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How do adults with dyslexia recognize spoken words? Evidence from behavioral and EEG data

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Abstract

Purpose: In speech processing, the impacts of persistent phonological deficits in dyslexic readers (DYS) are typically reported in meta-phonological, verbal short-term memory, and challenging speech identification tasks. Here, we examined whether such deficits also generalize to a less demanding speech recognition situation.

Method: Adults with and without dyslexia performed an auditory lexical decision task. Performance and event-related potentials (ERP) were recorded.

Results: Reaction times showed a lexicality effect in both groups, with overall slower responses in *DYS*. ERP data distinguished the two populations at the lexico-semantic stage of word recognition. The early phase of N400 showed an unusual amplitude enhancement for words compared to pseudowords in *DYS*. N400 amplitude in skilled readers dropped in the later phase of word recognition, leading to the typical lexicality effect, but this activity was sustained in *DYS*. Finally, skilled readers and *DYS* showed no difference in pseudoword processing.

Conclusions: The combination of the early enhancement and sustained N400 responses to words observed in *DYS* and the absence of a group effect during pseudoword processing indicate an over-reliance on semantic representations when *DYS* recognize spoken words. Further research is needed to determine whether this reflects a compensation mechanism or a residual impact of phonological deficits.

Keywords

Dyslexia, Adults, Lexical processing, Spoken language, Electroencephalography

Introduction

It is widely accepted that developmental dyslexia (hereafter, dyslexia) is associated with phonological processing deficits (Ramus, 2014; Ramus et al., 2003). The consequences of these deficits that persist in adulthood are typically observed through poor performances in meta-phonological tasks (Boets et al., 2013; Callens et al., 2014; Wilson & Lesaux, 2001), pseudoword naming (Cavalli et al., 2018), phonological working memory (Paulesu et al., 2001; Wilson & Lesaux, 2001), and tasks involving speech sound discrimination or phonotactic skills (Berent et al., 2013; Noordenbos & Serniclaes, 2015; Virtala et al., 2020).

Although the specific nature of the phonological deficits is still under debate (Castet et al., 2019; Ramus, 2014; Ramus & Szenkovits, 2008; Saksida et al., 2016; Szenkovits et al., 2016), most observations have pointed to the conclusion that these deficits may stem from either long-lasting difficulties in translating phonetic features and speech signal contrasts into stable phonological representations (Boets et al., 2007; Ziegler et al., 2009) or a laborious access to and retrieval of these representations (Boets et al., 2013; Mengisidou & Marshall, 2019; Ramus et al., 2013; Saksida et al., 2016). In their review article, Ramus & Szenkovits (2008) proposed the concept of *phonological access* which refers to all processes by which lexical or sublexical phonological representations are accessed for the purpose of external computations. The authors argued that deficits in phonological access could provide a unifying explanation for poor performances observed in the tasks that are particularly problematic in dyslexic population such as verbal short-term memory, phonological awareness, and rapid naming tasks. This hypothesis seems to be supported by several empirical studies (Boets et al., 2013; Mengisidou & Marshall, 2019; Ramus et al., 2013; Szenkovits et al., 2016).

So far, most studies that investigated this issue have been focusing on rather difficult speech processing situations. Only a few studies on dyslexia extended their investigations to speech recognition situations that emphasize neither fine-grained, explicit analysis nor discrimination of phonological/phonetic representations nor verbal memory load. This reduced interest in the impact of phonological deficits in more elementary speech recognition tasks may be explained by the assumption that, while dyslexic individuals show written word recognition deficits, their ability to recognize and understand spoken language remains intact, at least in non-demanding situations. Indeed, a few studies that examined spoken language comprehension in this population used rather challenging speech processing tasks. For instance, in a synonym judgment task (e.g., what is a synonym of '*capital punishment*'), Elbro and colleagues (1994), reported that dyslexic adults showed more difficulties than skilled readers in distinguishing phonologically similar spoken words (e.g., '*excursion*', '*excavation*', or '*execution*'). According to the authors, this result reflected a difficulty in processing ambiguous phonological input rather than limitations on vocabulary or differences in education or everyday reading practices between individuals with and without dyslexia. Ransby & Swanson (2003) used a listening comprehension task in which passages of increasing difficulty were presented orally to participants. The authors reported weaker listening comprehension performance in dyslexic adults compared to age-matched controls. However, the task strongly engaged complex cognitive resources such as working memory, general knowledge and vocabulary knowledge that were impaired in their sample of dyslexic participants. Therefore, their weak performance could not be directly attributed to the deficits in spoken language recognition per se. Other studies also reported speech processing difficulties in this population when speech was presented against background noise (Dole et al., 2012, 2014; Hazan et al., 2009, 2013) or with acoustic distortions (Gabay & Holt, 2021),

but not in a silent context (Blomert & Mitterer, 2004; Dole et al., 2014; Hazan et al., 2009, 2013).

Despite the absence of clear evidence that dyslexic adults show deficits in undemanding speech recognition situations, it is worth noting that previous studies relied mainly on behavioral measures such as reaction times or accuracy scores. Yet, one cannot exclude the possibility that these measures might not be sensitive enough to reveal more subtle deficits that may affect intermediate stages of speech recognition. Thus, to confirm that the ability of dyslexic individuals to recognize spoken language in optimal listening situations remains intact, further investigation using more fine-grained measures that can help to reveal the deficits at different stages of speech processing is needed.

Techniques with high temporal resolution such as electroencephalography (EEG) or magnetoencephalography (MEG) provide valuable tools for more detailed investigations of prelexical and lexical processing stages of spoken word recognition. According to classic models of spoken word recognition like, for instance, the COHORT activation model (Marslen-Wilson, 1987; Marslen-Wilson & Welsh, 1978), when speech is perceived, the initial phonemes of the stimulus rapidly and partially activate word candidates that match the incoming speech signal, forming the ‘word-initial cohort’ (Gaskell & Marslen-Wilson, 1997; Kocagoncu et al., 2016; Marslen-Wilson & Welsh, 1978; Zhuang et al., 2014). For example, the first phonemes (i.e., /rɒ/) of the word *robin* partially activate the words starting with /rɒ/ (e.g., *robin*, *rock*, *rod*) as well as their semantic features. This parallel activation of lexical candidates leads to lexical and semantic competition between them. Once the phonological uniqueness point is reached, i.e. the point at which only one lexical candidate remains consistent with the acoustic signal, a single target item that matches the phonological form being processed benefits more activation than other candidates, thus allowing the recognition of the word (Kocagoncu et al., 2016; Marslen-Wilson, 1987; Zhuang et al., 2014). Therefore,

during an auditory lexical decision task, words cannot be distinguished from pseudowords at the prelexical stage, before the phonological uniqueness/deviation point is reached. The distinction could be made later on, at the lexical stage, when all necessary phonological information becomes available.

In terms of ERP responses, the prelexical stage of spoken word recognition can be investigated through the N1 and P2 components which have been shown to reflect an initial analysis of acoustic/phonetic information (Elmer et al., 2017; Wagner et al., 2016). Interestingly, previous studies conducted on young children reported modifications of the N1 and P2 components' amplitude in dyslexic individuals compared to skilled readers in a wide range of tasks (auditory lexical decision task: Bonte & Blomert, 2004b; rhyming task: Breznitz, 2002; passive oddball tasks: Bonte et al., 2007). These observations have been argued to reflect group differences in the efficiency of phonetic processing. For instance, Bonte & Blomert (2004b) reported that dyslexic children exhibited a weaker N1 component but a stronger N2 component compared to skilled readers. Breznitz (2002) reported the P2 and P3 component to be of greater amplitude in dyslexic children compared to skilled readers. Finally, using a passive oddball task, Bonte et al. (2007) investigated implicit phonological processing of natural speech in dyslexic children through the *mismatch negativity* component (MMN) that has been widely used to examine the ability to automatically detect or discriminate changes in acoustic signals. The authors found that dyslexic children did not exhibit the typical MMN response to contrasts between high- versus low-phonotactic probability of phoneme sequences. They interpreted the lack of MMN response as indicating the existence of a subtle deficit in phonetic processing of natural speech in dyslexic children. Note that a reduced MMN amplitude was also reported in dyslexic adults, which suggested a persistence of the deficits, at least in those experimental paradigms that focused on the

perception or discrimination of phonetic or phonemic features. (Virtala et al., 2020; Wang & Bi, 2021, for a review see Gu & Bi, 2020).

The lexical processing stage is typically examined through the N400 component. Most studies in skilled readers have shown that pseudowords elicit a greater N400 component amplitude than words (O'Rourke & Holcomb, 2002; Tiedt et al., 2017). Some studies proposed more detailed analyses of this component by separating it into two phases (Friedrich et al., 2006; Helenius et al., 2009; Kocagoncu et al., 2016; O'Rourke & Holcomb, 2002). An initial phase, namely, *early 400*, is thought to reflect the access to lexical representations based on parallel activation of the phonological and semantic representations of the activated candidates. A later phase, namely, *late 400*, would be more likely to reflect a post-lexical stage, presumably involved in lexical selection and/or suppression of inappropriate lexical candidates during word processing, or a re-analysis of the phonological input during pseudoword processing.

Following this line of research, Helenius and colleagues (2009) used MEG to record the brain activity in adults with specific language impairment (SLI), dyslexia, and normal reading skills during an auditory task in which participants had to identify common proper names presented in sequences of words and pseudowords, which were critical nogo stimuli. The analyses of brain activity focused on these stimuli. The prelexical processing stage was examined through the N100m component and the lexical processing stage was examined through the early and late phases of the N400m component. The authors reported that the N100m component was not statistically different across groups, although its amplitude seemed higher in participants with language deficits. The later phase of the N400m component (from 400ms onward) was sensitive to stimulus lexicality, with long-lasting and more left-lateralized activation being observed for pseudowords compared to words in the three populations. This observation replicated existing findings in skilled readers (Friedrich et

al., 2006; O'Rourke & Holcomb, 2002). Although no behavioral task performance was reported, MEG signals showed that the magnitude of the lexicality effect tended to decrease linearly from skilled readers to participants with dyslexia and SLI. The authors interpreted the reduced lexicality effect in the two latter populations as a result of either their difficulty in deactivating inappropriate lexical candidates or their abnormally limited vocabulary which might lead to a prolonged N400m for words that are unknown to them. Although the second interpretation is consistent with the fact that the three groups of participants in Helenius et al.'s study differed on vocabulary knowledge, the first interpretation, namely that known words might not be processed in the same way in the different populations, seems somewhat inconsistent with the finding that responses elicited by spoken words did not reveal differences between the skilled-reader, dyslexic, or SLI adults (Helenius et al., 2009). Regardless of the underlying factors that led to the reported outcome, Helenius and colleagues (2009) provided a rare piece of neurophysiological evidence suggesting that the impact of phonological deficits in dyslexic adults might not be restricted to challenging speech processing situations as typically assumed, but it might also pervade more elementary spoken word recognition situations (Dole et al., 2014; Ziegler et al., 2009).

The present study

The current study further examined this underexplored research question of whether the phonological deficits that persist in dyslexic adults also impact elementary speech recognition processes that do not involve metaphonological abilities, verbal memory, or complex analyses of phonological information. Specifically, we focused on dyslexic adults who are high-achieving university students. This specific population is of interest for several reasons. First, unlike in young children, the speech processing system of adults has reached maturity and their phonological deficits have become stable (Ramus et al., 2003). Second, despite poor phonological and reading skills, this population has developed a relatively high

level of vocabulary, comparable to that of skilled readers (Cavalli et al., 2016). They are constantly exposed to written material and it is likely that most of them have developed adaptive reading strategies relying on oral comprehension or vocabulary skills that have allowed them to achieve a good level of reading comprehension (Callens et al., 2014; Cavalli et al., 2016). This hypothesis is supported by studies reporting an intact phonological grammar in dyslexic readers despite their deficits in acoustic/phonetic encoding (Berent et al., 2013, 2016). As described in the Method section, compared to skilled readers, the dyslexic participants of the present study showed deficits in tasks involving phonological processing. However, the two populations were perfectly matched on gender, chronological age, non-verbal IQ, educational level, field of study, and most importantly, vocabulary knowledge. This strict control allowed us to narrow down the potential explicative factors of the differences in speech processing ability that might be observed between the two populations.

During the experiment, we recorded EEG and behavioral measures while participants with and without dyslexia performed an auditory lexical decision task, a task which allowed us to examine how these two populations processed spoken inputs with and without lexical entries. Although a number of studies on dyslexia have already addressed this issue in the visual modality (Mahé et al., 2018; Shaul et al., 2012), evidence obtained in the auditory modality remains scarce. Our analyses focused both on the *lexicality effect*, by contrasting the performance and neural activity elicited by words and pseudowords in each population, and on the *group effect*, i.e., how individuals with and without dyslexia process words and pseudowords. In terms of the temporal dynamics, the analyses were conducted at both prelexical and lexical stages of speech recognition. The prelexical stage was examined through the N1-P2 complex, which reflects an initial analysis of acoustic/phonetic information (Elmer et al., 2017; Wagner et al., 2016). Then, we targeted the two stages of lexical processing by examining the early and the late phases of the N400 component. While

the effect of lexicality was not expected in the prelexical N1 and P2 components, the presence of the group effect at this early stage remains uncertain in adult populations especially in the context of a lexico-semantic task (Helenius et al., 2009; Rasamimanana et al., 2020). Based on the well-established literature on lexical processing, the effect of lexicality is expected on the N400 component. The aim of the present study is to provide novel information on the precise locus of the effect, i.e., at the early or late stage of lexical processing, which might depend on the group of participants. Finally, the analysis of the group effect on each type of stimuli should allow us to further test the proposal that known words might not be processed in the same way in skilled and dyslexic readers (Helenius et al., 2009).

Materials and methods

Participants

A total of sixty native French speakers [name deleted to maintain the integrity of the review process] took part in the study and were paid for their participation. None of the participants reported any neurological or psychiatric disorders. All were university students, had normal or corrected-to-normal vision and were right-handed. Half of the participants (15 females and 15 males) had a diagnosis of dyslexia during childhood or adolescence. Each dyslexic participant was matched with a skilled reader in gender, chronological age, education level, study field, and non-verbal IQ (all within the normal range, i.e., above the 75th percentile; minimum score in both groups = 42/60; Raven's Matrices: Raven et al., 1998). The experiment was conducted in accordance with the Declaration of Helsinki and was approved by the local ethics committee [name deleted to maintain the integrity of the review process]. A written consent was obtained from each participant before the experiment began.

As illustrated in Table 1, pretests administered to all the participants confirmed that dyslexic individuals had lower performances than skilled readers in pseudoword reading,

phonemic awareness, and verbal short-term memory tasks (from EVALEC, Sprenger-Charolles et al., 2005). As expected, they also showed lower reading skills, as assessed by a French standardize reading test for adults: *Test de l'Alouette* (Cavalli et al., 2018; Lefavrais, 1965). Nevertheless, the two groups were matched on their vocabulary knowledge (EVIP: Dunn et al., 1993, a French adaptation of the *Peabody Picture Vocabulary test-revised*, Dunn & Dunn, 1981). Based on the results obtained in three pretests (*L'Alouette*, irregular word and pseudoword naming tasks), the data of one dyslexic participant (and her matched skilled reader) were excluded from the study due to unusually low performances (> 2.5 standard deviation) compared to the other participants in the same group.

(Table 1)

Stimuli

Fifty-six monosyllabic French nouns were selected from the *lexique.org* database (New et al., 2001). To match words and pseudowords as much as possible, most of pseudowords (41 from 56) were created by recombining onsets and rimes extracted from word stimuli. For the remaining stimuli (i.e., when the combinations did not lead to pseudowords), different onset consonants were combined with the words' rimes. As illustrated in Table 2, words and pseudowords were matched for logarithmic values of token bigram frequency, number of letters, number of phonemes, number of phonological neighbors, phonological uniqueness/deviation point (New et al., 2001), and mean duration (all $ps > .10$).

(Table 2)

Stimuli were produced by a female French native speaker and were recorded in a soundproof room at a sampling rate of 48 kHz with 16-bit analog-to-digital conversion using

an AKG 1000S microphone. The intensity of the acoustic signal was standardized to, on average, 70 dB using *Praat* (Boersma & Weenink, 2015).

Procedure

Participants were comfortably seated in front of a computer screen in a soundproof Faraday cage. Stimuli were presented binaurally at a comfortable listening level (adjusted for each subject) through earphones. Participants were instructed to indicate as quickly and accurately as possible whether the target was a French word or pseudoword by pressing the corresponding button on the response box. Handedness associated with word and pseudoword responses was counterbalanced across participants. A trial consisted of the following sequence of events: a fixation cross (+) was presented at the center of the screen while the spoken stimulus was played, and it remained on-screen until the participant's response. Participants were asked to limit eye-blinks and movements while the fixation cross was present. The duration of the inter-trial interval (blank screen) varied randomly between 950 and 1050 msec. Response latency was measured from the onset of the auditory stimulus until the response.

Stimulus presentation was divided into 2 blocks. Each block contained 28 words and 28 pseudowords presented in the same pseudo-random order for each pair of participants, such that words or pseudowords never occurred in more than three consecutive trials. Two additional dummy trials were added at the beginning of each block, but they were not included in the analyses. The experiment began with a practice session containing eight words and eight pseudowords.

EEG recording procedure and preprocessing

Continuous EEG was recorded from 64 Ag/AgCl active electrodes held in place on the scalp by an elastic cap (Electro-Cap International, Eaton, OH). The electrode montage

included 10 midlines sites and 27 sites over each hemisphere (American Clinical Neurophysiology Society, 2006). Six other electrodes were attached over the right and left mastoids, above and below the left eye (for monitoring vertical eye-movements and blinks), and lateral to the left and right external canthi (for monitoring horizontal eye-movements). During recording the left mastoid served as reference. The 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 2048 Hz throughout the experiment. EEG was down-sampled to 512Hz and band pass filtered off-line (0.4 to 40Hz) using EEGLAB software (Delorme & Makeig, 2004). The signals were re-referenced to the average of both mastoids. Independent Components Analysis (ICA) was applied to isolate and correct ocular movements using the infomax algorithm (Bell & Sejnowski, 1995) implemented in the EEGLAB software. To avoid inadvertently removing task-related activity, a conservative approach was taken when removing ICA components and only those components presenting ocular movements were removed. After IC rejection, noisy electrodes were rejected and interpolated using spherical spline interpolation. The continuous data of each subject was segmented, and noisy trials were rejected. These artefact and noise rejections were conducted manually. The number of rejected trials per condition was uniform across subjects (averaged percentage of rejected items per subject: word condition: 9.5%, pseudoword condition: 10%).

EEG analyses

For each subject, averaged ERPs were computed off-line on correct trials free of ocular and muscular artifacts. T0 was time-locked to stimulus onset and a 200 msec pre-stimulus period was used as baseline. Time-windows of interest were selected based on the global field power (GFP, corresponding to spatial root mean squared of amplitude values at all electrodes; Lehmann & Skrandies, 1980) calculated on the grand average across all subjects and all experimental conditions. As illustrated in Figure 1, the selected time-windows

corresponded to 55-245, 245-465, and 465-700 msec after stimuli onset, which corresponded to the time-windows of the N1-P2 complex, early N400, and late N400 components, respectively. The N400 component was separated into two phases in order to distinguish between the early and later stages of lexical processing (Helenius et al., 2009; Kocagoncu et al., 2016).

(Figure 1)

Separate ERPs were extracted for participants with and without dyslexia and for each type of stimulus. Those groups of electrodes displaying significant effects of interest were determined via a cluster-based permutation test. This test is based on the clustering of adjacent spatio-temporal samples and simplifies the resolution of the Multiple Comparison Problem (Maris & Oostenveld, 2007). The permutation distribution was calculated by carrying out 2000 random partitions including all channels and subjects in each time-window separately. Then, we selected those samples with a permutation p -value below the critical cluster alpha-level ($p \leq 0.05$). From these samples, only the clusters comprising a minimum of three electrodes were formed based on their spatio-temporal adjacency. Neighboring electrodes were defined using the triangulation algorithm implemented in the Matlab toolbox, FieldTrip (Oostenveld et al., 2011). Finally, spatio-temporal clusters with a Monte-Carlo p -value < 0.025 (two-tailed test) were retained.

Results

Behavioral data

The average reaction times for correct responses and the accuracy scores for both groups are shown in Figure 2. Reaction times longer or shorter than the mean ± 2.5 SD for each subject and for each condition were eliminated from the analysis (4.1% of the data). ANOVAs performed on reaction times revealed main effects of group [$F(1,56) = 9.2$, p

<.005; $F_2(1,106) = 331.7, p <.001$] and stimulus type [$F_1(1,56) = 135.8, p <.001$; $F_2(1,106) = 58.6, p <.001$]. The interaction between the two factors was not significant ($F_s \leq 1$). Overall, we observed a lexicality effect in both groups, with words leading to shorter reaction times than pseudowords. Skilled readers responded faster than dyslexic individuals for both words and pseudowords. Analyses performed on the accuracy scores did not reveal any significant main effect or interaction (all $F_s < 1$).

(Figure 2)

The behavioral data showed the same pattern of lexicality effect in both populations. The only difference between them is the fact that, in order to reach the same accuracy score as skilled readers, dyslexic participants required more time. This performance pattern replicated what has been reported by a vast majority of studies (Breznitz & Misra, 2003; Janse et al., 2010; Metsala, 1997). Interestingly, as described below, when a more fine-grained electrophysiological measure was considered, more subtle inter-group differences in the manner in which they recognize spoken language were revealed.

EEG data

Scalp-maps and the corresponding ERP waveforms time-locked to the stimulus onset are presented in Figures 3 and 4, respectively.

(Figure 3)

(Figure 4)

N1-P2 complex (55-245 msec)

In the early part of this time-window, we observed, in both populations and for both stimulus types, a negative waveform over central electrodes corresponding to the N1

component. This early component was immediately followed by a positive waveform over fronto-central electrodes, corresponding to the P2 component (Figures 3 and 4). As shown in Figure 3b, neither the amplitude of the N1 component nor the one of the P2 component were significantly modulated by stimulus type or by group.

Early N400 component (245-465 msec)

As shown in Figure 3a, we observed the emergence of negative activity over central electrodes from 245-410 msec. From 410msec, the activity spread over the frontal electrodes in both hemispheres, for both groups of participants and for both types of stimuli. This wide-spread negativity corresponds to the early phase of the N400 component. In skilled readers, this component was not modulated by stimulus type. Interestingly, in dyslexic individuals, words elicited a larger negative waveform than pseudowords (Figure 4b). As can be seen in Figure 3b, this larger negative amplitude reached statistical significance over the left central and centro-parietal electrodes (C3, CP5, CP3, and CP1)¹. The comparison of individuals with and without dyslexia did not reveal any difference in this early part of the lexical process neither for words nor for pseudowords (bottom part of Figures 3b).

Late N400 component (465-700 msec)

In the late part of the lexical process, we observed a wide-spread negativity over frontal and central electrodes that persisted during the entire epoch. This negativity was associated with positive potentials over the parietal and occipito-parietal electrodes, which were particularly prominent at the end of the epoch. Although a similar pattern of brain activity was observed in both groups and for both stimulus types, it is noteworthy that the

¹ Note that the electrode cluster in the 245-300ms time interval is highlighted as showing a significant difference despite clearly presenting an average p value > 0.1. The reason for this is because the significant difference for these electrodes emerged in the last few msec of this time interval, as illustrated in Figure 4b.

amplitude of the negative waveform over the frontal and centro-frontal electrodes rapidly dropped in skilled readers when they processed words and, this reduced negativity is associated with a reverse polarity in the posterior electrodes (Figure 3a). As confirmed by the cluster-based permutation tests (Figure 3b), this pattern of neural activity resulted in two significant effects. First, there is a strong and wide-spread effect of lexicality in skilled readers but not in dyslexic individuals. In the latter population, the N400 component elicited by words (as well as by pseudowords) sustained in time and only weak posterior positivity was found (Figures 3a and 4b). Second, there is a significant difference between the two populations at the late stage of word processing at left central, centro-parietal, and parietal electrodes (CP5, CP3, P7, P5, P3, PO7) with a stronger positivity being observed in skilled readers (Figures 3b and 4c).

Discussion

The present study is interested in how high-potential dyslexic individuals process spoken language. Precisely, we examined whether the phonological deficits, typically observed in the tasks that have meta-phonological components or strongly rely on verbal memory, persist in a basic speech recognition situation, for instance, when one merely has to decide whether spoken inputs are part of the lexicon. To this end, we tested dyslexic adults who, despite their phonological (and reading) deficits, managed to attend university. A careful matching between these participants and skilled-reader controls allowed us to narrow down the factors that could explain the possible differences in their speech recognition ability and the underlying neural processes. We reported that individuals with and without dyslexia only differed in their reading scores (assessed through the Alouette test) and phonological abilities (assessed through pseudoword reading, phonemic awareness and verbal short-term memory tasks). Both groups were carefully matched on their chronological age, years of higher education, non-verbal IQ, and most importantly on vocabulary knowledge, which is a

potential confound that may cause a difference in word recognition ability and the underlying cognitive processes in the two populations regardless of the core phonological deficits.

During the experiment, participants performed an auditory lexical decision task. Both behavioral and EEG data enabling the investigation of the cognitive processes underlying the prelexical and lexical stages of spoken language recognition were recorded. Overall, both populations reached the same level of performance in terms of response accuracy. They also showed a comparable significant lexicality effect, with faster decisions for words than for pseudowords. However, dyslexic individuals were slower than skilled readers on both word and pseudoword recognition. At first glance, the fact that this general delay in dyslexic individuals has been frequently reported in the literature suggests that it might reflect a general cognitive profile rather than being specific to speech recognition (Breznitz & Misra, 2003; Janse et al., 2010; Metsala, 1997). However, as argued further below, it is premature to exclude the possibility that the slowing-down might to some extent reflect specific deficits related to spoken language recognition. This assumption is supported by evidence from studies using gating tasks showing that dyslexic individuals needed more phonological information than skilled readers to correctly identify spoken words (Metsala, 1997). Thus, the slower reaction times observed here might, at least partly, result from a need for additional information before making lexical decisions.

The EEG analyses provided more insightful information by revealing a different cognitive pattern in the two groups of participants. The prelexical processing stage was investigated by looking at the N1-P2 complex, which reflects an initial analysis of the acoustic/phonetic information (Elmer et al., 2017; Wagner et al., 2016). The lexical stage of speech recognition was investigated by considering the early and late phases of the N400 component. The early N400 is suggested to reflect the parallel activation of lexicophonological and semantic representations of the word candidates that are compatible with the

incoming speech signal (i.e., the activation of the lexical cohort; Gaskell & Marslen-Wilson, 1997; Marslen-Wilson, 1987). The late N400 is posited as reflecting the processes involved in lexical selection and/or suppression of word competitors when processing words, or an additional lexico-semantic memory search when the speech input does not match the existing lexical entries (Friedrich et al., 2006),

The cluster-based permutation analyses conducted on the N1-P2 complex showed no significant difference either between groups or between the two types of stimuli. The absence of a lexicality effect is not surprising given that the distinction between words and pseudowords could not be detected in this early time-window. Regarding the absence of the groups effect, our finding replicated those reported by Helenius and colleagues (2009) who also used a simple speech recognition task to study adult populations with and without language deficits. Indeed, in the present study, as in Helenius et al.'s (2009), while the N1 amplitude seemed somewhat reduced in dyslexic compared to skilled readers, statistical difference did not reach significance. Two related reasons can be put forward to explain this lack of a significant difference between participants with and without dyslexia in this early stage of sublexical processing. First, the present task focused on lexical processing rather than on the perception or explicit analysis of sublexical phonological units. Whereas in children, N1/P2 complex differences between individuals with and without dyslexia have been reported in a wide range of auditory tasks (auditory lexical decision task: Bonte & Blomert, 2004b; rhyming task: Breznitz, 2002; passive oddball tasks: Bonte et al., 2007), in adults, such differences have only been reported in tasks focusing on the perception or discrimination of phonetic or phonemic features (Virtala et al., 2020; Wang & Bi, 2021; for a review, see Gu & Bi, 2020). The second reason is related to the characteristics of the speech processing system in adults. Compared to children, adults have more experience with spoken language processing, more developed vocabulary knowledge, and their language system has already

reached maturity. Indeed, in a primed lexical decision task comparing spoken word processing in children and adults, Bonte & Blomert (2004a) reported developmental changes that reflected a modulation of the morphology and latency of the early ERP components (i.e., N1, P1, P2). According to the authors, the observation that certain developmental changes affected the early stages of speech processing further indicates that children and adults might not process word onset in the same way. The difference could be attributed to the growth of vocabulary, and probably reading acquisition, that induced substantial lexical restructuring at the level of phonological processing and representation. Such restructuring possibly changes the contribution of word onset information to lexical processing. With regards to the present finding, the more optimal lexical processing in dyslexic adults compared to children might somehow mitigate the impact of phonological deficits on the early stage of speech recognition.

The analyses of the ERP signals recorded during the lexical stage showed different neural patterns in the early and late phases of lexical processing. In skilled readers, our results replicate those typically reported in the literature (Friedrich et al., 2006; Hunter, 2016). The analysis conducted on the early phase of lexical processing (early N400) showed no difference between the two stimulus types. In contrast, the analysis conducted on the late phase of lexical processing (i.e., late N400) showed a clear difference between the ERP amplitudes elicited by words and pseudowords and this difference was distributed over most electrode sites (Figure 3b). This lexicality effect reflects the typical larger negativity elicited by pseudowords than by words (Figure 4a). The sustained negative ERP observed for pseudowords suggests that, once a word stimulus is recognized (i.e., when there is a match between the incoming signal and a lexical entry), the associated neural activity drops, while the activity associated with an unknown stimulus is still maintained (MacGregor et al., 2012). Our observation is in line with the findings reported by Friedrich and colleagues (2006) who

suggested that the early phase of the N400 is closely related to the initial lexical activation and that an additional analysis or search process is necessary when the signal does not correspond to existing lexical entries, as is the case for pseudowords (see Kocagoncu et al., 2016; Mahé et al., 2018 for a similar interpretation).

Although both individuals with and without dyslexia showed a similar behavioral pattern, more fine-grained analyses of their neural activity clearly showed that the observed performances were not supported by the same neural mechanisms. In dyslexic individuals, a significant lexicality effect was already observed on the early N400 with a greater negative amplitude for word compared to pseudoword processing. This stronger word-induced activity is restricted to the central and centro-parietal electrodes in the left hemisphere. Interestingly, unlike the ERP pattern observed in skilled readers, the initial increase in neural activity in response to words was not followed by a rapid drop of activity in the latter time-window but by a sustained negative ERP. This sustained word-induced negativity observed in dyslexic participants explained why, in this late time-window, 1) we did not observe any difference between words and pseudowords processing in this population, and 2) there was a significant group effect on word recognition observed in the central and centro-parietal electrodes in the left-hemisphere.

How could an early enhancement, followed by a sustained N400 that characterized the way dyslexic adults recognized spoken words be explained?

In the present situation, participants had to decide whether each auditory input corresponded or not to a known word. Logically, word decisions could be made based on the available phonological input alone. Yet, several studies have shown that other kinds of representations associated with speech, such as the orthographic or semantic representations, can also be activated in a top-down manner and, thereby, contribute to the decision made by

participants (Friedrich et al., 2006; Kretzschmar et al., 2015; Tune et al., 2014). Based on the assumptions of the division-of-labor hypothesis elaborated within the connectionist framework (Cox et al., 2015; Harm & Seidenberg, 2004), the relative contribution of these representations should depend on several factors including participants' ability to process phonological information. Dyslexic individuals are known to exhibit persistent phonological deficits as well as a difficulty in accessing orthographic representations and in establishing automatic connections between phonological and orthographic representations (Boets et al., 2013; Jones et al., 2016; Paz-Alonso et al., 2018; Ramus & Szenkovits, 2008). However, their semantic knowledge remains intact (Rasamimanana et al., 2020).

In line with the division-of-labor hypothesis, a parsimonious explanation could be put forward if we interpret the present increase of activity within the N400 time-window as a stronger resort to the semantic representations stored in long-term memory to distinguish words from pseudowords. Firstly, this explanation is coherent with the observation that the increase of neural activity in dyslexic compared to skilled readers was induced by words but not by pseudowords. Secondly, it is also supported by existing literature; a number of studies have shown that semantic richness (i.e., more semantic features) is associated with an enhancement of the N400 component (Cheyette & Plaut, 2017; Kounios et al., 2009). More importantly, the idea of a stronger reliance on, or an over-activation of, semantic representations is coherent with a series of studies that reported a greater sensitivity to semantic information in dyslexic individuals compared to skilled readers (Cavalli, Colé, et al., 2017; Cavalli, Duncan, et al., 2017; Corkett & Parrila, 2008; Law et al., 2015; Rasamimanana et al., 2020). For instance, when examining the influence of sentence context on word recognition among university students with and without dyslexia, Corkett and Parilla (2008) observed a stronger impact of semantic context in dyslexic participants. In relation to neural responses, using MEG, Cavalli, Duncan, and colleagues (2017) reported that dyslexic adults

showed a spatiotemporal reorganization of written word recognition and that this was reflected by an earlier contribution of the semantic property of morphological information in individuals with dyslexia compared to skilled readers. The authors argued that this mechanism probably allowed dyslexic individuals to cope with their deficits. The present findings further suggest that such functional reorganization might have consequences, not only on visual word processing, but also on speech processing. A similar conclusion was also proposed by Rasamimanana et al. (2020) who reported that, while phonological deficits hindered dyslexic participants' performance in the phonological tasks, they did not impede their learning of the meaning of novel spoken words. However, given the increase of N400 activity and the generally longer processing times in dyslexic individuals reported here, it remains difficult to draw a firm conclusion on whether the observed neural pattern truly reflects a compensatory mechanism allowing dyslexic individuals to alleviate the impact of phonological deficits, or a subtle yet long-lasting difficulty in recognizing spoken words. So far, most studies examining dyslexia in adults have attempted to precisely identify their underlying deficits. Only very few studies have focused on the compensatory mechanisms that this population might have developed and the very concept of compensation remains under debate (Colé et al., 2020; Livingston & Happé, 2017). Our study provides data and interpretations that can inform this debate and that should also stimulate further research.

Conclusion

To recognize spoken words, individuals with and without dyslexia seem to rely on different cognitive dynamics. The difference between the two groups was not located at the acoustic/phonetic processing stage but at the lexical processing stage. We argued that, despite their phonological deficits, the dyslexic participants in the present study, who were undergraduate students with a good level of vocabulary, would resort to available and intact semantic knowledge to decide whether an auditory input corresponded to a lexical entry. This

claim is in line with an increasing number of studies that argue for the role of semantic knowledge as a valuable source of information that helps dyslexic individuals to overcome their difficulties in word recognition in both modalities (written modality: Cavalli, Duncan, et al., 2017; Elbro et al., 1994; Law et al., 2015; auditory modality: Rasamimanana et al., 2020). Although future studies that directly manipulate the semantic features of spoken words are needed to further support our claim, the present finding clearly showed that speech recognition does not remain intact in dyslexic individuals. Nevertheless, the consequences in this domain are far more subtle than in visual word recognition and the resulting brain responses warrant further research into the reorganization of the language network in this population.

Declaration of interest statement

The authors declared no potential conflicts of interests with respect to the authorship and/or publication of this article.

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Figure 1: Global field power waveform calculated from the grand average across all subjects and all experimental conditions, from stimulus onset until 800 msec. The dashed lines show the time-windows selected for the analyses.

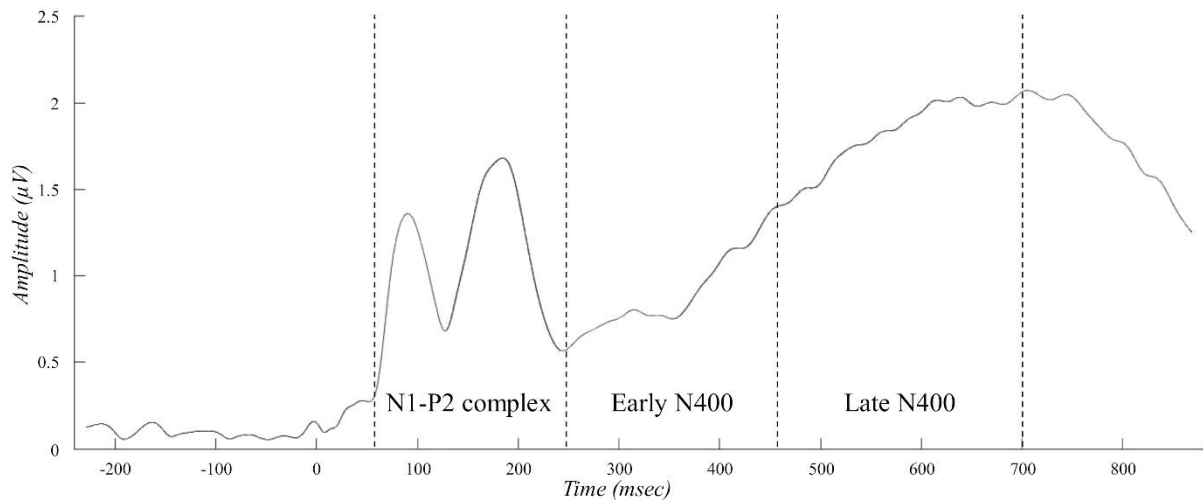


Figure 2: Mean reaction times (left panel) and accuracy scores (right panel) for each group of participants and each stimulus type. Error bars represent standard deviation.

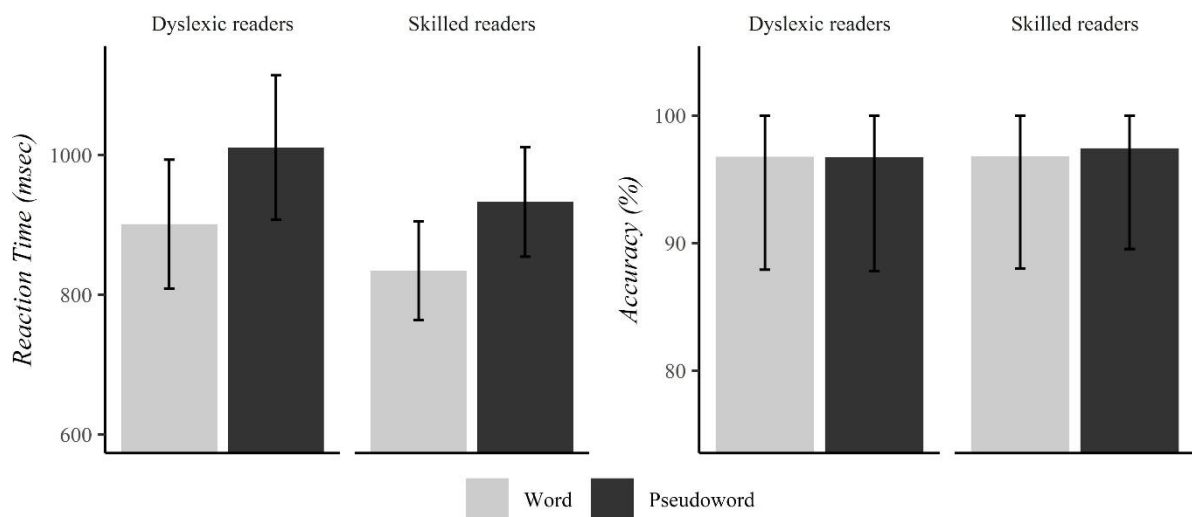


Figure 3: Scalp-maps of the ERPs from 55 to 700 msec covering the three time-windows identified in the global field power analysis. (a) The signal amplitude (in μV) for words and pseudowords in skilled and dyslexic readers. (b) The *p* values obtained in the cluster-based permutation tests showing the lexicality effect in each population and the group effect for

each stimulus type. The white dots indicate the electrodes showing a significant effect of lexicality or group. The p values are expressed as logs ($-\log_{10}(pvalue)$) to facilitate plotting; the color-bar indicates the corresponding p values.

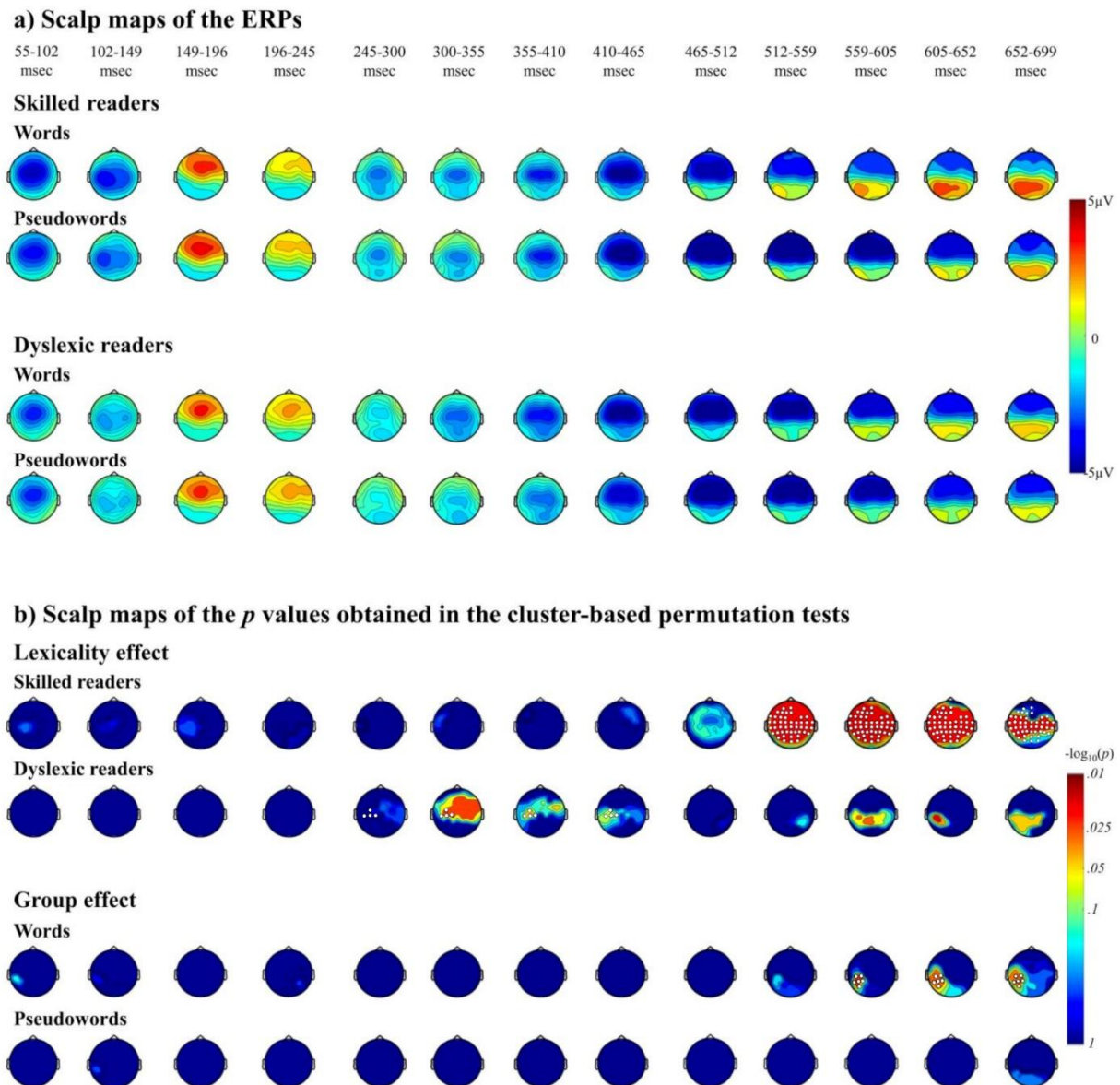


Figure 4: ERPs illustrating the lexicality and the group effects. (a) Comparison between words and pseudowords (lexicality effect) obtained in skilled readers. (b) Comparison between words and pseudowords (lexicality effect) obtained in dyslexic individuals. (c) Comparison between individuals with and without dyslexia (group effect) obtained on words. (d) Comparison between individuals with and without dyslexia (group effect) obtained on

pseudowords. For each comparison, the ERP waveforms were averaged over the electrodes showing significant effects in Figure 3 (except for the last comparison where the group effect is not significant, the waveforms were extracted from the electrodes showing a significant group effect on words). The gray areas highlight the time-windows of interest where the cluster-based permutation tests showed significant lexicality and group effects ($p \leq .025$).

