Exploring dyslexics' phonological deficit II :

Phonological grammar

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Abstract

Language learners have to acquire the phonological grammar of their native language, as well as different levels of representations on which this grammar operates. Developmental dyslexia is associated with a phonological deficit, which is most commonly assumed to stem from degraded phonological representations. In the present study, we investigate some aspects of phonological grammar, namely phonotactics and phonological assimilation rules, in dyslexia. Specifically, we tested whether adult dyslexics have normally acquired phonological rules in speech production, and if they compensate for them in perception. Contrary to the ‘degraded phonological representations hypothesis, they produced phonological assimilations, and perceptually compensated for assimilations to the same extent as controls. This suggests that dyslexics have normally acquired the phonological rules of their native language and implies that they must have fairly well specified phonological representations, at least with respect to the contrasts we tested. Nevertheless, these adult dyslexics still exhibit the typical phonological deficit as measured by phonological awareness, verbal short term memory and rapid automatic naming tasks. Thus, the explanation for their phonological deficit may lie elsewhere than in phonological representations and grammar, for instance in verbal short term memory processes.

Keywords: developmental dyslexia, phonological deficit, phonological grammar, speech processing

1 Introduction

Developmental dyslexia is a neurodevelopmental disorder whose defining symptom is a specific disability in learning to read (Lyon, Shaywitz, & Shaywitz, 2003). In spite of long-standing debates on theories of dyslexia, there is a wide agreement that, at least in a majority of dyslexics, the main underlying cognitive cause is a so-called phonological deficit (Ramus, 2003; Snowling, 2000; Vellutino, Fletcher, Snowling, & Scanlon, 2004), although admittedly a minority of cases may more adequately be explained by a visual-attentional deficit (Valdois, Bosse, & Tainturier, 2004). This agreement holds because, apart from purely visual theories, alternative theories of dyslexia actually propose alternative views of distal mechanisms (e.g., auditory, motor, magnocellular, cerebellar), but all assume that a phonological deficit is the most proximal cause of reading disability (Nicolson, Fawcett, & Dean, 2001; Stein, 2001; Tallal, 2004). Therefore, leaving aside the issue of distal causes, and focusing on the majority of dyslexics who do have a demonstrated phonological deficit, the present study aims to further investigate the nature of dyslexics' phonological deficit, a matter of interest regardless of theoretical affiliations.

The default, most accepted view of the phonological deficit may be termed the "degraded phonological representations hypothesis". According to this view, dyslexics' phonological representations are somehow degraded. The nature of the presumed degradation is more or less specified and varies from author to author, but includes increased noise, feature underspecification, decreased temporal or spectral resolution, and/or less categorical representations (Adlard & Hazan, 1998; Elbro, 1998; Harm & Seidenberg, 1999; Manis et al., 1997; Mody, Studdert-Kennedy, & Brady, 1997; Snowling, 2000; Tallal, 1980). A major challenge in dyslexia research remains to determine whether this hypothesis is correct, and if it is, what exactly the nature of the degradation is.

Although different versions of the degraded phonological representations hypothesis may make different predictions, it seems to us that they all broadly predict that mental processes operating on small phonological units such as phonemes must be generally disordered. In fact it is widely thought that this prediction has been fully empirically confirmed, given the large amount of data showing dyslexics' difficulties with phoneme awareness, and sometimes with phoneme discrimination and categorization (although the latter point does not go unchallenged: Ramus et al., 2003; White et al., 2006). Nevertheless, these tasks do not exhaust the range of mental processes that apply to phonemes.

Phonology is *par excellence* the discipline that studies such processes, and formalizes them as a phonological grammar. The main phenomenon to be explained by phonology is the fact that words are pronounced differently in different utterances, depending on the other words that surround them. It has been shown that some of these variations (assimilations, liaisons, epentheses, elisions…) are systematic and depend on the precise phonological context in which they occur. This has led linguists to formulate abstract rules (or constraints) that explain the mapping between words' underlying form (stored in the mental lexicon) and their surface form (actually uttered) depending on the phonological context. These abstract rules or constraints form the phonological grammar[1] (Chomsky & Halle, 1968; Clements, 1999; Prince & Smolensky, 1993). Furthermore, phonological grammar varies from language to language, and therefore must be acquired by each child by mere exposure, typically within the first few years of life (Peperkamp, 2003; Ramus et al., in press).

Phonological grammar offers a new domain of investigation within which the degraded phonological representations hypothesis may be further tested. Indeed, the processes involved in phonological grammar typically involve phonemes or phonetic features. If these units are poorly represented by dyslexics, this should plausibly affect the reliability of their mapping processes between words' underlying and surface forms. Alternatively, disrupted phonological processes might reflect a deficit in the grammar itself (i.e., the rules), rather than in the representations. In this paper we will therefore consider a couple of representative phonological phenomena, and attempt to test and contrast two alternative hypotheses: the degraded phonological representations hypothesis, and what we will call the "deficient phonological grammar hypothesis".

[1] By using the term "phonological grammar" we simply mean that phonological processes *can* be described by grammatical formalisms, and often are (by linguists). But we imply no specific claim regarding the nature and the format of the cognitive processes that are at stake. In particular, the present investigations do not crucially depend on the assumption that the brain implements an abstract grammar made of symbolic rules (or constraints). We use grammatical formalism simply because it provides the most efficient description of the phenomena that we are studying.

2 General methods and diagnostic battery

2.1 *Participants*

Here we describe the general characteristics of our entire pool of participants. Different subsets of this pool took part in the three sets of experiments. Results of each subset are not different from those of the entire pool, and will be described in each corresponding section.

All participants were recruited through adverts in Parisian universities. They received 10 € per hour of participation. Twenty presumed dyslexic and nineteen control participants of similar academic background and non-verbal IQ took part in the study. The lack of systematic screening and/or diagnosis of dyslexia in France, made us initially rely on dyslexics' self-identification, however in order to ensure that they met pre-established inclusion criteria for dyslexia, they all went through a diagnostic battery.

Inclusion criteria were (1) to be a native, monolingual speaker of French, aged above 18 (2) to report no known neurological/psychiatric disorder or hearing impairment, (3) to have a non-verbal IQ above 90, (4a) for controls: to report no known history of reading/oral language difficulties, and to have a reading age above the ceiling (14 years old) of our standardized reading test, (4b) for dyslexics: self- or institutional identification as a dyslexic person, and a reading age below 14 years old. In addition, since we specifically targeted the phonological deficit to the exclusion of any other possible cause of dyslexia (e.g., purely visual), the diagnostic battery included a set of classic phonological tasks and we verified that all dyslexics had poor performance on those.

2.2 *Diagnostic battery*

Participants underwent three separate testing sessions. On the first session, they took the diagnostic battery, and then the experimental battery was split over the next two sessions. All tests and experiments were programmed, presented and scored on a laptop computer using E-Prime (Schneider, Eschman, & Zuccolotto, 2002) and DMDX (Forster & Forster, 2003) softwares.

2.2.1 Intelligence

Nonverbal intelligence was assessed by using Raven's Advanced Progressive Matrices Set I and Set II (Raven, Raven, & Court, 1998). Participants are required to complete 36 test items in time-limited condition (40 minutes). Set I was used to familiarize participants with the test, Set II to calculate non-verbal IQ scores derived from the percentiles of United States norms (1993).

2.2.2 Literacy

Reading skills were assessed by the standardized French reading test "L'alouette" (Lefavrais, 1967). The text comprises 265 words ranging from common to rarely used words. Participants are instructed to read the text as fast and as accurately as possible. Standardized reading scores are computed by combining total reading time and reading errors. We used combined scores because in languages with a more regular orthography than English, reading accuracy rapidly reaches ceiling. Hence, reading scales have to incorporate a speed measure in order to detect dyslexics (Sprenger-Charolles, Colé, Lacert, & Serniclaes, 2000; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Korne, 2003).

2.2.3 Standard phonological tasks

Digit Span: From the French version of WAIS-III (Wechsler, 2000). Forward and backward spans were used to compute age-appropriate scaled scores, to obtain a measure of phonological working memory.

Spoonerisms: Participants were auditorily presented with pairs of words and were instructed to swap the first sound of each word, and then pronounce the resulting pseudo-words while maintaining their correct order.

Rapid Automatic Naming: Participants completed three versions of a Rapid Automatic Naming test : picture and digit naming (2 sheets of 50 objects or digits) adapted from the Phonological Assessment Battery (Frederickson, Frith, & Reason, 1997), and color naming (2 sheets of 50 colors). The picture naming test consists in the naming of five pictures (hat, ball, box, table, door) presented on a A4 sheet, repeated 10 times in a random order. Participants were required to name the objects accurately and as fast as possible. The digit naming test consists in the naming of 10 strings of 5 digit numbers (e.g. 23929). Participants were asked to name the digits in the stream one by one, as fast and as accurate as possible. The color naming test consisted in the naming of 5 colors (red, green, yellow, black, blue) in a A4 sheet, each one presented 10 times. Each naming test was administrated twice with different sheets. The score is the sum of total naming time for each naming test separately (object, digit and color).

2.3 Psychometric data

Following the analyses, six presumed dyslexics were excluded from our cohorts, because they did not match inclusion criteria, thus the reaming participants were 19 controls and 14 dyslexics. Results of the diagnostic battery for the remaining subject pool are summarized in Table 1.

One-Way ANOVAs revealed significant group differences on all variables but age and nonverbal IQ.

Insert Table 1 about here

In order to better appreciate each participant's overall performance on literacy and phonology variables, we computed two factors: 'Phonology' is the average z-score of phonological tests' (spoonerisms, rapid naming and digit span) and 'Literacy' is the average of reading and orthography z-scores, except for 5 subjects, with missing data (one control and four dyslexics) for whom Literacy factor comprises the reading z-score only. Figure 1 shows the scatter plot of the two factors. It demonstrates a clear split between the two groups and the fact that every single participant in the dyslexic group is impaired on both, literacy and phonological skills, as would be expected from dyslexics with a phonological deficit.

Insert Figure 1 about here

3 Perceptual tuning to phonotactic regularities

While Saussure pointed out that there is no obvious relation between the sound shape of a word and its meaning, the sound sequences in natural language are not arbitrary. Rather, an intricate set of “phonotactic” rules determines the possible sequences of speech sounds in a given language. For instance, some languages like French and English allow complex consonant clusters to occur, while others like Japanese disallow them. These language-specific constraints also play a role in speech perception. Indeed, listeners are sensitive to the phonotactic regularities of their native language (Massaro & Cohen, 1983). For example, Vitevitch et al. (1997) have shown using an auditory naming task, that adults’ subjective “wordness” rating of pseudo-words, as well as response times coincide with their phonotactic probability. That is, subjects rated high phonotactic probability pseudo-words more word-like and repeated them faster than those with a low phonotactic probability (Vitevitch & Luce, 1999; Vitevitch et al., 1997). Furthermore, Dupoux et al. (1999) showed, in a cross-linguistic study, that Japanese, but not French adult listeners perceive an illusory epenthetic vowel [u or o] when listening to complex consonant clusters that are disallowed in Japanese, such as [ebzo].

The sensitivity to native phonotactics can be shown in infants as well. Jusczyk, Friederici, et al. (1993) tested 9-month-old American and Dutch infants and observed that both groups preferred words with legal phonemic sequences in their respective mother tongue compared to illegal ones. This indicates that 9-month-old infants’ listening preferences are already shaped by the ambient language. The same observation was made in 9-month-olds for legal consonant clusters in a legal position compared to an illegal position (Friederici & Wessels, 1993). Furthermore, Mattys and Jusczyk (1999) showed that 9-month-ols infants use phonotactic probabilities to segment fluent speech. In sum, by 9 months, infants are attuned to the phonotactic regularities of their native language: they discriminate legal/frequent from illegal/rare phonemic patterns and take into account their position within words. Furthermore, they seem to use this sensitivity for word segmentation, and probably for other aspects of language acquisition.

The goal of the present experiment is to examine whether dyslexic adults have acquired the phonotactic regularities of their native language. French phonotactics disallow consonant clusters such as [dl] and [tl] at the onset of syllables, although they remain pronounceable. Hallé and colleagues (1998) have previously shown that as a consequence French listeners undergo a perceptual illusion when listening to such ‘illegal’ clusters. Namely, they perceive [gl] when listening to [dl] and [kl] when listening to [tl]. That is, they perceptually assimilate these ‘illegal’ clusters to the phonetically closest legal ones. One manifestation of this phenomenon is subjects’ reduced ability to discriminate between an illegal cluster and the closest legal one. Under one possible construal of the deficient phonological grammar hypothesis, dyslexic children (or even infants) might be less able to perceive and learn the phonotactic regularities of their native language. This would then predict that their speech perception system would be less shaped by and attuned to these regularities. In the case of the specific perceptual phenomenon just described, this hypothesis would predict that dyslexics should show less perceptual illusion due to phonotactically illegal clusters, and therefore that they would discriminate those clusters better than controls.

3.1 Materials

Stimuli were monosyllabic minimal pairs of pseudo-words with CCVC syllable structure, with target onset consonants /g, k, t, d /. For half, the target items’ initial consonants were followed by the liquid [ʁ], e.g. kʁ, tʁ, dʁ, gʁ (‘legal context’). For the other half, by the liquid [l] e.g. gl, kl, tl, dl, (‘illegal context’). Stimuli were recorded by two native speakers of French (one male and one female), in a sound-proof room, on a PC computer at 22050 Hz sampling rate. We used Cool Edit 2000 (Syntrillium Software, Phoenix AZ) to verify and edit the speech recording off-line. The overall amplitude of the stimuli was equalized using PRAAT software (Boersma, 2001).

3.2 Participants and Procedure

A subgroup of participants, eleven dyslexic and fifteen control participants took part in this experiment[2]. The experiment was programmed and presented on a laptop computer using E-Prime software (Schneider et al., 2002). Participants were tested individually. They were seated comfortably in front of a computer monitor and listened to the stimuli through

[2] Within this subset, dyslexics and controls remained matched in age and IQ, but highly discrepant on reading and phonology factors [Age: $F(1,24) = 1.26$, *ns*; Nonverbal IQ: $F(1,24) < 1$ *ns*; Digit Span: $F(1,24) = 13.6$, $p<$

headphones. One trial consisted of a pair of pseudo-words pronounced by two different speakers (male and female), separated by 1 second of unintelligible "babble" noise (which was the superimposition of several speech sound tracks). Both the speaker change and the babble noise were used to prevent subjects from performing the task at a purely acoustic representation level. Indeed because of the voice change, pseudo-words were always acoustically different, even when phonologically identical. Moreover, babble noise resets the auditory buffer, thereby prevents participants from relying on echoic memory.

Half the trials were "same" and half were "different" (28 pairs of each). "Same" trials included two identical pseudo-words. In the "different" trials, the pseudo-words differed only by the place of articulation of their onset (d-g, t-k). Participants' task was to decide and respond on a response box, with clear labels, whether the two pseudo-words were the same or different.

3.3 Predictions

According to "the deficient phonological grammar hypothesis", if dyslexics fail to properly acquire the phonological regularities of their native language, they should not assimilate the illegal clusters to the closest legal ones. This, in turn, should result in better syllable discrimination in the illegal condition, and thus lead to a group difference, in this condition only, and thus to a Group x Context interaction.

A slightly different prediction follows from "the degraded phonological representations hypothesis". If dyslexics' representations of speech sounds are noisy, underspecified or less categorical, one would also predict to find a different pattern of responses between the two groups. In the legal context dyslexics should make more errors due to miscategorization. In the illegal context they might make fewer errors if they sometimes misperceive an illegal cluster as legal (e.g. dla -> bla). Again, there should be a Context x Group interaction.

In contrast, if dyslexics have normally acquired phonological grammar and representations, they should not show any difference in either context.

.001; Spoonerisms: $F(1,24) = 19.83$, $p < .001$; Reading: $F(1,24) = 46.9$, $p < .001$; RAN average Z-scores: $F(1,24) = 34.59$, $p < .001$]

3.4 Results

Analyses of Experiment 1 were run using A' scores computed from HIT and FALSE ALARM rates[3]. HITS correspond to the correct detection of the difference in the 'different' trials and FALSE ALARMS correspond to the incorrect detection of a difference in the 'same' trials. A Repeated-Measures ANOVA with Context (legal vs. illegal) as within-subject variable and Group (dyslexics vs. controls) as between-subject variable revealed a significant effect of Context ($F(1,24) = 243.9$ $p< .000$), but no Group effect ($F(1,24)<1$, *ns*) and no Context x Group interaction ($F(1,24)<1$ *ns*). A One-Way ANOVAs did not reveal any significant group differences, neither in the legal ($F(1,24)< 1$, *ns*), nor in the illegal context ($F(1,24)< 1$, *ns*). These results indicate that the Context in which the consonant to discriminate appeared affected both groups to the same extent, decreasing their performance equally in the illegal context compared to the legal one. A data plot is shown in Figure 2.

Insert Figure 2 about here

3.5 Discussion

In the legal context, controls easily discriminated syllable pairs and were at ceiling performance. So did dyslexics. In the illegal context, on the other hand, they were close to chance performance. And so were dyslexics. In other words, participants fell victim to the predicted perceptual illusion. Illegal clusters were assimilated to the legal ones so that illegal context pairs could hardly be discriminated. The absence of a Context x Group interaction indicates that both groups underwent the assimilation process to the same extent.

One might argue that our data merely reflect ceiling and (close to) floor effects. Nevertheless, the important fact is that dyslexics show exactly the same floor and ceiling effects as controls, whereas both the deficient phonological grammar and degraded representations hypotheses would predict that they would not show as much of a floor effect in the illegal context, and the degraded representations hypothesis would predict less ceiling effects in the legal context.

Interestingly, these results also seem to conflict with a slightly different hypothesis, according to which dyslexics might retain and use more acoustic or phonetic details in their

[3] A' is a non-parametric measure of signal detection.

speech processing. One variant is that dyslexics might retain allophonic information in their phonological representations (Serniclaes, Van Heghe, Mousty, Carré, & Sprenger-Charolles, 2004). If this were the case, they might be able to better pick up the phonetic differences between the clusters in the illegal context. But this prediction is not supported here. Of course, it all depends on which phonetic details are assumed to be retained by dyslexics, which may differ between various hypotheses.

To summarize, the present results suggest that dyslexics' apply implicit phonotactic knowledge during speech processing to the same extent as control participants. Therefore, this suggests that they have normally acquired this particular aspect of phonological grammar.

4 Phonological rules : production and perceptual compensation.

Some language-specific phonological rules substitute, insert or delete entire segments as a function of speaking rate and phonological context. In English, for example, coronal stops may undergo place assimilation, taking on the place of articulation of the following stop in connected speech (Barry, 1985; Nolan, 1992). Hence the compound *football* may be realized as *foo[p]ball.* In French, obstruents may undergo voicing assimilation, taking the +/- voice feature from the following consonant (Snoeren, Halle, & Segui, 2006; Wetzels & Mascaró, 2001) Thus the same word *football* tends to be realized as *foo[d]ball*. Such rules are common across the world's languages and tend to be productive, applying to novel items.

Furthermore, because these rules substantially affect the phonetic shape of words, such changes can potentially disrupt lexical recognition. Indeed they can neutralize existing contrasts between phonemes, and hence contrasts between lexical items. This in turn may render the identification of lexical entries problematic. The surprising fact is that these phonological changes seem to matter very little in everyday continuous speech recognition. In fact, most people are not even aware of the existence of these phonological changes. This may be explained by language-specific perceptual compensation mechanisms, which may implement inverse phonological rules, although the specific mechanisms implicated in perceptual compensation remain debated (I. Darcy, Peperkamp, & Dupoux, in press; Isabelle Darcy, Ramus, Christophe, Kinzler, & Dupoux, in press; Gaskell & Marslen-Wilson, 1996; Gow & Zoll, 2002; Mitterer & Blomert, 2003).

Thus, assimilation phenomena, both in speech production and perception, are one aspect of the implicit phonological knowledge that the child normally acquires during the first years of life. It therefore seems relevant to ask whether dyslexic children also acquire this phonological knowledge, and whether this knowledge shapes the mature state of their speech production and perception system to the same extent as for controls.

So far, little is known about assimilation processes in dyslexia, in particular in speech production. Concerning perceptual compensation, Blomert et al. (2004) provided some evidence regarding compensation for place assimilation in Dutch dyslexic children. In their study, the authors investigated context effects in speech perception at multiple levels of processing: in (i) acoustic, (ii) phonetic and (iii) phonological contexts. Across three experiments the authors used semi-natural stimuli in a two-alternative forced-choice (2AFC) paradigm. In their first experiment, they examined if dyslexic and normal reading children differed in their use of auditory context when identifying speech sounds, which were either ‘tart’ or ‘kart’. Here the auditory context was a sinusoid tone (high or low) preceding the stimuli. The results did not show any evidence for a speech perception deficit, nor for a reduced use of context in the dyslexic group. In their second experiment, the authors looked for phonetic context effects on speech sound identification (again ‘tart’ or ‘kart’). Here, the phonetic context were /al/ and /ar/ syllables. It is assumed that due to compensation for coarticulation, participants are more likely to perceive /ta/ after context /ar/ than after /al/ (Mann, 1980). The authors found that the context influenced identification more strongly in the dyslexic group, in the expected direction, than in the control group. However, in this experiment, control subjects failed to show the expected compensation effect at all, so the group difference is not easily interpreted. Finally, in the third experiment, they examined phonological context effects on speech perception. Participants listened to pairs of nouns (a target word followed by a context word), and had to indicate which target word they heard ([tuin] ‘garden’ or its assimilated form [tuim], which is a pseudo-word). The target appeared in three conditions: in a viable assimilatory context, a non-viable assimilatory context, and in a non-assimilatory context. The authors did not find any group differences, that is, both groups compensated for the assimilation to the same extent.

Overall Blomert et al. found that dyslexics seem to show normal compensation. The only group difference that they found would deserve to be replicated given the anomalous performance of the control group. A replication and generalization of these results seem call the more necessary since they were obtained on a very limited set of stimuli (one word pair).

The purpose of our experiments was to test 1) whether French dyslexics apply voicing assimilation rules during elicited speech production, and if so, to what extent, and 2) whether they perceptually compensate for them during lexical access.

4.1 Assimilation in speech production

In order to investigate voicing assimilation processes in sentence production, we used a sentence production task, with sentences including phonological contexts favoring (or not) assimilations.

4.1.1 Materials

The experimental items were drawn from Darcy et al. (in press). We used two sets of 16 target items: a Voicing and a Place Set (32 items in total). Target contexts comprised a monosyllabic noun followed by an adjective. The initial consonant of the adjective provided a phonological context influencing the assimilation of the noun's final consonant (see examples below). Contexts were either assimilatory (either for voicing, according to French phonology or for place, according to English phonology) or neutral with regard to assimilatory processes. The design yielded three experimental factors: Context (assimilatory vs neutral), Feature (voicing vs place) and Group (dyslexics vs controls). In order to create both voicing and devoicing assimilatory contexts, all items in the Voicing Set ended with a final obstruent, half voiced and half unvoiced. These target contexts (nouns plus adjectives) were then embedded in 64 sentence frames (32 for the Voicing and 32 for the Place Sets). The sentence frames were matched in number of words and in position of the insertion slots across the two Sets. Sample sentences are: 'La petite fille jette sa *cape grise*' [kabgrʁiz] (assimilatory, voicing), 'La petite fille jette sa *cape noire*' [kapnwʁ] (non-assimilatory, voicing), 'Il habite dans une *zone portuaire*' [zompoʁtyɛʁ] (assimilatory, place): 'Il habite dans une *zone fluviale*' [zonflyvjal] (non-assimilatory, place). The complete list of sentences is listed in Annexe 1.

4.1.2 Participants and Procedure

A subgroup of our cohort, 10 dyslexic and 13 control participants took part in this experiment[4]. They were tested individually in a sound proof room. The experiment was programmed and run on a PC computer using DMDX software (Forster & Forster, 2003). Prior to each experimental trial, participants were familiarized with the sentence. It was presented in black color on white computer screen. Participants were asked to read it aloud at least twice or more if necessary to allow a clear and fluent pronunciation. Once they felt comfortable, they pushed the space bar on the keyboard, consequently the color of the sentence changed into red indicating that recording was on and they pronounced the sentence. They were asked to pronounce it clearly and with a fast speech rate because fast speech is known to facilitate assimilation processes. The sentence remained in red on the screen for four seconds, then the next sentence appeared. The experiment took approximately 15 minutes. 64 sentences (16 per context) were recorded per participant.

For further inspection and analysis of the recordings, target nouns (64 items per participant) were edited out from their context, using CoolEdit (Syntrillium Software, Phoenix AZ). In order to classify each recorded noun as assimilated or not, we presented them auditorily to 8 native speakers of French, blind to the purpose of the experiment. Simultaneously to the auditory presentation, the orthographic forms of the target item in assimilated and in unassimilated forms were presented on the screen (eg. 'rope' and 'robe' respectively). Listeners listened to the target word and had to indicate on a response box, which orthographic form was its best transcription. Target words were assigned to seven blocks. Before beginning the experiment, participants had four practice trials. The first six blocks contained the target words from four participants, two dyslexics and two controls (4 participants * 6 blocks = 24), and the last block contained the targets of two speakers, (one dyslexic and one control). The order of the target words as well as the side (left/right) of the orthographic words on the screen was randomized. This post-test was programmed in E-prime (Schneider et al., 2002) and took approximately 80 minutes. Participants could have a pause between blocks.

[4] Within this subset, dyslexics and controls remained matched in age and IQ, but highly discrepant on reading and phonology factors [Age: F<1 *ns*; Nonverbal IQ F<1 *ns*; Digit Span $F(1,21) = 12.12$, $p < .01$; Spoonerisms: $F(1,21) = 18.33$, $p < .001$; Reading: $F(1,21) = 35.85$, $p < .001$; RAN average Z-scores: $F(1,21) = 26.35$, $p < .001$]

4.1.3 Predictions

The deficient phonological grammar hypothesis might make a number of different predictions: 1) That dyslexic children fail to acquire assimilation processes, i.e. that they produce no (or fewer) assimilations; or 2) that they produce a universal pattern of assimilations (those that occur in all languages), but unaffected by the specific rules and contexts defined by the phonology of their native language; or 3) that they produce generalized assimilation, so that they would have a tendency to assimilate all phonetic features between all phonemes, which would make their speech excessively co-articulated and less distinct, perhaps in the way suggested by Elbro (1998). Although these versions of the deficient phonological grammar hypothesis differ in the specific predictions they make, they do converge in predicting that dyslexics should be less (if at all) sensitive to both Context and Feature factors.

On the other hand, degraded phonological representation hypotheses, to the extent that they concern output phonological representations, would broadly predict noisier data for dyslexic subjects (because of less precise realisations of target phonemes), and decreased sensitivity to the Context factor (because the phonological Context itself would have a degraded representation).

4.1.4 Results

One pair of sentences from the Voicing Set was excluded from the analyses because it did not include the correct assimilation context. A Repeated-Measures ANOVA with Context (assimilatory, control), Feature (voicing and place) and Group as factors revealed significant main effects of Feature F(1,21) = 73.19, $p<.001$ and Context F(1,21) = 47.87 $p<.001$, and a Context x Feature interaction (F(1,21) = 45.8, $p<.001$) but no Group effect (F<1). Furthermore, none of the interactions with the Group factor reached significance (Feature x Group, Context x Group and Context x Feature x Group; all Fs< 1). Figure 3 shows the percentage of unassimilated words in each condition.

French native speakers tended to produce voicing assimilations about 40% of the time (under these experimental conditions), but only in the assimilatory context. French dyslexics showed exactly the same pattern, as indicated by the lack of Group effect and of Group x Context interaction. The significant Context x Feature interaction shows that, as predicted by French phonology, the influence of Context depends on the Feature: It is large for voicing (t(22) = -7.13, $p<.001$) and inexistent for place (t(22) = -1.69, *ns*). Again, the same is observed in dyslexics, as shown by the lack of a Context x Feature x Group interaction.

Voicing context: In a further Repeated-Measures ANOVA with Context (assimilatory and control), Voicing (+/- voice) and Group factors, we looked for a possible asymmetry between +/-voice assimilations. Indeed, it has been shown that French speakers tend to produce more often +voice than -voice assimilations (e.g., more often “cape grise” -> [kabgrʁiz] than “robe sale” -> [ʁɔpsal]), a bias possibly reflecting the respective frequencies of voiced and voiceless consonants in French (Snoeren et al., 2006). Results revealed a main effect of Context F(1,21) = 47.36, *p<.001* but neither Voicing (F(1,21) = 2.78, *p=.11 ns*) nor Group (F<1) nor any of the interactions reached significance (Fs<1). Although there is a tendency, the bias in favor of voicing assimilation does not reach statistical significance, and this does not differ between groups.

Place context: Repeated-Measures ANOVAs with the factors Context and Group revealed neither a main effect nor an interaction (Context, Group and Context x Group Fs<1). Figure 3 shows percent of unassimilated word production, in each condition. In assimilatory contexts, French native speakers produced place assimilations in ~5% of the time, which is not different from the control context (t(22) = -1.69, *ns*), suggesting that this is just response noise. Furthermore this did not differ between groups.

Insert Figure 3 about here

4.1.5 Discussion

Our results first provide an important confirmation of phenomena that have been described before (Barry, 1985; Nolan, 1992; Snoeren et al., 2006): French native speakers produce voicing assimilations, in contexts previously described as legal in French, but not in others; and they do not produce place assimilations in contexts, where this would be legal in English. Furthermore, we find that French dyslexics show exactly the same effects as control participants.

These results suggest that dyslexics have normally acquired those aspects of French phonological grammar, and that this implicit phonological knowledge shapes their speech production in the same way as for controls.

Since dyslexics apply voicing assimilation during speech production, this suggests that they have a sufficiently accurate representation of voicing, at least in the output pathway. Furthermore, their representation of the phonological contexts (with plosive and fricative features), in which assimilation is possible in French, must be accurate too. This seems in conflict with the degraded phonological representations hypothesis.

4.2 Perceptual compensation for assimilations

Whether dyslexics produce assimilations in their speech or not, it is also relevant to ask whether they compensate for other speakers' assimilations in their speech perception. Even if, as we suggest, dyslexics normally produce assimilations, this does not necessarily imply that they have correctly acquired the inverse phonological rules in perception. For one thing, they might have a deficit in their input, but not in their output, phonological representations or processes (e.g. Szenkovits & Ramus, 2005).

Therefore, our aim here was to investigate to which extent dyslexics, during lexical access, mentally compensate for phonological rules, and whether they do so precisely for the features and in the contexts determined by the phonology of their native language.

4.2.1 Materials

The experimental items were the same as in Darcy et al. (in press). We kept the same two sets (Voicing and Place) and in addition, 120 pseudo-words ([psw]) were created. Half by switching the voicing feature of the final obstruents, (e.g. robe /rob/ 'dress'→ rope /rop/ [nw]; and lac /lak/ 'lake'→ lague /lag/ [psw]); and half, by changing the place of articulation of the final consonant (e.g. moine /mwan/ 'monk'→ moime /mwam/ [psw]; or guide /gid/ 'guide' → guibe /gib/ [psw]). Each of the target items was associated with 3 adjectives, leading to three context conditions: assimilatory, non-assimilatory and control conditions. The association (pseudo)noun-adjective always yielded a legal consonant cluster in French. All target items are listed in Annexe 2.

Three sentence frames were used for each of the 32 target items. The sentence frames were matched in number of words and position of the insertion slots across the Voicing and the Place Sets. The three conditions with the three sentence frames resulted in 9 sentences that were associated to each item. This resulted in a total of 288 sentences.

To avoid confounding sentence frame with condition, three experimental lists were defined. In each list, all three conditions were present for each item, but in different sentence frames. The sentence frames were rotated across the three lists, so that across the experimental lists all three conditions appeared in all three sentence frames. Thirty additional filler sentences were constructed that were similar to the experimental sentences. These filler sentences did not include any assimilation but served as training (18 trials) and distractors (12 trials).

All sentences were recorded by a female native speaker of French. They were digitized at 16 kHz and 16 bits on an OROS AU22 sound board, and edited using CoolEdit (Syntrillium Software, Phoenix AZ) and Praat (Boersma, 2001) softwares. For a more detailed description of the materials, see Darcy et al. (in press). All target words were recorded by a male native speaker of French and digitized.

4.2.2 Participants and Procedure

A subgroup of our cohort, 14 dyslexic and 19 control participants took part in this experiment[5]. They were tested individually in a sound proof room. The experiment was programmed and run on a PC computer using E-Prime software (Schneider et al., 2002).

The experiment was preceded by a training session comprising 18 sentences with feedback. Once the training session accomplished, the experiment begun, and feedback stopped. In a trial, participants first listened to the target word pronounced by a male speaker, then after 500 ms of silence, they listened to the sentence pronounced by a female speaker. The task was to decide whether the target word appeared, correctly pronounced, in the sentence, or not. In the control condition, the target word appeared identically in the sentence (which was the baseline for word detection, e.g. 'robe rouge' [ʁɔbʁuʒ]). In the non-assimilatory context condition, the target word appeared "mispronounced" in the sentence (which was the baseline for word rejection, e.g. 'robe noir' [ʁɔpnwaʁ]). And finally, in the assimilatory context condition, the target word appeared also "mispronounced" in the sentence, but in a legal assimilatory context that promoted that particular pronunciation (e.g. 'robe sale' [ʁɔpsal]. Participants were instructed and trained to respond 'YES' if the target word was included and properly pronounced in the sentence, and 'NO' if it was not.

[5] Within this subset, dyslexics and controls remained matched in age and IQ, but highly discrepant on reading and phonology factors [Age: $F<1$ *ns*; Nonverbal IQ $F(1,31) = 1.49$ *ns*; Digit Span $F(1,31) = 17.07$, $p<.001$; Spoonerisms: $F(1,31) = 34.66$, $p<.001$; Reading: $F(1,31) = 33.06$, $p<.001$; RAN average Z-scores: $F(1,31) = 56.00$, $p< .001$]

Participants were allowed 3000 ms after the word onset to make their response, then the next trial was initiated. The test phase was split into three blocks of 36 trials (32 test items and 4 fillers) and a given test item appeared only once within each block. The order of the trials within each block was randomized for each participant. The experiment lasted about 20 minutes. Participants could have a short break between blocks.

4.2.3 Predictions

Predictions of the deficient phonological grammar hypothesis are as follows: 1) That dyslexic children fail to acquire native assimilation processes, i.e. that they do not compensate(or less so) for assimilations that exist in their native language; or 2) that they compensate for a universal pattern of assimilation, but not specifically for that defined by the phonology of their native language (thus they would show no difference between place and voicing assimilation); or 3) that they over-compensate, that is, they would have a tendency to compensate regardless of Context, even in the control context. Similarly to the production experiment, these versions of the deficient phonological grammar hypothesis differ in their specific predictions, however they do converge in predicting that dyslexics should be less (if at all) sensitive to both Context and Feature factors, and should show less (if at all) Context x Feature interaction.

On the other hand, degraded phonological representation hypotheses, to the extent that they concern input phonological representations, would broadly predict noisier data for dyslexic subjects (because of less precise representations of target phonemes), thus less clear effects overall, and decreased sensitivity to the Context factor (because the Context itself would be less well represented).

4.2.4 Results

A Repeated-Measures ANOVA with Feature (voicing vs place), Context (assimilatory, non-assimilatory, control) and Group (dyslexics vs controls) factors revealed significant main effects of Feature $F(1,31) = 42.85$, $p < .001$ and of Context $F(1,31) = 26.75$ $p < .001$, a Feature x Context interaction $F(2,62) = 88.19$, $p < .001$, but no Group effect ($F(1,31) = 1.80$, $p = 0.18$), and none of the possible interactions with Group reached significance (Feature x Group, $F(1,31) = 1.52$, *ns*; Context x Group, $F(1,31) = 1.24$, *ns;* Feature x Context x Group, $F(1,31) =$

1.51, *ns*). Participants compensated for assimilation more in the assimilatory than in the non-assimilatory context, and more for voicing than for place assimilation. Furthermore none of these effects differed between groups. Thus, both groups compensated to the same extent in the voicing assimilatory context (about 80% of the time), but much less in the non-assimilatory context (between 15-30%), and were almost 100% accurate in simple word detection (the control condition). Figure 4 shows the mean word detection by Feature and Context, for both groups.

In order to quantify compensation for assimilation free of response bias, we also computed a "compensation index"[6] (see Isabelle Darcy et al., in press), which normalises compensation in "assimilatory" conditions with respect to word detection rate in non-assimilatory and control conditions. A Repeated-Measures ANOVA with Feature (voicing vs place) and Group (dyslexics vs controls) factors revealed significant main effect of Feature $F(1,31) = 181.5$, $p < .001$, but neither the Group effect nor the Feature x Group interaction reached significance ($Fs<1$). Both groups compensated to the same extent in voicing and place contexts. Figure 5 shows the compensation index in both place and voicing sentences.

Insert Figure 4 and 5 about here

In order to investigate the potential asymmetry between +/-voice assimilations in compensation as well, we computed the compensation index separately for + and – voice targets. The Repeated-Measures ANOVA with Voicing (+ vs - voice) and Group (dyslexics vs controls) factors revealed significant main effect of Voicing $F(1,31) = 17.92$, $p < .001$ but neither the Group effect nor the Voicing x Group interaction reached significance ($Fs<1$), indicating that both groups compensated more in voicing than in devoicing context. Figure 6. shows the compensation index in both voicing and devoicing contexts.

Insert Figure 7 about here

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[6] Compensation index = (%detection $_{assim}$ –%detection $_{non\text{-}assim}$)/(%detection $_{control}$ –%detection $_{non\text{-}assim}$)

4.2.5 Discussion

The results obtained here fully replicate those of Darcy et al. (in press): French listeners compensate most of the time for voicing assimilations (80%), but only when these occur in assimilatory contexts. Furthermore, they compensate to a much smaller extent for place assimilations (around 30%), possibly reflecting universal compensation processes. Finally, they compensate more often for +voice than for –voice assimilations. Dyslexics do exactly the same in all respects. Moreover these results mirror those obtained in production.

The prediction of a 'deficient phonological grammar hypothesis' was that dyslexics should show less sensitivity to Context and/or to Feature factors. Degraded phonological representation hypotheses (e.g. if dyslexics had less precise representations of target phonemes) predicted noisier data and decreased sensitivity to the Context and Feature factors. The results we obtained here do not support the predictions of either hypothesis, but on the contrary suggest that dyslexics not only have acquired assimilation rules in speech production, but also have normally acquired compensation mechanisms in speech perception. Furthermore, this pattern of results suggests that dyslexics must have a fairly good representation of voicing and place features, otherwise their patterns of compensation would be less consistent, less specific to context and to the feature to be assimilated.

5 General discussion

One of the primary cues that adult listeners use to segment words from continuous speech is the recognition of the lexical items already present in their lexicon. They can recognize words despite large acoustic, phonetic and sometimes phonological variations. That is, they achieve a perceptual constancy of words. They also exploit a number of phonological regularities specific to their native language, such as syllable structure, phonotactics, prosodic and allophonic regularities etc. Some regularities are language-specific, hence must be acquired during language acquisition. This sensitivity to language-specific regularities begins during the first year of life and is thought to facilitate spoken language acquisition (Auer & Luce, 2005; Friederici & Wessels, 1993; Jusczyk, 1999; Massaro & Cohen, 1983; Mattys et al., 1999).

In the present study, we investigated whether dyslexics have acquired this implicit language-specific knowledge. First, we tested one specific phonotactic regularity, and asked whether it constrains their speech perception to the same extent as controls'. The results showed that illegal clusters were assimilated to phonotactically legal ones. Furthermore, dyslexics perceptually assimilated the illegal clusters to legal ones to the same extent as controls, as indicated by the absence of a Group effect and of a Context x Group interaction. This suggests that they did acquire this specific aspect of French phonotactics, and moreover that it constrains their speech perception to the same extent as that of controls'. This results is in contrast with the predictions of both the deficient phonological grammar and degraded representations hypotheses. Interestingly, these results are also in conflict with a slightly different hypothesis, according to which dyslexics' phonological representations would be more detailed, including for instance allophonic information (Serniclaes et al., 2004). If this were the case, they might be able to deal with phonetic differences between clusters better in the illegal context. But this prediction was not supported here.

These results also contrast with those obtained by Bonte et al. (2007), who investigated neural responses of implicit phonological processing in dyslexic children, using two legal pseudo-words, which were either of high ([notsel]) or of low ([notkel]) phonotactic probability. The authors reported that the amplitude of the MMN (mismatch negativity) to the change from the standard to the deviant pseudoword was greater in control than in dyslexic children. They interpreted this effect as a difference in sensitivity to phonotactic probability. However, let us note that with just one item (albeit uttered four different times) per condition, the effect might as well be due to any phonological.difference or even uncontrolled stimulus-specific artefact between the two pseudowords (see Clark, 1973). Nevertheless, taking these results at face value, Bonte et al. suggest that dyslexic children are less sensitive to quantitave variations in phonotactic probability. Here, we have focused on the more extreme case where phonotactic probability is null, thus inducing a perceptual illusion. Our results suggest that this effect at least is normal in dyslexics, but do not exclude the possibility that they might be less sensitive to more subtle quantitative variations in phonotactic probability. Another possible source of differences between the two studies is of course the age of the participants. It is perfectly possible that dyslexic children, owing to their phonological deficit, incur a delay in their tuning to phonotactic probabilities, but that in adulthood they eventually reach normal phonotactic sensitivity, albeit later than controls.

The next questions that we investigated were whether dyslexics produce lawful phonological variations and whether they compensate for them during lexical access. For this purpose, we tested two phonological rules, one found in French phonology, regressive voicing assimilation, and another one found in English phonology, regressive assimilation of place of articulation.

In an elicited speech production task, we recorded participants’ speech production, then quantified the amount of assimilations they produced. The results showed that participants of both groups produce voicing assimilations, but no place assimilations. And both groups do so to the same extent. There was also a non significant trend towards producing more voicing than devoicing assimilations, which again did not differ between groups.

Therefore, the results obtained in the speech production task suggest that dyslexics have normally acquired these aspects of French phonological grammar, and that it shapes their speech production in the same manner as for controls. Moreover, since they apply voicing assimilation during speech production but not place assimilation, this suggests that they should have a quite accurate representation of voicing and place, at least as far as output representations are concerned. Furthermore, their representation of the phonological contexts (plosive and fricative features) in which assimilation occurs in French must be accurate too.

To test whether dyslexics perceptually compensate for phonological variations introduced by the same phonological rules, we used a word detection task in sentences, containing the target words in assimilated form, embedded in contexts that were either consistent with those assimilations or not. Our results replicated previous findings that French listeners compensate for voicing assimilations (80% of the time), when these occur in legal French assimilatory contexts. Furthermore, they compensate to a much smaller extent for the non-native place assimilation rule (30% of the time). As in production, we also looked for the +/-voicing assimilations asymmetry and found a significant bias towards compensation for voicing assimilation, relative to devoicing assimilation.

Interestingly in this experiment again, and in all respects, dyslexics performed exactly like controls. They compensated for voicing assimilation to the same extent as controls, much less so for place assimilation (but as much as control participants), and showed the same bias towards voicing assimilation. Hence, these results mirror exactly those obtained in the production task.

These results are against inconsistent with the predictions of the 'deficient phonological grammar hypothesis', as well as those of the degraded phonological representation hypotheses, which would have predicted noisier data and decreased sensitivity to the Context and Feature factors in dyslexics.

Throughout the three experiments, we have consistently failed to find group effects, and interactions between group and the other factors. This suggests that dyslexics have normally acquired these aspects of the phonological grammar of their native language, that they apply them in production, and compensate for them in perception. Furthermore, in order to correctly apply these regularities, they must have fairly good representations of the phonological features that are assimilated and of the phonological contexts in which they can or cannot be assimilated. This runs even more against the hypothesis of degraded phonological representations. Of course, one might argue that the degradation could be so subtle as not to affect the use of these phonetic features in phonological processes and grammar. But then the degraded phonological representations hypothesis becomes much weaker and less likely to be able to explain a reading deficit.

One possible critique of the present study is that given the consistent lack of group effects and of interactions between group and other factors, all our conclusions rest on null results. However, our results show much more than null effects. Indeed, in each experiment, we have obtained very specific and significant effects and interaction patterns, replicating previously published data, and consistent with phonological theory. Simply the dyslexic group showed exactly the same patterns of significant effects and interactions. The consistent lack of any trend towards a group difference further argues against a lack of power to detect group effects. Furthermore, on literacy and standard phonological measures, statistical power was amply sufficient to detect group differences. There is thus every reason to believe that the absence of group differences is a real, albeit null, result.

Another potential critique is that, since we tested a highly achieving, probably well compensated dyslexic adult population, (1) they might have had no phonological deficit, or (2) they might have recovered from it. However, all participant were included in the study based on both a history and direct evidence of reading and writing difficulties, and furthermore they did show significantly lower performance on standard phonological tests than their age- and IQ matched controls. Therefore, there is good reason to believe that these participants were dyslexic with a phonological deficit as generally understood.

To conclude, our results suggest that dyslexics normally acquire at least some phonological grammatical rules, and that they must have fairly well specified phonological representations, at least for the features tested. Nevertheless they exhibit the typical phonological deficit as shown by phonological awareness, verbal short term memory and rapid automatic naming tasks. Therefore, our results are overall inconsistent with the two hypotheses that we aimed to test, the degraded phonological representations hypothesis, and the deficient phonological grammar hypothesis. They are more consistent with the idea that the phonological deficit may lie elsewhere than in phonological representations and grammar. The present study cannot answer the question of where exactly it might lie and what form it might take, but our results are at least consistent with the hypothesis that the deficit may lie in the ability to efficiently and rapidly access phonological representations (Ramus & Szenkovits, 2008).

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Table 1. Psychometric data. Table reports **mean scores** and (standard deviations). The data from the spoonerisms tasks captures both accuracy and speed**.**

	Controls (n = 19)	Dyslexics (n = 14)	One Way ANOVAs
Age	**23.57**	**22.5**	$F(1,31) < 1$ *ns*
	(3.65)	(3.56)	
Nonverbal IQ [a]	**115**	**109.67**	$F(1,31) = 1.4$ *ns*
	(12.7)	(11.77)	
Digit span [b]	**11.15**	**7.14**	$F(1,31) = 17.64$ $p< .000$
	(2.83)	(2.53)	
Spoonerisms [c]	**0.15**	**0.04**	$F(1,31) = 35.26$ $p< .000$
	(0.06)	(0.04)	
Reading [d]	**72.3**	**137.2**	$F(1,31) = 60.5$ $p< .000$
	(7.04)	(35.67)	
RAN [e]			
Object	**54.71**	**75.05**	$F(1,31) = 37.2$ $p< .000$
	(6.64)	(12.35)	
Digit	**27.09**	**38.34**	$F(1,31) = 36.65$ $p< .000$
	(4.63)	(6.05)	
Colour	**47.33**	**62.21**	$F(1,31) = 20.71$ $p< .000$
	(8.12)	(10.67)	
RAN average z-score	**-1**	**-3.11**	$F(1,31) = 57.9$ $p< .000$
	(1)	(1.35)	

[a] Ravens' matrices Standard Scores.

[b] WAIS-III[FR] Scaled scores.

[c] Percentage correct responses divided by average response time (sec.).

[d] Adjusted reading time (sec.) for the French 'Alouette' reading test.

[e] Average of the two passages for each Rapid Automatic Naming test.

Figure 1. Subjects' distribution among phonology and literacy factors.

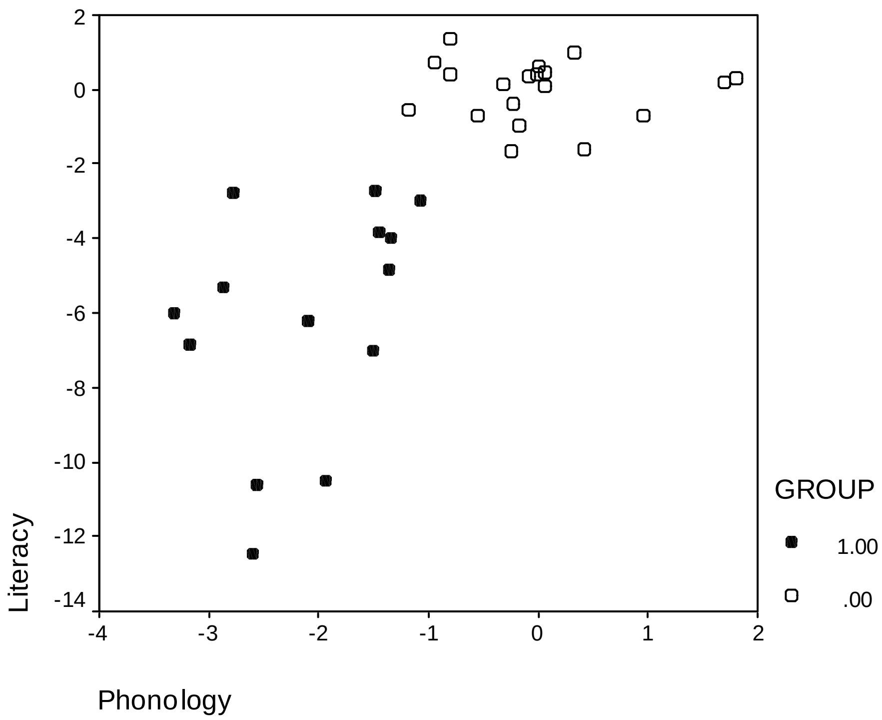


Figure 2. Context x Group interaction.

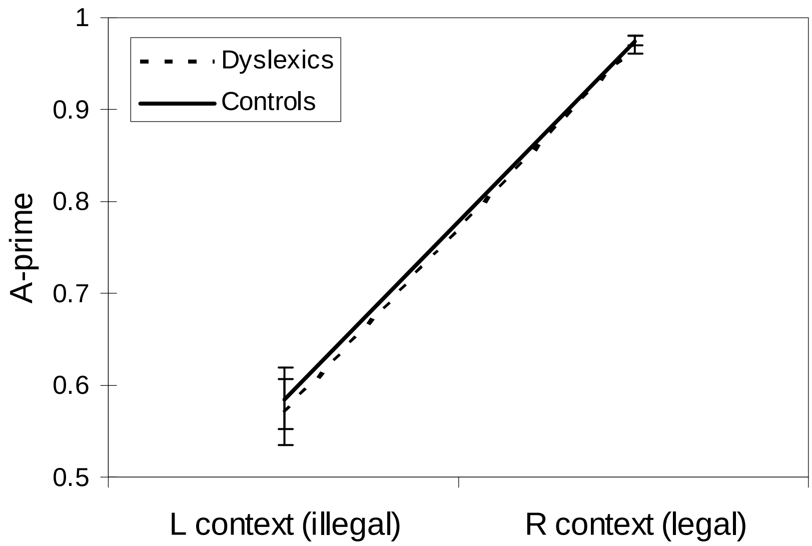


Figure 3: Bar charts depict the percentage (and standard error bars) of unassimilated word for each group, in each condition.

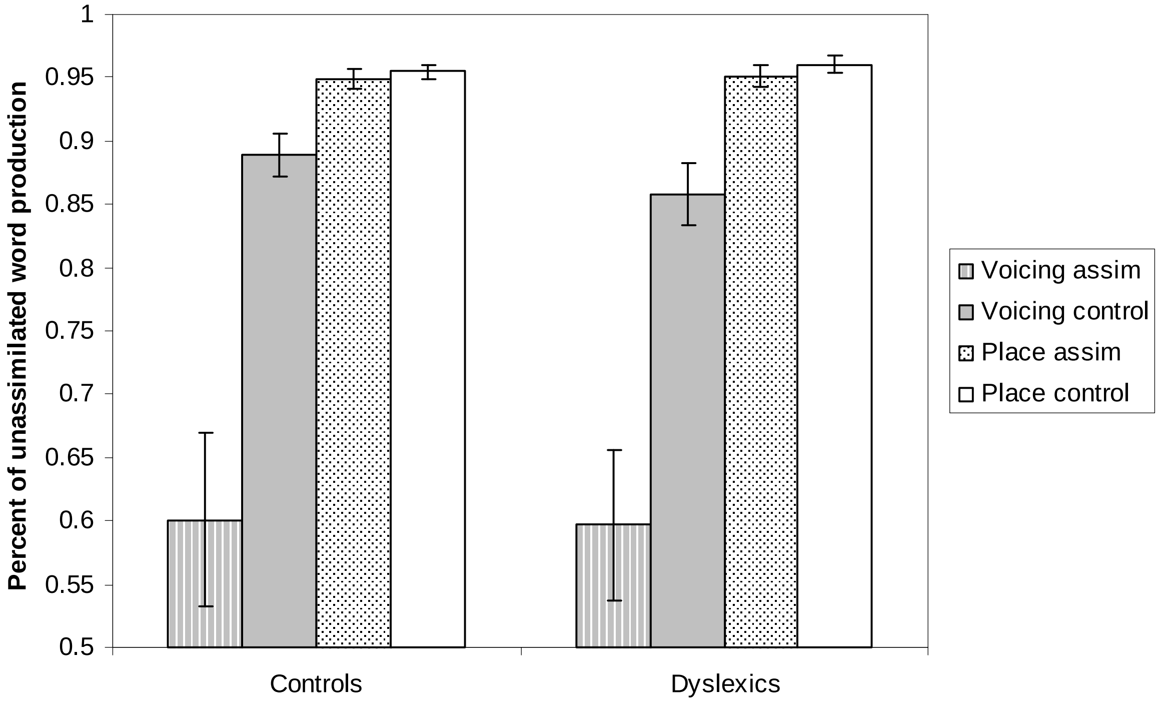


Figure 4: Bar charts capture the mean word detection (and standard error bars) for both Features (voicing and place) and Conditions (assimilatory, non-assimilatory and control context) for each group.

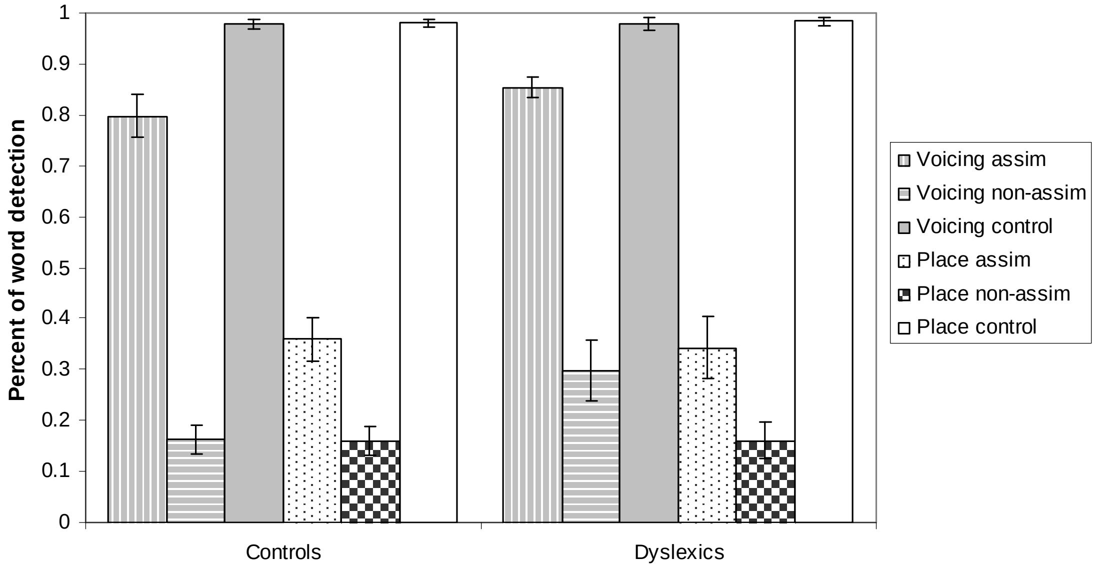


Figure 5. The degree of compensation for both groups, in both place and voicing contexts.

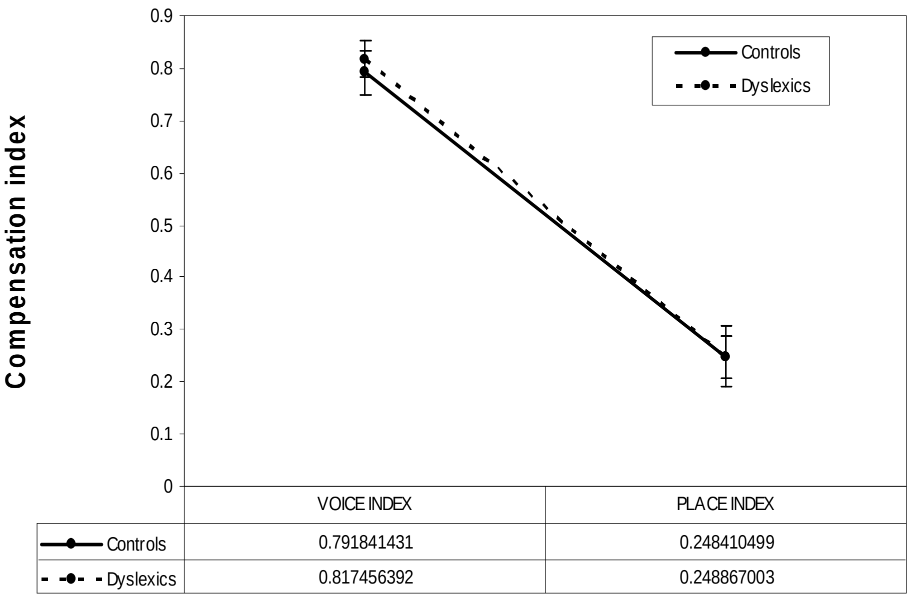
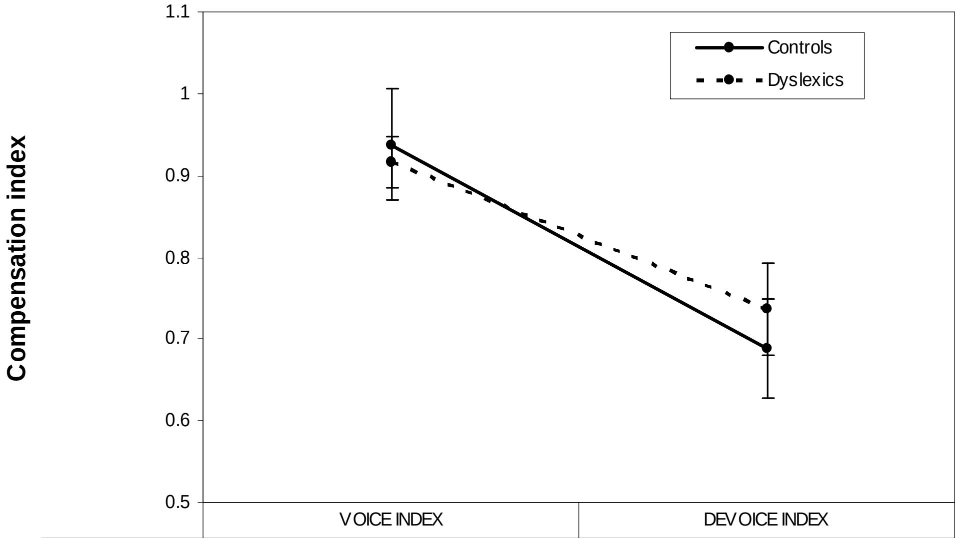


Figure 6. The degree of compensation for both groups, in both voicing and devoicing contexts.



	VOICE INDEX	DEVOICE INDEX
Controls	0.937548194	0.687577017
Dyslexics	0.915848727	0.735685818

Annexe 1: Materials for the production task.

Sentences in the voicing assimilation set, for each target word a target sentence followed by the control sentence.

Voicing Set	Target word
La petite fille jette sa robe sale Elle n'aime pas sa robe noire	robe
Il a eu le coude tordu pendant quinze jours Il avait un coude raidi depuis son accident	coude
Au plafond on voit tourner un globe pailleté Il a un globe lumineux dans sa chambre	globe
J'ai horreur de la neige poudreuse Les rues sont pleines de neige marron	neige
Des tonnes de lave pâteuse descendent de la montagne Une couche de lave rugueuse recouvre tout	lave
Le ciel se couvre de nuages chargés On voit quelques nuages nacrés qui se forment	nuage
Le liquide se trouve dans une cuve fendue L'apprenti a renversé la cuve remplie	cuve
On leur a donné un badge parfumé Les employés portent un badge ravissant	badge
Elle est belle, cette nappe brodée J'ai mis la nappe rustique sur la table	nappe
Personne n'a remarqué cette faute discrète Il commet une faute légère en début de jeu	faute
La voiture roule sur une route dangereuse Tous les matins, il prend une route nationale	route
Le chèque volé n'a pas été encaissé Le chèque reçu n'est pas couvert	cheque
Il faut enlever la couche jaunie avant de continuer On voit partout une couche marron	couche
Les sorcières portent une cape grise pour aller au bal Il a mis sa cape neuve sur le dossier de la chaise	cape
Les lacs gelés sont plus dangereux qu'on ne croit Les lacs nordiques sont souvent magnifiques	lac

Sentences for the place assimilation set, for each target word a target sentence followed by the control sentence.

Place Set	Target word
Il y a une bête poilue dans la cave Il a vu une bête féroce qui lui a fait peur	bête
Il pleuvait très fort et il a mis ses bottes pointues Il n'y a que ces bottes rayées pour aller avec ton pantalon	botte
Elle garde son argent dans une boîte carrée Il y a une boîte fermée sur la table	boite
Il a recueilli et apprivoisé une chouette craintive J'ai vu une chouette sauvage traverser le jardin	chouette
Ce guide bourru critique tout ce qu'il voit L'agence a renvoyé le guide vulgaire ce matin	guide
La ville veut remplacer le stade bétonné par un ensemble neuf Le stade démodé doit bientôt disparaître	stade
Cette année, la mode guerrière fait fureur On ne parle que de mode zoulou	mode
Une ride gracieuse rendait son visage mémorable Il a une ride discrète au menton depuis toujours	ride
Frère Jean est vraiment un moine bavard C'est un moine serviable qui nous a fait la visite	moine
On ne voit rien, la lune pâle est cachée par les nuages Cette nuit, la lune rousse est étonnante	lune
Il a ramassé des prunes pourries tombées de l'arbre Sa maman lui interdit de manger des prunes sucrées	prune
En général, les reines paresseuses sont rares Jeanne était une reine respectée qui a vécu longtemps	reine
Il admirait cette longue dune brumeuse Il faut grimper sur cette dune sauvage	dune
Cette ruine baroque est de toute beauté Nous avons visité une ruine célèbre	ruine
C'est cet artisan qui a sculpté le trône princier Le trône royal est situé au centre de la pièce	trône
Il habite dans une zone portuaire Une zone fluviale est toujours dangereuse	zone

Annexe 2: Target items for the perception compensation task.

Target	Gloss	Un-changed form	Changed form	No-change Context	Unviable Context	Viable Context
				Place		
bête	(beast)	[bɛt]	[bɛp]	nuisible 'cumbrous' [nɥizibl]	feroce 'ferocious' [feʁɔs]	poilue 'hairy' [pwaly:]
boîte	(box)	[bwat]	[bwak]	marron 'brown' [maʁɔ̃]	fermee 'closed' [fɛʁme:]	carrée 'square' [kaʁe:]
botte	(boot)	[bɔt]	[bɔp]	montantes 'high' [mɔ̃tɑ̃t]	rayées 'striped' [ʁɛje:]	pointue 'spiky' [pwɛ̃ty:]
chouette	(owl)	[ʃwɛt]	[ʃwɛk]	malade 'sick' [malad]	sauvage 'wild' [sovaʒ]	craintive 'frightened' [kʁɛ̃tiv]
dune	(dune)	[dyn]	[dym]	lointaine 'remote' [lwɛ̃tɛn]	sauvage 'wild' [sovaʒ]	brumeuse'brumous' [bʁymøz]
guide	(guide)	[gid]	[gib]	raciste 'racist' [ʁasist]	vulgaire 'vulgar' [vylgɛʁ]	bourru 'grouchy' [buʁy]
lune	(moon)	[lyn]	[lym]	jaune 'yellow' [ʒon]	rousse 'red' [ʁus]	pâle 'pale' [pɑl]
mode	(fashion)	[mɔd]	[mɔg]	locale 'local' [lokal]	zoulou 'Zulu' [zulu]	guerrière 'combat' [gɛʁjɛʁ]
moine	(monk)	[mwan]	[mwam]	rusé 'wily' [ʁyze]	serviable 'helpful' [sɛʁvjabl]	bavard 'talkative' [bavaʁ]
prune	(plum)	[pʁyn]	[pʁym]	juteuses 'juicy' [ʒytøz]	sucrées 'sweet' [sykʁe:]	pourries 'rotten' [puʁi:]
reine	(queen)	[ʁɛn]	[ʁɛm]	généreuse'generous'[ʒeneʁøz]	respectée'respected'[ʁɛspɛkte:]	paresseuse 'lazy' [paʁɛsøz]
ride	(wrinkle)	[ʁid]	[ʁig]	légère 'light' [leʒɛʁ]	discrète 'discreet' [diskʁɛt]	gracieuse 'graceful' [gʁasjøz]
ruine	(ruin)	[ʁɥin]	[ʁɥim]	romaine 'Latin' [ʁomɛn]	célebre 'famous' [selɛbʁ]	baroque 'baroque' [baʁɔk]
stade	(stadium)	[stad]	[stab]	rénové 'renovated' [ʁenove]	démodé 'outdated' [demode]	bétonné 'concrete' [betone]
trone	(throne)	[tʁon]	[tʁom]	rocheux 'rocky' [ʁoʃø]	royal 'royal' [ʁwajal]	princier 'princely' [pʁɛ̃sje]
zone	(zone)	[zon]	[zom]	rurale 'rural' [ʁyʁal]	fluviale 'riverine' [flyvjal]	portuaire 'harbor' [pɔʁtɥɛʁ]
				Voicing		
badge	(badge)	[badʒ]	[batʃ]	métallique 'metallic' [metalik]	ravissant 'charming' [ʁavisɑ̃]	parfumé'perfumed' [paʁfyme]
cape	(cape)	[kap]	[kab]	longue 'long' [lɔ̃g]	neuve 'new' [nøv]	grise 'grey' [gʁiz]
chèque	(check)	[ʃɛk]	[ʃɛg]	mensuel 'monthly' [mɑ̃sɥɛl]	reçu 'received' [ʁəsy]	volé 'stolen' [vole]
couche	(layer)	[kuʃ]	[kuʒ]	neigeuse 'snow' [neʒøz]	marron 'brown' [maʁɔ̃]	jaunie 'yellowed' [ʒoni:]
coude	(elbow)	[kud]	[kut]	meurtri 'injured' [mœʁtʁi]	raidi 'rigid' [ʁedi]	tordu 'twisted' [tɔʁdy]
cuve	(tank)	[kyv]	[kyf]	mobile 'mobile' [mobil]	remplie 'full' [ʁɑ̃pli:]	fendue 'ripped' [fɑ̃dy:]
faute	(error)	[fot]	[fod]	majeure 'major' [maʒœʁ]	légère 'light' [leʒɛʁ]	discrète 'discreet' [diskʁɛt]
globe	(globe)	[glɔb]	[glɔp]	miroitant 'mirroring' [miʁwatɑ̃]	lumineux 'luminous' [lyminø]	pailleté 'sequined' [pajəte]
lac	(lake)	[lak]	[lag]	limpide 'clear' [lɛ̃pid]	nordique 'Nordic' [nɔʁdik]	gelé 'frosted' [ʒəle]
lave	(lava)	[lav]	[laf]	mouvante 'moving' [muvɑ̃t]	rugueuse 'cragged' [ʁygøz]	pateuse 'pasty' [pɑtøz]
nappe	(tablecloth)	[nap]	[nab]	rayée 'striped' [ʁɛje:]	rustique 'rustic' [ʁystik]	brodée 'embroidered' [bʁode:]
neige	(snow)	[nɛʒ]	[nɛʃ]	mouillée 'wet' [muje:]	marron 'brown' [maʁɔ̃]	poudreuse 'powder' [pudʁøz]
nuage	(cloud)	[nɥaʒ]	[nɥaʃ]	rosés 'rosy' [ʁoze]	nacrés 'pearly' [nakʁe]	chargés 'loaded' [ʃaʁʒe]
plaque	(plate)	[plak]	[plag]	noircie 'blacked' [nwarsi:]	rouillée 'rust' [ʁuje:]	brillante 'shiny' [bʁijɑ̃t]
robe	(dress)	[ʁɔb]	[ʁɔp]	rouge 'red' [ʁuʒ]	noire 'black' [nwaʁ]	sale 'dirty' [sal]
route	(road)	[ʁut]	[ʁud]	magnifique'beautiful'[maɲifik]	nationale 'main' [nasjonal]	dangereuse'dangerous'[dɑ̃ʒəʁøz]