retrieval of semantic information from the visual stimulus may be bolstered by the "privileged access" of visual descriptions to semantic features (Glaser, 1992; Gordon, 1997). Most probably then, picture naming performance should be related to individual differences in semantic ability. So, in this study we also included a semantically related condition to test whether skilled and dyslexic readers differ in their ability to retrieve semantic information, and so whether dyslexics' naming impairments can be somewhat traced to that.

In comparing semantically related versus unrelated stimulus pairs, behavioral and ERP findings patterned together: for both groups, the observed behavioral facilitation was also reflected in the ERP waveform between 100 and 200 ms (N/P190) and between 350 and 550 ms (electrophysiological semantic priming), which was smaller (less negative) to target pictures that were semantically primed. We take the 350–550 ms electrophysiological modulation to be an N400 effect, similar to what has previously been found in studies examining the N400 response to pictures (Barrett and Rugg, 1990; Blackford et al., 2012; Chauncey et al., 2009; Eddy and Holcomb, 2010; Holcomb and McPherson, 1994; McPherson and Holcomb, 1999), while we could not detect a separable N300 component preceding the N400 when assessing semantic priming.

For both groups, semantic priming yielded suppressed N400 response, though being less widespread distributed in dyslexics. Hence, in dyslexic adult readers the active viewing of familiar objects can likewise elicit circuits engaged in retrieval of semantic information (indexed by smaller N400 to related targets), and these readers can indeed take advantage of the semantic similarities between consecutive items. It thus seems unlikely that their naming impairments stem from a selective deficit in semantic access/retrieval and integration of semantic information, as suggested already by some behavioral studies (Faust and Sharfstein-Friedman, 2003; Murphy and Pollatsek, 1988). Electrophysiological studies on semantic processing in subjects with reading disorders are scarce (to our knowledge, none with naming tasks) and have yielded rather mixed results (Jednoróg et al., 2010; Rüsseler et al., 2007; Schulz et al., 2008; Silva-Pereyra et al., 2003). Some studies on sentence processing have reported an attenuation of N400

effect in semantic priming in dyslexics compared to controls (Helenius et al., 1999; Schulz et al., 2008; but see also Robichon et al. (2002) for enhanced N400) whereas others have found semantic priming to be relatively intact in individuals with dyslexia (Jednoróg et al., 2010). The nature of the tasks may prove important in understanding theses discrepancies, for example, attenuated N400 incongruent effects in dyslexics has mainly been found in studies requiring subjects to explicitly judge the congruency of the final words with the preceding context. In Jednoróg et al.' study (2010) – used word lists with congruent and incongruent endings – no overt judgments were required, like in our study.

In sum, our findings support previous claims that perceptual processing of pictures automatically leads to the activation of corresponding semantic information, even when the task does not explicitly require such information, and that the N400 indexes something fundamental about this stage of processing. One possibility, based on Levelt and colleagues' model of speech production (Levelt, 2001; Levelt et al., 1999), is that the N400 evoked by pictures in naming tasks reflects activity at the interface between the picture's conceptual features and a more abstract word-level representation (the lemma), in other words, at a stage of whole-word semantic processing (Blackford et al., 2012; but see Kutas and Federmeier (2011), for an extensive overview about the cognitive nature of the N400). More important, from our results it is also apparent that retrieving semantic information in the context of an implicit condition is not clearly impaired for adults with dyslexia, though the neural processes underlying it are topographically less widely distributed. This fits well within a framework in each naming efficiency in dyslexia does not imply a specific deficit in the semantic domain (Nation, 2005; Nation et al., 2001), extending these earlier results to a neural marker of semantic processing, the N400.

4.3. Phonological onset relationship

A significant modulation in the ERP waveform between 350 and 550 ms in centro-parietal and parieto-ocipital regions, indicates that control subjects were fully capable of distinguishing phonological overlapping items from unrelated ones at the neural level, even if behaviorally we have failed to observe a priming effect. Less-negative going ERPs in the 350–550 ms were observed when the prime overlapped phonologically with the target picture's name compared to the unrelated condition, while no divergences were found in the earlier waveforms for the phonological contrast. Likewise, at least two previous ERP studies that have examined phonological processing during picture naming also found a diminished ERP amplitude for the phonologically primed stimulus (Dell'Acqua et al., 2010; Jescheniak et al., 2002). Facilitation for phonologically related stimulus can be explained under the assumption that some of the units out of which the target word forms need to be constructed already become activated when the prime is presented; apparently, this facilitates the phonological encoding of the target (i.e., the construction of its word form; Levelt, 2001; Levelt et al., 1999; but see Bock (1987), Sevald and Dell (1994) and Wheeldon (2003), for examples of phonological inhibition or interference phenomena).

But our main interest in this study was to investigate for neural correlates of phonological processing inefficiencies that has been argued to underpin dyslexics' naming deficits (e.g., Faust and Sharfstein-Friedman, 2003; Swan and Goswami, 1997a, 1997b; Nation et al., 2001). So far, (behavioral) studies tackling the phonological deficit in dyslexia have been numerous, while these studies not always agree about the exact nature of this underlying impairment (for example, whether dyslexics' phonological representations or/and processes for lexical access are preserved, or

not). For example, Truman and Hennessey (2006) reported enhanced facilitation of naming RTs from hearing phonologically related distracters in dyslexic readers compared to controls. The authors attributed this effect to a retrieval mechanism that is less automated in dyslexia, and so more vulnerable to external influences.

In the current study, regarding dyslexic readers, we did find an electrophysiological effect of phonological priming in the N400 time window – i.e., attenuated N400 to pictures preceded by phonemic related primes vs. unrelated – while this effect was more widespread distributed and more pronounced over the right hemisphere compared to the controls. To some extent, this finding resembles previously reported patterns of increased right-hemisphere participation in phonological and reading tasks in individuals with dyslexia, likely to compensate for the dysfunctional left posterior reading systems (e.g., Pugh et al. (2000), Shaywitz et al. (1998) and Richlan et al. (2009) for a review). We note here that N400 effects in the current study arose at the phonological onset level (though occasionally there were matching segments past the initial positions), and not reflect phonological processing related to rhyme decisions as has been found elsewhere (e.g., Grossi et al., 2001).

In previous ERP studies on reading, dyslexic readers have already been found to exhibit deviant phonological priming in the N400 range (Ackerman et al., 1994; McPherson et al., 1998), although manipulating other dimensions of phonological processing (rhyming and non-rhyming stimuli). Our results add to these studies indicating that phonological processing assessed both in terms of rhyme and phonological onset priming is deviant in dyslexia – at least in terms of the topography of the effect – and, more importantly, pointing to a possible common neural basis for deficits in reading and visual naming. Interestingly, recent ERP findings on reading also raised the possibility that an absent or atypical N320 and N400 ERP modulation in dyslexic adults may not reflect an impaired perceptual sensitivity to phonology per se, but perhaps relates to some form of reduced maintenance and integration of phonological information in memory in dyslexia (Araújo et al., 2015; see also Savill and Thierry (2011)). In their review, Ramus and Szenkovits (2008) argue also against the hypothesis that individuals with dyslexia have degraded phonological representations: for example, dyslexics show as much subliminal repetition priming with words as controls. Arguably, in (conscious) priming tasks as we used here participants have to hold the phonology of the prime in their memory, and one may speculate that N400 effects that we observed could reflect less efficient phonological memory processes in dyslexia. Though this interpretation is tempting, further naming research is warranted to clarify the nature of N400 effect in dyslexia as reflecting phonological encoding or phonological memory processes (or even other dimension of the phonological system).

4.4. Limitations of the present study

Some limitations of the present study should be noted. Although there is substantial evidence that dyslexics present impaired naming under discrete presentation, our groups showed no difference in their RTs, perhaps because our sample of (high-functioning, university educated) adults with dyslexia have compensated already to some extent their overt symptoms; however, differences appear when more sensitive measures such as ERPs are used. Regarding the semantic condition, in particular, it was not possible to perfectly match related and unrelated pairs in terms of visual similarity, which conceivably might have introduced a confound (though we think this is unlikely). Moreover, probably due to the small sample size, some of the observed ERP effects were not as robust (a special note here to the N/P190 analysis), and

therefore interpretations have to be drawn cautiously. Lastly, in this paper we further attempted to use the intra-class correlation (not reported here) as a global measure of similarity of an individuals' ERP waveform to a grand average waveform expected from the reference group (ICC; see Bishop et al. (2007)). There is, however, considerable variability in our sample in overall amplitudes as to render some of the waveforms to be mirrors of the mean data; this may well be related to the fact that we are using complex stimuli, which may have resulted on ERPs with a less typical morphology. Arguably, then, one should be aware that the group averages may not be a perfect representation of the individual data.

5. Conclusion

In this study we used ERPs to characterize the online timing of cognitive activities involved in processing information during a discrete-naming task in dyslexic and normal readers. Unlike typical readers, subjects with dyslexia showed reduced sensitivity to perceptual priming (i.e., no differential mean amplitude to visually related versus unrelated target objects) in the N/P190 and in particular the N300 range, indexing early and late visual processing stages, respectively. Our findings suggest that matching of features to patterns conforming to stored form-specific representations might be the crucial low-level factor involved in naming performance in dyslexia, compared to visual processing for feature detection/extraction per se. Moreover, responses to semantic priming in the N400 range indicated relatively intact integration of semantic information in dyslexics, but the N400 phonological priming suppression showed a topographic distribution that was characterized by a predominant asymmetry over the right hemisphere in the dyslexic group in contrast to the controls. Different sources or factors might be the foundation of a suboptimal, atypical, phonological processing in dyslexia that needs to be further investigated in future research (e.g., localized at an early stage of lexical encoding, or at the phonological output stage as recently discussed, see Jones et al. (2016)).

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia. 2016.07.007.

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