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Exploring dyslexics' phonological deficit II: Phonological grammar

Gayaneh Szenkovits and Quynliaan Darma
CNRS, EHESS, ENS Paris, PSL Research University, France

Isabelle Darcy
CNRS, EHESS, ENS Paris, PSL Research University, France; Indiana University – Bloomington, USA

Franck Ramus
CNRS, EHESS, ENS Paris, PSL Research University, France

Abstract

Language learners have to acquire the phonological grammar of their native language, and different levels of representations on which the grammar operates. Developmental dyslexia is associated with a phonological deficit, which is commonly assumed to stem from degraded phonological representations. The present study investigates one aspect of the phonological grammar, phonological assimilation rules. Specifically, it examines whether dyslexic adults have acquired phonological rules in speech production normally, and whether they compensate for them in perception. Contrary to the 'degraded phonological representations hypothesis', these adults produced phonological assimilations, and perceptually compensated for assimilations to the same extent as control participants. This suggests that individuals with dyslexia have acquired the phonological rules of their native language normally, and implies that they must have well-specified phonological representations, at least with respect to the features tested here. Nevertheless, these dyslexic adults still exhibit the typical phonological deficit as measured by phonological awareness, verbal short-term memory and rapid automatic naming tasks. Thus, it is suggested that the explanation for their phonological deficit must lie elsewhere than in their phonological representations and grammar.

Corresponding author:
Franck Ramus, Laboratoire de Sciences Cognitives et Psycholinguistique, Ecole Normale Supérieure, 29 rue d'Ulm, 75230 Paris Cedex 05, France.
Email: franck.ramus@ens.fr

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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 widespread agreement that, at least in a majority of individuals with dyslexia, the main underlying cognitive cause is a so-called phonological deficit (Ramus, 2003; 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). Nonetheless, all views assume that the most proximal cause of the reading disability in dyslexia is the phonological deficit (Nicolson, Fawcett, & Dean, 2001; Stein, 2001; Tallal, 2004). Therefore, leaving aside the issue of distal causes, and focusing on the majority of people with dyslexia who do have a phonological deficit, the present study aims to further investigate the nature of that deficit, a matter of interest regardless of theoretical affiliation.

Nevertheless, the precise nature of the phonological deficit is still debated (Ramus & Szenkovits, 2008). The most broadly accepted view may be termed the 'degraded phonological representations hypothesis'. According to this view, phonological representations are somehow degraded in dyslexia. The nature of the presumed degradation is more or less specified and varies from author to author. It includes increased noise, phonetic under-specification, 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). However, this view has been increasingly challenged in recent years (Boets et al., 2013; Ramus, 2014; Ramus & Ahissar, 2012). One possible alternative hypothesis is that the phonological representations of dyslexic individuals are intact, but that their access and use is more difficult in certain tasks that particularly challenge conscious awareness, verbal short-term memory, or speeded access (Ramus & Szenkovits, 2008). New studies investigating fine-grained aspects of phonological representations and processes are needed to distinguish different hypotheses and unravel the nature of the phonological deficit.

Phonology is *par excellence* the discipline that studies phonological processes, and formalizes them as 'phonological grammar'. One of the main phenomena to be explained by phonology is the fact that a word can be pronounced differently depending on its surrounding words (or context). It has been shown that some of these variations (such as assimilations, liaisons, epentheses, elision, etc.) are systematic and depend on the precise phonological context in which they occur. This has led linguists to formulate abstract rules (or constraints) explaining the mapping between the underlying form of a word (the form that is stored in the mental lexicon) and its surface form (the one that is uttered) depending on the phonological context. The set of these abstract rules (or constraints) forms the phonological grammar (Chomsky & Halle, 1968; Clements, 1999; Prince & Smolensky, 1993). Furthermore, phonological grammar varies from language to language, therefore it must be acquired by each child by mere exposure, typically within the first few years of life (Peperkamp, 2003; Ramus et al., 2010).

Phonological grammar offers a new domain of investigation, within which the degraded phonological representations hypothesis may be further examined. Indeed, phonemes and/or phonetic features are intrinsically involved in the operations of the phonological grammar. Thus, according to any theory of dyslexia that postulates that these units are poorly represented by people with dyslexia, the reliability of their mapping processes between words' underlying and surface forms should be affected. Alternatively, disrupted phonological processes might reflect a deficit in phonological grammar itself (i.e. the rules acquired by the child), rather than in the representations. Such disruptions in either phonological representations or grammar might have cascading effects on other aspects of language development, eventually culminating in difficulties learning to read (Schiff & Lotem, 2011). In this article we consider a particular phonological process, assimilation, and test whether dyslexic individuals produce it, and compensate for it in speech perception and lexical access, and thus whether they have properly acquired the specific phonological rules of their native language.

Thus, just as Heather van der Lely used syntactic theory to help clarify the nature of language deficits in specific language impairment (SLI) (van der Lely, 1998, 2005), we propose to use phonological theory to achieve a deeper understanding of phonological deficits in dyslexia.

Phonological rules: Production and perceptual compensation

Some language-dependent 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 regressive place assimilation, taking on the place of articulation of the following obstruent in connected speech (Barry, 1985; Nolan, 1992). Hence the compound *football* may be realized as *foo[p]ball*, where the alveolar place of articulation of [t] is partly or fully changed into the labial place of articulation of the following [b]. In French, obstruents may undergo regressive voicing assimilation, taking the +/– voice feature from the following consonant if it is an obstruent (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, as 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 more difficult or problematic. However, surprisingly these changes seem to matter very little in everyday continuous speech recognition. In fact, most people are not even aware of the existence of these phonetic 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 (Darcy, Peperkamp, & Dupoux, 2007; Darcy, Ramus, Christophe, Kinzler, & Dupoux, 2009; Gaskell & Marslen-Wilson, 1996; Gow & Zoll, 2002; Mitterer & Blomert, 2003).

Thus, the phenomenon of assimilation, both in speech production and perception, is 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 non-dyslexic individuals.

So far, little is known about assimilation processes in dyslexia, in particular in speech production. Blomert, Mitterer, and Paffen (2004) tested compensation for place assimilation in Dutch dyslexic children. They found this process to be normal, although they reported that in one condition, dyslexic children tended to rely more than control children on contextual phonetic cues. Another study investigated compensation for place assimilation in English children with either dyslexia or SLI. While many children with SLI had some difficulties with the requirements of the task, children with dyslexia did not differ from age-matched control children (Marshall, Ramus, & van der Lely, 2010). Thus, the available evidence suggests normal compensation for place assimilation in dyslexic children, in two Germanic languages that have place assimilation processes.

The present study aims to extend these sparse findings in several ways. First, by investigating another language, French, that shows voicing, but not place assimilation. It is important to investigate phonology in dyslexia in a variety of languages, not only because writing systems differ across languages (Share, 2008), but also because phonological systems and their acquisition differ too (Saaristo-Helin, Kunnari, & Savinainen-Makkonen, 2011). Second, by directly comparing voicing and place assimilations processes, in order to distinguish acquired, language-dependent from potentially universal phonological processes (Darcy et al., 2009). And third, by investigating for the first time, not only compensation for assimilation in speech perception, but also the production of assimilations in speech.

Methods and materials

Participants

All participants were recruited through adverts in Parisian universities. They received €10.00 per hour of participation. Twenty self-declared dyslexic and 19 control participants of similar academic background and non-verbal IQ took part in the study. In order to ensure that they met pre-established inclusion criteria for dyslexia, they all went through a diagnostic battery. Application of the inclusion criteria and attrition reduced the sample to 10 dyslexic and 13 control participants in Task 1, and 14 dyslexic and 19 control participants in Task 2.

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 control participants: to report no known history of reading/oral language difficulties, and to have a reading age above the ceiling (14 years old) of the standardized reading test, and (4b) for dyslexic participants: self- and/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 to verify that all dyslexic participants had poor performance on those.

Diagnostic battery

Participants were tested in three separate testing sessions. In the first session, they took the diagnostic battery. The experimental battery was split over the next two sessions, one for the production and one for the perception task. Not all participants were able to attend both sessions, hence the slight mismatch in participant numbers.

Intelligence. Non-verbal intelligence was assessed with Raven's Advanced Progressive Matrices Set I and Set II (Raven, Raven, & Court, 1998). This comprises 36 test items to be completed in a time-limited condition (40 minutes). Set I was used to familiarize participants with the test, and Set II to calculate non-verbal IQ scores derived from the percentiles of United States norms (1993).

Literacy. *Reading skills* were assessed with 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 quickly and accurately. The standardized reading scores take into account both speed (total reading time) and accuracy (total reading errors). We used combined scores because in languages with a more regular orthography than English, reading accuracy can rapidly reach ceiling. Hence, reading scales have to incorporate a speed measure in order to detect dyslexia (Sprenger-Charolles, Colé, Lacert, & Serniclaes, 2000; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Korne, 2003).

Orthographic skills were assessed with a speeded orthographic choice task. Participants saw pairs of minimally different words (such as 'judiciaire – judicière') printed on the computer screen, and had to choose as quickly as possible the orthographically correct form.

Phonological skills. We assessed participants' phonological skills along the three main dimensions known to be impaired in dyslexia: verbal short-term memory, phonological awareness and rapid naming (Wagner & Torgesen, 1987).

Digit span was adapted 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 (such as 'fumée – bretelle') and were instructed to swap the first sound of the two words, then pronounce the resulting pseudo-words while maintaining their correct order ('bumée – fretelle').

Rapid automatic naming. Participants completed three versions of a rapid automatic naming test: picture and digit naming (two sheets of 50 objects or digits) adapted from the Phonological Assessment Battery (Frederickson, Frith, & Reason, 1997), and colour naming (two sheets of 50 colours). Participants were required to name the items accurately and as quickly as possible. 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 colour).

Task 1: Assimilation in speech production

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

Materials. The experimental items were drawn from Darcy et al. (2009). 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 was an obstruent providing 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 (dyslexic vs control). 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:

> 'Les sorcières portent une **cape grise** pour aller au bal' [ka**pg**riz] (assimilatory, voicing)
>
> 'Il a mis sa **cape neuve** sur le dossier de la chaise' [kapnœv] (non-assimilatory, voicing)
>
> 'Il habite dans une **zone portuaire**' [zo**np**ortyɛr] (assimilatory, place)
>
> 'Une **zone fluviale** est toujours dangereuse' [zonflyvjal] (non-assimilatory, place).

The complete list of sentences is given in Appendix 1.

Procedure. Participants 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 on a white background. 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, then the colour 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 4 seconds, and then the next sentence appeared. The experiment took approximately 15 minutes. There were 64 sentences (16 per context) recorded per participant.

For analysis of the recordings, the 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 had them rated by eight 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 (e.g. 'cabe' and 'cape' respectively). Raters had to indicate on a response box which orthographic form was the best transcription of each auditory item. Target words were split into seven blocks. Before beginning the experiment, participants had four unambiguous practice trials. The order of the target words, of the speakers, as well as the side (left/right) of the orthographic words on the screen were randomized. This post-test was programmed in E-prime (Schneider, Eschman, & Zuccolotto, 2002) and took approximately 80 minutes. Raters could have a break between blocks.

As a result of these post-test ratings, each participant's degree of assimilation of a given word in a given context was taken to be the mean rating of the eight raters. This was then analysed according to Feature (voicing, place) and Context (assimilatory, non-assimilatory).

Task 2: Perceptual compensation for assimilations

Materials. The target items were the same as for the production experiment (Appendix 1) and are fully listed in Tables 7 and 8 in Darcy et al. (2009). They include the same two sets of sentences (Voicing and Place) as in the production experiment. In addition, 120 pseudo-words were created as the fully assimilated version of each target noun. Half were created by switching the voicing feature of the final obstruents (e.g. robe [rob]'dress'→ rope [rop]; and lac [lak] 'lake'→ lague [lag]); and half, by changing the place of articulation of the final consonant (e.g. moine [mwan] 'monk'→ moime [mwam]; or guide [gid] 'guide' → guibe [gib]). Each target noun (or the corresponding assimilated pseudo-word) was associated with three adjectives, leading to three conditions:

- Viable change (fully assimilated noun in a viable assimilatory context);
- Unviable change (fully assimilated noun in a non-assimilatory context);
- No change (unassimilated noun in a non-assimilatory context).

In the Voicing set, half of the assimilatory contexts yielded voicing assimilation (e.g. cape grise [kabgriz]), and half devoicing assimilation (e.g. robe sale [ropsal]). The association between (pseudo-)noun and adjective always yielded a legal consonant cluster in French.

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 nine 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 distracters (12 trials).

Sample sentences are:

‘Les sorcières portent une **[kab] grise** pour aller au bal’ [kabgriz] (viable change, voicing)

‘Il a mis sa **[kab] neuve** sur le dossier de la chaise’ [kabnœv] (unviable change, voicing)

‘La petite fille a jeté sa **cape longue**’ [kaplõg] (no change, voicing)

‘Il habite dans une **[zom] portuaire**’ [zompɔrtyɛr] (viable change, place)

‘Une **[zom] fluviale** est toujours dangereuse’ [zomflyvjal] (unviable change, place)

‘Les **zones rurales** sont souvent magnifiques’ [zonryral] (no change, place).

All sentences were recorded by a female native speaker of French, and all target words were recorded by a male native speaker of French. Recordings 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) software.

Procedure. Participants 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 was accomplished, the experiment began, 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. Their task was to decide whether the target word (e.g. ‘cape’) appeared correctly pronounced in the sentence or not. In the No change condition, the target word appeared identically in the sentence (which was the baseline for word detection, e.g. ‘cape longue’ [kaplõg]). In the non-assimilatory context condition, the target word appeared ‘mispronounced’ in the sentence, hence giving rise to a pseudo-word. This condition was the baseline for word rejection, e.g. ‘cabe neuve’ [kabnœv]. And finally, in the assimilatory context condition, the target word also appeared ‘mispronounced’ in the sentence, thus becoming a pseudo-word, but in a legal assimilatory context that promoted that particular pronunciation (e.g. cabe grise’ [kabgriz]). Participants were instructed and trained to respond ‘YES’ if the target word was included and correctly pronounced in the sentence, and ‘NO’ in all other cases. Participants were allowed 3000 ms after the target word onset to make their response before 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.

In a nutshell, a perfect native listener would be expected to always respond YES in the No change and NO in the Unviable change conditions. In the Viable change condition, the percentage of YES responses reflects the degree to which the listener compensates for this type of assimilation. As shown by our previous study (Darcy et al., 2009), this degree of compensation is high for a native assimilation (in French, of the voicing feature) but low for a non-native one (in French, of the place feature).

Predictions

If dyslexic participants' representations of native phonemes are degraded, or simply different from those of control participants, one would broadly predict (1) to obtain overall noisier data for dyslexic participants (because of less precise production/perception of target phonemes), and (2) to observe decreased sensitivity to the Context factor, because the phonological Context where assimilation may occur would also be poorly represented.

Regardless of the quality of their phonological representations, if, during language acquisition, individuals with dyslexia fail to acquire the implicit phonological rules of their native language for speech production, they might (1) produce no assimilations at all; or (2) produce a universal pattern of assimilations, that is those occurring in all languages, but unaffected by the specific rules and contexts defined by their native language phonology; or (3) produce generalized assimilations such 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).

Similarly, if dyslexic participants fail to acquire native compensation for assimilation processes, one would predict them (1) to compensate less, if at all, for assimilations that exist in their native language; or (2) to compensate for a universal pattern of assimilation, but not specifically for that defined by the phonology of their native language (they thus would show no difference between place and voicing assimilation); or (3) to over-compensate, that is, to have a tendency to compensate regardless of Context, even in the Unviable change condition.

In sum, these predictions converge in predicting that if dyslexic participants have not acquired the assimilation rules of their native language (whether in production or in perception), they should be less (if at all) sensitive to both factors Context (where assimilation may occur) and Feature (segment types and phonetic features that undergo assimilation in their native language), and should show a lower (if at all) Context × Feature interaction, which crucially reflects the fact that speakers only produce and compensate for native (voicing) assimilations, and only in viable contexts.

Finally, if dyslexic individuals both have intact phonological representations, and have acquired phonological grammar normally, their performance should not differ from that of control participants.

Results

Psychometric data

Following the analyses, six presumed dyslexic participants were excluded from our cohorts, because they did not match the inclusion criteria. Therefore there remained 19 control and

Table 1. Psychometric data: Mean scores and (standard deviations). The data from the orthographic choice and the spoonerisms tasks capture both accuracy and speed.

	Controls (n = 19)	Dyslexics (n = 14)	One-way ANOVAs
Age	23.57 (3.65)	22.5 (3.56)	$F(1,31) < 1$, ns
Non-verbal IQ[a]	115 (12.7)	109.67 (11.77)	$F(1,31) = 1.4$, ns
Digit span[b]	11.15 (2.83)	7.14 (2.53)	$F(1,31) = 17.64$, $p < .0001$
Spoonerisms[c]	0.15 (0.06)	0.04 (0.04)	$F(1,31) = 35.26$, $p < .0001$
Reading[d]	72.3 (7.04)	137.2 (35.67)	$F(1,31) = 60.5$, $p < .0001$
Orthography[e]	0 (1)	−2.17 (1.14)	$F(1,27) = 29.49$, $p < .0001$
RAN[f]			
Object	54.71 (6.64)	75.05 (12.35)	$F(1,31) = 37.2$, $p < .0001$
Digit	27.09 (4.63)	38.34 (6.05)	$F(1,31) = 36.65$, $p < .0001$
Colour	47.33 (8.12)	62.21 (10.67)	$F(1,31) = 20.71$, $p < .0001$
RAN average z-score	0 (1)	−3.11 (1.35)	$F(1,31) = 57.9$, $p < .0001$

[a]Raven's 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]z-transformed orthography scores of 29 participants (4 participants have no data). These scores capture both response time and accuracy (Accuracy/RT*1000).
[f]Sum of naming speed (sec) of the two passages for each rapid automatic naming test.

14 dyslexic participants, whose results are summarized in Table 1. One-way ANOVAs revealed significant group differences on all variables but age and non-verbal IQ.

All of them participated in Task 2, and a subset of 10 dyslexic and 13 control participants took part in Task 1. This subset remained matched on age and non-verbal IQ, and different on all other variables.

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. Z-scores were computed relative to the control group's mean and standard deviation for each test. 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 dyslexic individuals with a phonological deficit.

Task 1: Assimilation in speech production

One pair of sentences from the Voicing set was excluded from the analyses because it did not include the correct assimilation context. The analyses were run on percentage of unassimilated words. 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 × Feature interaction, $F(1,21) = 45.8$, $p < .001$, without any Group effect, $F < 1$. Furthermore, none of the interactions with the factor Group reached

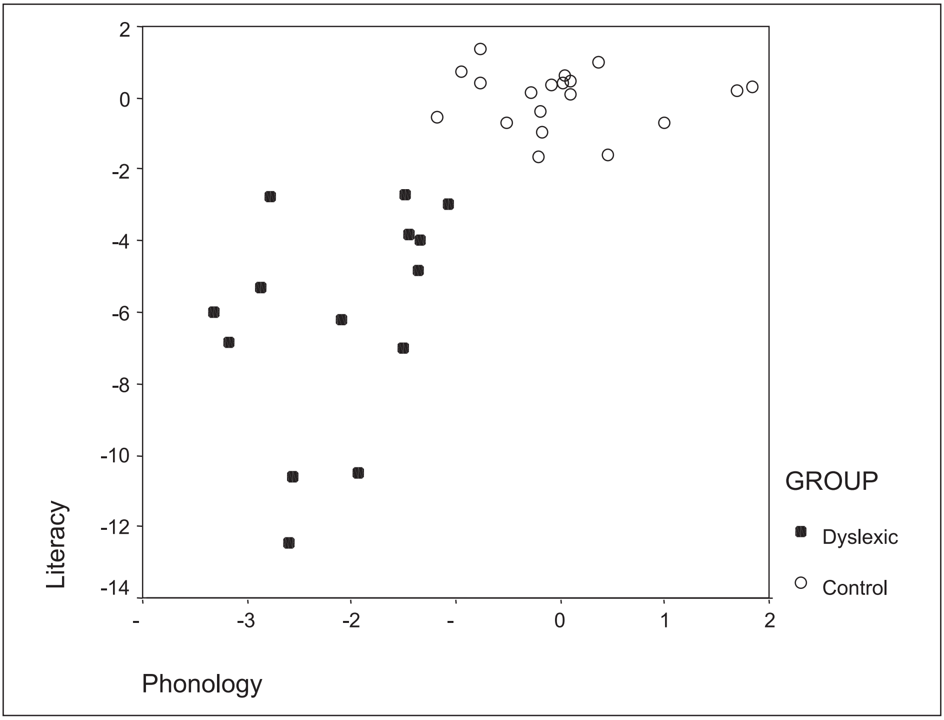

Figure 1. Participants' distribution along phonology and literacy factors.

significance (Feature × Group, Context × Group and Context × Feature × Group; all Fs < 1). Table 2 and Figure 2 show the percentage of unassimilated word production in each condition.

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

Task 2: Perceptual compensation for assimilations

Word detection rates are reported in Table 3 and Figure 3(a). Of the six conditions, only one showed a nominally significant group difference: in the Unviable change condition of the Voicing context, dyslexic participants' word detection rate was 29.7%, and 17% for controls, $F(1,31) = 4.61$, $p = .04$. However this would not survive a correction for multiple tests (a Bonferroni correction would yield a threshold of 0.008).

Table 2. Task 1. Mean percentage of unassimilated words produced (standard deviation).

	Voicing						Place					
	Assimilatory			Non-assimilatory			Assimilatory			Non-assimilatory		
	M (SD)	Min	Max	*M* (SD)	Min	Max	*M* (SD)	Min	Max	*M* (SD)	Min	Max
Controls	60 (25)	29	93	89 (6.3)	79	98	95 (2.7)	91	99	95.4 (2)	93	100
Dyslexics	60 (19)	22	80	86 (7.8)	73	96	95 (2.8)	91	99	96 (2.2)	91	98

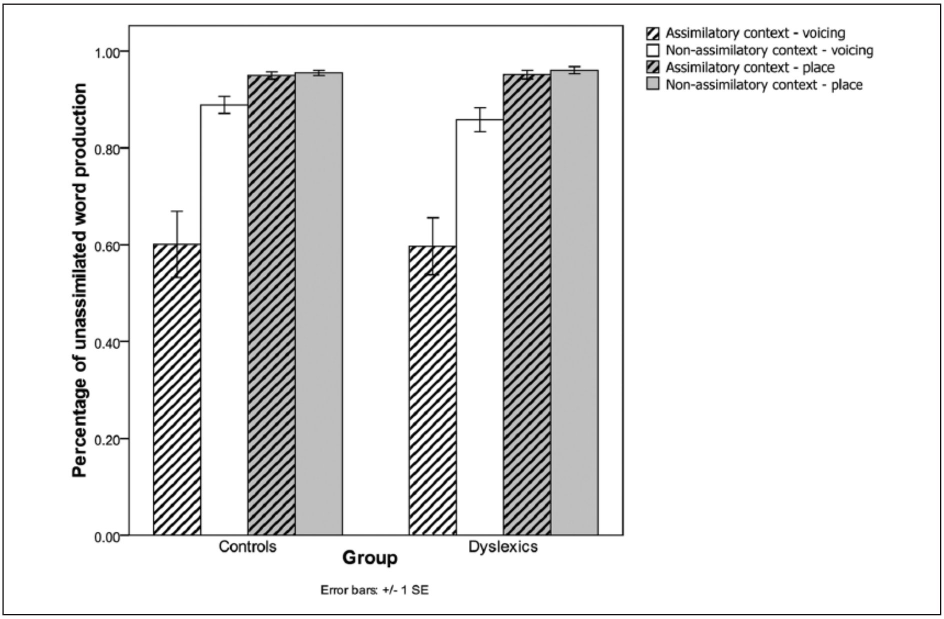

Figure 2. Task 1. Percentage of unassimilated word production for each group, according to Context (assimilatory context for voicing – cross-hatched bars, and non-assimilatory context – plain bars) and Feature (voicing – white background, and place – grey background). Error bars represent the standard error of the mean.

Consistently with the analysis in Marshall et al. (2010), signal detection theory was used in order to account for word detection and response bias (Macmillan & Creelman, 2005). To do so, data were transformed into Hit and False Alarm (FA) rates. The design of the current experiment leads to the computation of two Hit rates, allowing the further computation of two d' scores:

1. A compensation hit rate, which is the percentage of word detection in the Viable change condition, and
2. A baseline hit rate, corresponding to the percentage of word detection in the No change condition.

Table 3. Task 2. Mean percentage words detected and d' (standard deviation). Panel A: Voicing, Panel B: Place.

A.	Voicing								
	Viable change			Unviable change			No change		
	M (SD)	Min	Max	*M* (SD)	Min	Max	*M* (SD)	Min	Max
% Word detection*									
Controls	79 (18)	38	97	17 (12)	3	44	96 (2.2)	88	97
Dyslexics	85.3 (0.02)	69	94	29.7 (0.06)	7	69	97.8 (0.012)	88	97
	Compensation			Word detection			Bias		
	M (SD)	Min	Max	*M* (SD)	Min	Max	*M* (SD)	Min	Max
d'									
Controls	2.06 (0.44)	1.2	2.7	2.8 (0.5)	1.7	3.7	–1.09 (0.5)	−1.86	−0.15
Dyslexics	1.8 (0.76)	0.7	3.1	2.4 (0.8)	0.7	3.4	–0.07 (0.7)	−1.51	0.5

B.	Place								
	Viable change			Unviable change			No change		
	M (SD)	Min	Max	*M* (SD)	Min	Max	*M* (SD)	Min	Max
% Word detection									
Controls	36 (18)	3	69	16 (12)	3	38	96 (2.3)	88	97
Dyslexics	34.3 (0.061)	7	82	16 (0.036)	3	46	98.2 (0.007)	94	97
	Compensation			Word detection			Bias		
	M (SD)	Min	Max	*M* (SD)	Min	Max	*M* (SD)	Min	Max
d'									
Controls	0.7 (0.5)	−0.3	2	2.9 (0.6)	1.5	3.7	−1.1 (0.5)	−1.86	−0.31
Dyslexics	0.6 (0.4)	0	1.2	2.9 (0.5)	1.9	3.4	−1.09 (0.5)	−1.86	−0.1

*$p < .05$ uncorrected.

The False Alarm rate corresponds to the percentage of (incorrect) word detection in the Unviable change context. The two d' scores were computed as follows:

1. Compensation d' = z(compensation hit rate) – z(FA). This reflects the degree to which a participant perceives an assimilated word in an assimilatory context to be the target word;
2. Word detection d' = z(baseline hit rate) – z(FA). This reflects the degree to which a participant perceives an unassimilated word to be the target word. It therefore indexes performance in the word detection task.

Z is the inverse of the normal distribution function
The bias towards the word detection response was also computed as z(FA).

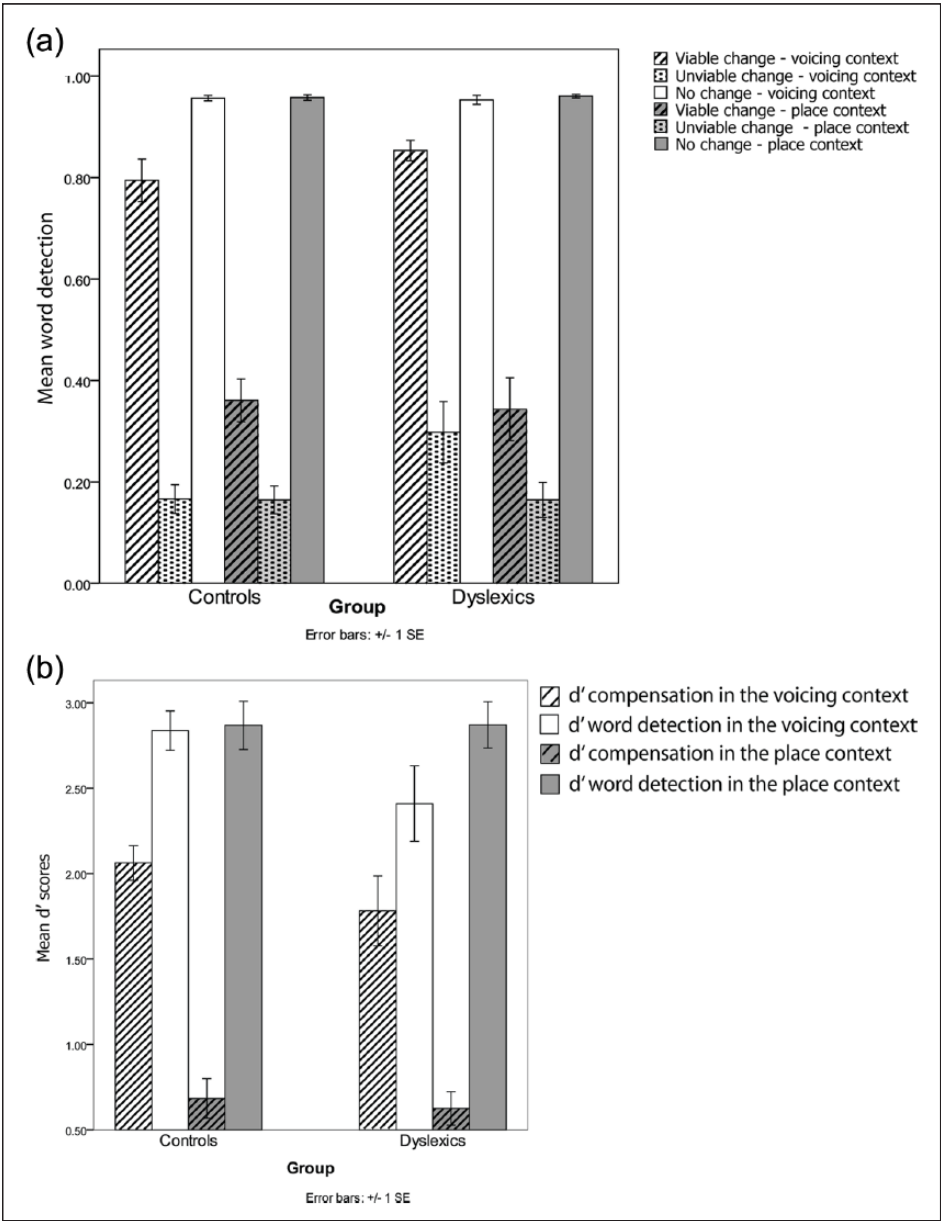

Figure 3. Task 2. (a) Mean % word detection according to Feature (voicing – bars with white background, and place – grey background) and Condition (Viable change – cross-hatched bars, Unviable change – dotted bars, No change – plain bars) for each group. (b) Mean d' scores according to Feature (voicing – white background and place – grey background) and Condition (compensation d' – cross-hatched bars, word detection d' – plain bars). Error bars represent one standard error of the mean.

Table 3 and Figure 3(b) show the mean d' scores for Features (voicing and place) in each Condition (Compensation, word detection).

A repeated-measures ANOVA was run on the d' scores with Feature (voicing vs place), Condition (compensation vs word detection) and Group (dyslexic vs control) factors. This revealed significant main effects of Feature, $F(1,31) = 21.5$, $p < .0001$, and Condition, $F(1,31) = 375.16$, $p < .0001$, and a Feature × Condition interaction, $F(1,31) = 108.7$, $p < .0001$, but no Group effect, $F(1,31) = 2$, $p = .17$, ns. None of the possible interactions with Group reached significance (Feature × Group, $F(1,31) = 2.18$, $p = .15$, ns; Condition × Group, $F(1,31) < 1$, ns; Feature × Condition × Group, $F(1,31) < 1$, ns). Because some p values are below .2 and our statistical power may be somewhat limited, we have also carried out a Bayesian analysis following the method described by Masson (2011). For the group effect, the Bayes factor is BF = 2.09 and the posterior probability of the null hypothesis $p(H0|D) = .68$. For the Feature × Group interaction, BF = 1.94 and $p(H0|D) = .66$.

Another repeated-measures ANOVA was run on the bias scores with factors Feature (voicing vs place) and Group (dyslexic vs control). This analysis did not reveal any significant effects (Feature, $F(1,31) = 1.9$, $p = .17$, ns; Group effect, $F(1,31) = 2.7$, $p = .11$, ns, BF = 1.55, $p(H0|D) = .61$; and Feature × Group, $F(1,31) = 1.67$, $p = .2$, ns, BF = 1.94, $p(H0|D) = .66$).

These results indicate that participants compensated for assimilation more in the assimilatory (about 80% of the time for voicing) than in the non-assimilatory context (between 15 and 30%) (main effect of Condition), and more so for voicing than for place assimilation (80% for voicing but 30–40% for place; main effect of Feature). Furthermore, none of these effects differed between groups. Thus, both groups compensated to the same extent for assimilation, and this was modulated by whether the assimilation was native (voicing) or non-native (place), to the same extent in both groups.

Discussion

In the present study, we brought phonological theory to bear on the nature of the phonological deficit in development dyslexia. We focused on systematic variations introduced by speakers in their production of words (assimilations), and on their perceptual ability to compensate for these variations in order to reliably recognize lexical items in the speech of others. Because these assimilations and their perceptual compensation apply only to specific phonetic features in specific phonological contexts, these mechanisms provide a means to probe the integrity of one's phonological representations and grammar. Furthermore, because these processes are to a large extent language-dependent, they also offer the opportunity to probe the extent to which one's phonological representations and grammar have been shaped by the acquisition of a native language. Thus, these phenomena provide an invaluable opportunity to further refine our understanding of the nature of the phonological deficit in development dyslexia. 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 Task 1, an elicited speech production task, we recorded participants' speech production and then used naïve listeners to quantify how frequently they produced assimilations in each context. The 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 other contexts; and as expected, they do not produce place assimilations in contexts where this would be legal in English. Furthermore, we find that dyslexic French native speakers produce exactly the same assimilations as control participants.

In Task 2, 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. The results fully replicate those of Darcy et al. (2009) and mirror those obtained in production: French listeners compensate most of the time for voicing assimilations (80%), but only when these occur in native assimilatory contexts. Furthermore, they compensate to a much smaller extent for place assimilations (around 30%), possibly reflecting universal compensation processes. Dyslexic participants do exactly the same in all respects, consistent with two previous studies (Blomert et al., 2004; Marshall et al., 2010).

According to various versions of the 'degraded phonological representations hypothesis', dyslexic participants should have shown in both experiments overall less reliable responses, and a decreased Context effect, reflecting their less precise representations of phonological contexts, and their less precise production and perception of phonetic features. According to a slightly different hypothesis, according to which dyslexic individuals acquire less well the phonological grammar of their native language, they should have shown again, in both experiments, a decreased Context effect, and a decreased Context × Feature interaction, reflecting their weaker sensitivity to the rules characterizing their native language.

None of these predictions was supported. We have consistently failed to find any group difference, and any interaction between group and the other factors. Our results suggest that dyslexic individuals have acquired these aspects of the phonological grammar of their native language normally, that they apply them adequately in production, compensate for them in perception, and do so exclusively in the phonological contexts expected in their native language. Furthermore, in order to do so, they must have fairly good representations of the phonological features that are assimilated (place and voicing) and of the phonological contexts in which they can or cannot be assimilated (plosive and fricative features). This runs against any variant of the degraded phonological representations hypothesis that involves a degradation of voicing or place features. As far as we know, all studies reporting a speech perception deficit in dyslexia involve either place or voicing (Noordenbos & Serniclaes, 2015).

One might also argue that the degradation could be so subtle as not to affect the use of these phonetic features in phonological processes and grammar. After all, phonological awareness and reading may well put more demands on the phonological system than online speech perception and production, such that phonological deficits may surface more easily in these particular tasks than in more implicit speech perception and production tests. This is almost certainly true. However, the degraded phonological representations hypothesis contends that phonological deficits are also evident in more simple tasks reflecting more directly the nature of phonological representations, such as phoneme discrimination and categorization tasks. If that hypothesis were correct, one would expect to also observe deficits in our sentence production and word detection tasks. Yet we do not. The results we obtained here suggest that dyslexic individuals have both intact phonological representations and a normal phonological grammar, or that if their phonological representations or grammar are affected, they are so subtly affected as to seriously diminish the plausibility of such degradation significantly affecting reading acquisition.

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, and we may have had limited statistical power to detect small effects. For the sake of argument, let us consider group effects or interactions that come closest to statistical significance. In the raw data (Table 3 and Figure 3(a)), there is only one condition in which dyslexic participants marginally differ from controls, the Unviable change – voicing context condition. In that condition, people with dyslexia have a tendency to detect the word slightly more frequently than controls, i.e. they have a numerically higher False Alarm rate. Note that the fact that such a trend is not observed for the place contrast, if anything, does not increase confidence in this tendency. This then translates into a numerically smaller d', both for compensation (1.8 vs 2.06) and for word detection (2.4 vs 2.8). Thus, assuming that this difference is reliable at all, this would only show that dyslexic participants have an overall more liberal bias (–.07 vs −1.09, $p = .11$) for word detection than controls, a similar finding as in Marshall et al. (2010). Thus, at most, dyslexic participants may be slightly less confident about mispronunciations, and more likely to give the speaker the benefit of the doubt. However, despite this bias, their compensation for assimilation is at the same level as for controls, and the specificity of that compensation to language-specific assimilations is the same as for controls.

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 dyslexic participants 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, as illustrated in Figure 1. Therefore, there is good evidence that these participants were dyslexic with a phonological deficit as generally understood.

To conclude, our results suggest that dyslexic individuals acquire at least some phonological grammatical rules normally, and that they must have fairly well specified phonological representations, at least for the voicing and place 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 it is consistent with many other studies (Boets et al., 2013; Hazan, Messaoud-Galusi, Rosen, Nouwens, &

Shakespeare, 2009; Marshall, Harcourt-Brown, Ramus, & van der Lely, 2009; Marshall et al., 2010; Messaoud-Galusi, Hazan, & Rosen, 2011; Mundy & Carroll, 2012, 2013; Ramus, Marshall, Rosen, & van der Lely, 2013; Soroli, Szenkovits, & Ramus, 2010; reviewed in Ramus & Ahissar, 2012; Ramus & Szenkovits, 2008).

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Appendix 1

Materials for the production task

Table A1. Sentences of the voicing assimilation set. Each sentence is listed first in assimilatory context, then in neutral context. Target nouns are indicated in bold.

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

Table A2. Sentences of the place assimilation set. Each sentence is listed first in assimilatory context, then in neutral context. Target nouns are indicated in bold.

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