Phonemic feature involvement in lexical access in grades 3 and 5: Evidence from visual and auditory lexical decision tasks

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Abstract

Numerous studies have evidenced the involvement of the phonological code during visual word recognition not only in skilled adult readers but also in child readers. Moreover, in skilled adult readers, visual word processing has been shown to be sensitive to phonetic details such as phonemic features (e.g., manner of articulation, place of articulation, voicing and nasality in French) which are typically involved in phonological lexicon access during speech processing. In contrast, it is not known whether and when visual word recognition is affected by phonemic features during learning to read. The present study investigates this issue in third and fifth graders. A lexical decision task was performed in visual and auditory modalities. Targets were French words (e.g., *piano* [piano]) and pseudowords created from target words. Mismatching was on the first phoneme. There were one- feature phoneme mismatch pseudowords (e.g., *tiano*) and multiple-feature phoneme mismatch pseudowords (e.g., *liano*). The pseudowords were used as a marker of the sensitivity to phonemic features in phonological lexicon access. Phonemic feature effects were found in visual and auditory lexical decision tasks in both grades, indicating that phonological lexicon access involves phonemic features in print processing as in speech pro- cessing. In contrast, the absence of difference between both grades seems to indicate that this effect is in- dependent of age or, more precisely, of phonological development and reading performance.

Keywords : Word recognition Children Phonology Phonemic feature
Lexical decision task

1. Introduction

The phonological code is known to play a critical role in lexical access during visual word recognition in skilled adult readers (for re- views, see Berent & Perfetti, 1995; Frost, 1998; Rastle & Brysbaert, 2006; Van Orden, Pennington, & Stone, 1990) and child readers (e.g., Booth, Perfetti, & MacWhinney, 1999; Goswami, Ziegler, Dalton, & Schneider, 2001; Grainger, Lété, Bertand, Dufau, & Ziegler, 2012; Johnston, Rugg, & Scott, 1988; Johnston & Thompson, 1989; Sauval, Casalis, & Perre, 2016; Ziegler, Bertrand, Lété, & Grainger, 2014). Furthermore, it has been shown in skilled adult readers that visual word recognition is sensitive to phonemic features (Lukatela, Eaton, Lee, & Turvey, 2001) that are typically involved in speech processing (Connine, Blasko, & Titone, 1993). On the other hand, it is not known whether the phonological code is involved at such a detailed level in visual word recognition in children. This is an important issue because it might show the development of the deep inter-connection between the written word and speech processing systems and the importance of creating close links between orthography and phonology during learning to read (Hatcher, Hulme, & Ellis, 1994). The present experiment attempted to provide evidence for the involvement of phonemic features in lexical access during reading development.

Numerous studies in skilled adult readers have shown that written word recognition involves activation of the phonological lexicon (Ferrand & Grainger, 1992, 1993, 2003; Grainger & Ferrand, 1996; Perfetti, Bell, & Delaney, 1988; Van Orden, 1987; Ziegler, Ferrand, Jacobs, Rey, & Grainger, 2000; for a review see Berent & Perfetti, 1995; Frost, 1998; Rastle & Brysbaert, 2006). Recent data obtained in skilled adult readers suggest that visual word processing is affected by pho- netic details that are typically used in spoken language processing such as vowel length, stress and phonemic features (Ashby, Sanders, & Kingston, 2009; Cooper, Cutler, & Wales, 2002; Lukatela et al., 2001; Lukatela, Eaton, Sabadini, & Turvey, 2004). Phonemic features char- acterize phonemes. For French consonantal phonemes, phonemic fea- tures are the manner of articulation, the place of articulation, voicing and nasality. Consonants are phonologically close when they share three phonemic features (e.g., /z/ and /s/ share the place and manner of articulation and nasality) and phonologically distant when they share fewer than three phonemic features (e.g., /v/ and /s/ share only the manner of articulation and nasality). In a masked priming

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experiment performed in skilled adult readers, Lukatela et al. (2001) found a phonemic feature effect: visual words were recognized faster when the visual masked prime was a pseudoword phonologically close to the target (e.g., ZEA-sea) than when it was a pseudoword phonolo- gically distant from the target (e.g., VEA-sea). This indicates that the orthographic code automatically activates the phonological code at a level as fine as sub-phonemic units during visual word recognition. Lukatela et al. (2001) suggested that the visual word recognition system is deeply inter-connected with the spoken word recognition system in skilled adult readers.

As mentioned above, spoken word processing involves phonetic details such as vowel length, stress and phonemic features (Friedrich, Schild, & Röder, 2009, Soto-Faraco, Sebastián-Gallés, & Cutler, 2001, in adults; Gerken, Murphy, & Aslin, 1995; Schild, Röder, & Friedrich, 2011; Swingley, 2003, in children). Studies in skilled adult readers have investigated phonological lexicon activation by varying the degree of matching between the auditory item and the phonological lexical re- presentation (e.g., Connine et al., 1993; Dumay et al., 2001; Friedrich, 2005; Friedrich, Kotz, Friederici, & Gunter, 2004; Slowiaczek, Nusbaum, & Pisoni, 1987; Soto-Faraco et al., 2001), especially by ma- nipulating phonemic features (e.g., Andruski, Blumstein, & Burton, 1994; Cole, 1973; Connine, Titone, Deelman, & Blasko, 1997; Friedrich et al., 2009; Milberg, Blumstein, & Dworetzky, 1988; Schild, Röder, & Friedrich, 2012). In a priming experiment using pseudowords as primes, Connine et al. (1993) showed that the target NUMBER was recognized faster when the prime was a one-feature phoneme mismatch pseudoword (/'mʌmbəʳ/) than when it was a multiple-feature phoneme mismatch pseudoword (/'kʌmbəʳ/). This result supports the idea that lexical activation depends on the number of phonemic features shared between the spoken item and the lexical representation.

The bi-modal interactive-activation model (BIAM; e.g., Diependaele, Ziegler, & Grainger, 2010; Grainger & Ferrand, 1994; Grainger, Kiyonaga, & Holcomb, 2006; Grainger & Ziegler, 2011; based on the interactive-activation model of McClelland & Rumelhart, 1981) combines spoken and written input and processing in a single model. In the BIAM, the description of spoken language processing is based on the TRACE model of speech perception (McClelland & Elman, 1986), which is organized into three levels of processing: feature, phoneme and word. Lexical activation depends on the number of phonemes activated and their activation level, which depends on the number of phonemic fea- tures activated by speech (see note[1] for a detailed explanation). This means that the BIAM takes phonemic features in lexicon activation from speech into account. Regarding written language processing, a visual word stimulus first activates a set of visual features, which in turn activates the grapheme representations. A central interface between orthography and phonology (O ⇔ P) enables grapheme representations to be mapped onto their corresponding phoneme representations. Thus,
a set of phoneme representations is activated and spreads activation to phonological lexical representations. Even if connections between phoneme and phonemic feature representations are present in the BIAM model, the authors did not report any involvement of phonemic fea- tures in phonological lexical activation during visual word processing. At the lexical level, connections between orthographic and phonolo- gical representations also influence the course of visual word recogni- tion.

In children, the phonological code is known to be involved in word reading (e.g., Booth et al., 1999; Goswami et al., 2001; Grainger et al., 2012; Johnston et al., 1988; Johnston & Thompson, 1989; Sauval et al., 2016; Ziegler et al., 2014). In a lexical decision task, Grainger et al. (2012) showed that the phonological code was involved from first to fifth grade and in skilled adult readers. This involvement decreased as reading level increased. These results suggest that phonological med- iation is essential at the beginning of learning to read, i.e. during the phonological recoding phase, and that its impact remains even when reliance on orthographic processing increases, namely when words are familiar and recognized automatically without recourse to phonological recoding (Booth et al., 1999; Sauval, Perre, & Casalis, 2017; Ziegler et al., 2014). In children, involvement of the phonological code during visual word recognition has always been studied at lexical or phonemic levels and, to our knowledge, phonological involvement at phonemic feature level has not yet been investigated (for a study in pre-reader children, see Rack, Hulme, Snowling, & Wightman, 1994). It is still not known whether phonemic features are activated during print proces- sing and, if so, whether phonemic features are involved from the onset of visual word recognition or whether this occurs more with age and as relationships between orthography and phonology become deep and finely tuned (Lukatela et al., 2001). The aim of this study was to ex- amine this issue in children, who mostly use word recognition to pro- cess reading, i.e. after the stage of phonological recoding. The present study therefore focused on two stages of learning to read: third and fifth grades.

We investigated this issue using a lexical decision task. This task has two advantages: (1) it does not require the spoken phonological code, unlike a naming task; and (2) it is not a simple binary choice such as deciding whether a stimulus is red or blue but involves different pro- cesses according to the type of items (words vs. pseudowords). In a lexical decision task, words are processed more accurately and faster than pseudowords. The “yes” decision (“it is a word”) is a function of lexical activity (mainly dependent on word frequency) generated by the stimulus, whereas the “no” decision (“it is not a word”) is determined by how much the pseudoword looks like a real word (e.g., Binder, Medler, Westbury, Liebenthal, & Buchanan, 2006; Rubenstein, Richter, & Kay, 1975; Stanners, Forbach, & Headley, 1971). The more the pseudoword resembles a real word, the greater the amount of lexical activity and the less the “no” answer is accurate (there are more errors) and quick (for models, see the diffusion model, Ratcliff, Thapar, Gomez, & McKoon, 2004; the Bayesian reader model, Norris, 2009; the multiple read-out model, Grainger & Jacobs, 1996; or the leaky competing ac- cumulator model, Dufau, Grainger, & Ziegler, 2012). In our experiment, we focused on the “no” response it because reflects the amount of lexical activity generated by pseudowords.

We created two types of pseudowords by varying the number of phonemic features shared with the French target words, hereafter called basewords. The phonologically close pseudowords varied in only one phonemic feature (e.g., *tiano* from *piano* [piano]) whereas the phonologically distant pseudowords varied in multiple phonemic fea- tures (e.g., *liano* from *piano*). The pseudowords were used as a marker of the degree of precision with which the phonological lexicon is activated during visual word recognition. Our hypotheses were the following: (1) if phonemic features are involved in lexical access from visual stimuli (Lukatela et al., 2001), then a phonemic feature effect may be expected,
i.e. it should be harder to reject the one-feature phoneme mismatch pseudoword (e.g., *tiano*) than the multiple-feature phoneme mismatch pseudoword (e.g., *liano*); and (2) if phonological code activation during visual word recognition becomes more precise with age and thus finer, then the phonemic feature effect should be stronger in fifth grade than in third grade. Additionally, an auditory lexical decision task using the same material was performed in order to ensure that children in both grades activated phonological lexical representations at a phonemic feature level of precision (Schild et al., 2011). In the auditory lexical decision task, we expected the same pattern of results in both grades,
i.e. a lexical effect and a phonemic feature effect.

[1] The architecture of the TRACE model (McClelland & Elman, 1986) consists of a large number of units organized into three levels: feature, phoneme and word. Input is sent sequentially to the feature unit level in successive slices as the speech stream unfolds over time. The speech cue determines a pattern of activation over the feature units. Each ac- tivated feature activates all the phonemes including this feature. Given that phonemes receive activation from one or more features, the phoneme activation level is proportional to the input pattern from the feature level. Furthermore, phonemes send activation to all words including these phonemes. The word activation level depends on the number of phonemes activated and their activation level. Excitatory feedback is also sent from lexical to phoneme level and from phoneme to feature level.

2. Method

2.1. Participants

Children were 37 third graders (mean age = 8 years, 11 months, SD = 3 months) and 38 fifth graders (mean age = 10 years, 10 months, SD = 4 months). All participants were native speakers of French. The participants' reading level was evaluated using the standardized Alouette-R test (Lefavrais, 2005), which is a text-reading task. This task was used to ensure that all readers were reading at the expected grade level and to exclude children with potential reading impairment. Children with a reading score on the Alouette-R reading test of 24 months below the expected level were excluded from the study. The mean reading age was 8 years, 11 months (SD = 12 months) in third graders and 10 years, 7 months (SD = 14 months) in fifth graders. Reading instruction at school was based on phonics, i.e. teaching the correspondence between sounds and graphemes. All participants had normal or corrected-to-normal vision. According to their teachers, none of them had any language impairment or learning difficulties. All children had normal hearing (ELDP; Macchi et al., 2012). Informed parental consent was obtained for all participants included in the study. The protocol followed the general ethics rules defined by the Helsinki guidelines for human experiments and was in accordance with the principles of the Declaration of Helsinki (World Medical Organization, 1996).

2.2. Materials

A set of 43 words (mean length = 7.00 letters, SD = 0.93; range: 5–8) was used as the basewords for the pseudowords. The mean fre- quency of the words was 117 occurrences (range: 5–722) per million (SD = 142) according to the Manulex database (Lété, Sprenger- Charolles, & Colé, 2004) and most were nouns (84%). All basewords began with a consonant which was changed to form pseudowords in the two conditions. To minimize interactions at the lexical level (Ziegler & Muneaux, 2007), we selected basewords without phonological or or- thographic neighbors and for which the pseudowords created did not have phonological (except for one pseudoword in each condition, $F < 1$) or orthographic (except for 7 and 5 pseudowords, respectively in each condition, $F < 1$) neighbors besides the baseword itself. The two types of pseudowords were created (see Appendix A) by changing the baseword first letter, i.e. a consonant. The first-letter position was chosen in order to reduce error rates in lexical decision. Indeed, nu- merous letter identification tasks have shown a first-letter advantage in skilled readers (Marzouki & Grainger, 2014; Scaltritti & Balota, 2013; Stevens & Grainger, 2003; Tydgat & Grainger, 2009) and in children (Grainger, Bertrand, Lété, Beyersmann, & Ziegler, 2016), suggesting that readers pay more attention to the first-letter position (Gomez, Ratcliff, & Perea, 2008; Leclercq & Siéroff, 2016). Additionally, the first letter always corresponded to the first phoneme, which was necessarily taken into account in the auditory task owing to its position before the uniqueness point, i.e. the position of the phoneme in the word beyond which the word diverges from all other words in the lexicon. In the phonologically close condition (e.g., *tiano*), the first letter was replaced by a letter phonologically close to the original letter of the baseword (e.g., *piano* [piano]), whereas in the phonologically distant condition (e.g., *liano*), it was replaced by a letter phonologically distant from the original letter. Consonantal phonemes are phonologically close when they share three out of four phonemic features (e.g., /p/ and /t/ share all phonemic features except the place of articulation) and are phono- logically distant when they share none, one or two out of four phonemic features (e.g., /p/ and /l/ share only the nasality). Both types of pseudowords were equal in their orthographic resemblance to the baseword. The mean first bigram frequency (*tiano* – *liano*) in the two sets of pseudowords was 274 (SD = 276) for the one-feature phoneme mismatch pseudowords and 229 (SD = 308) for the multiple-feature phoneme mismatch pseudowords ($F < 1$; Manulex infra database, Peereman, Lété, & Sprenger-Charolles, 2007). The uniqueness point defines the earliest phoneme at which a word can be theoretically re- cognized (i.e., the word diverges from all other words in the lexicon). We computed the phonological uniqueness point and the cohort (i.e., the number of words sharing the first phonemes until the uniqueness point) for each pseudoword (Peereman et al., 2007). A paired-samples *t*-test was conducted to compare the one-feature phoneme mismatch pseudoword condition and the multiple-feature phoneme pseudoword mismatch condition. Pseudoword conditions did not show any differ- ence on the uniqueness point (with respectively, M = 3.88 (SD = 0.91) and M = 3.81 (SD = 0.91), $t(42) = 0.38$, $p = 0.71$) or on the cohort (with respectively, M = 16.58 (SD = 23.24) and M = 13.37 (SD = 13.97), $t(42) = 0.90$, $p = 0.37$). The first-letter perceptual si- milarity between related items (e.g., *piano* - *tiano* - *liano*) was computed (Courrieu, Farioli, & Grainger, 2004) and was not significantly different ($F < 1$). To avoid repetition effects for related items, three versions of the experiment were created in which only one item from the related items appeared (e.g., *piano* in List 1, *tiano* in List 2 and *liano* in List 3). In addition, 15 words selected from the Manulex database were added to each list for the purpose of the lexical decision task. For the auditory lexical decision, the material was the same but in auditory modality. Each item was pronounced by a male French native speaker and digi- tally recorded (Protools HD V6.9.2, 16 bit, 44.1 kHz) in a professional recording studio. Mean item durations were not significantly different between conditions ($F < 1$).

2.3. Procedure

Participants were assessed individually at their school in a quiet room. They were seated on a chair in front of a DELL computer using the E-prime software. They were tested in two counterbalanced sessions consisting of an auditory lexical decision task and a visual lexical de- cision task, each lasting about 20 min. Each child processed two dif- ferent lists (one in the visual lexical decision task and another in the auditory lexical decision task) in such a way that they did not see the same items twice. Additionally, the sessions were administered at least two weeks apart in order to prevent children developing strategies due to the resemblance of items between the visual and auditory lexical decision tasks. For the auditory lexical decision task, the children wore headphones. They performed a 15-trial practice session before the ex- periment. Each trial was organized as follows: a fixation cross (800 ms), a hash mark mask (800 ms), then the visual target (until response or 3000 ms) in the visual lexical decision; and a fixation cross (800 ms), a hash mark mask (800 ms), then simultaneously a hash mark and the auditory target (until response or 3000 ms) in the auditory lexical de- cision. There was a short pause after each series of 20 items. Participants were instructed to perform a lexical decision task. They were asked to decide whether the letter sequence was a word or not and then to press one of two response buttons on the SRbox as quickly and as accurately as possible. Latency was measured from target onset until the participant's response.

3. Results

Four basewords producing > 40% errors were excluded from the analysis as well as the corresponding pseudowords. RTs below 300 ms and > 3 SDs from the mean per participant were discarded from the analysis, i.e. < 0.1% of the data. RT analyses were conducted only on correct responses. Repeated Measures Analyses of Variance (ANOVA) were performed by participant (reported as F_1) and by item (reported as F_2). Analyses were based on a 3 (type of item: word, one-feature pho- neme mismatch pseudoword, multiple-feature phoneme mismatch pseudoword) × 2 (grade: third, fifth) pattern. The mean error percen- tages and correct RTs are summarized in Table 1 (auditory modality) and Table 2 (visual modality).

Table 1
Means and standard deviations (SDs) for response times (RT, in ms) and error rates (err, in %) as a function of Grade and Type of item in auditory modality.

Type of item	Grade 3		Grade 5	
	RT (SD)	err (SD)	RT (SD)	err (SD)
Baseword	1148 (136)	7.70 (7.11)	1095 (129)	5.30 (7.13)
O-pseudoword	1316 (154)	25.04 (16.01)	1245 (145)	19.13 (11.15)
M-pseudoword	1278 (143)	9.51 (8.58)	1200 (144)	5.04 (7.15)

Note. O-pseudoword: one-feature phoneme mismatch pseudoword; M-pseudoword: multiple-feature phoneme mismatch pseudoword.

Table 2
Means and standard deviations (SDs) for response times (RT, in ms) and error rates (err, in %) as a function of Grade and Type of item in visual modality.

Type of item	Grade 3		Grade 5	
	RT (SD)	err (SD)	RT (SD)	err (SD)
Baseword	1055 (246)	10.15 (10.82)	914 (237)	8.06 (7.89)
O-pseudoword	1409 (415)	20.96 (20.67)	1148 (345)	15.80 (12.48)
M-pseudoword	1405 (413)	13.14 (14.67)	1133 (368)	6.81 (8.79)

Note. O-pseudoword: one-feature phoneme mismatch pseudoword; M-pseudoword: multiple-feature phoneme mismatch pseudoword.

3.1. Results in auditory modality

The overall percentage error was 12%. The ANOVA on error percentages revealed a main effect of type of item ($F_1(2,146) = 62.79$, $p < 0.001$, $\eta_p^2 = 0.46$; $F_2(2,152) = 22.29$, $p < 0.001$, $\eta_p^2 = 0.23$) and a main effect of grade, with fifth graders responding more accurately than third graders (error rates 10% vs. 12%, respectively), $F_1(1,73) = 8.63$, $p = 0.004$, $\eta_p^2 = 0.11$; $F_2(1,75) = 5.21$, $p = 0.025$, $\eta_p^2 = 0.06$. In contrast, interaction between type of item and grade was not significant (Fs < 1). Consequently, the following analysis was carried out with all children taken together. Given that the items were of two kinds, words and pseudowords, and that the items of interest were the one-feature phoneme mismatch pseudoword and the multiple- feature phoneme mismatch pseudoword, planned comparisons were carried out. These revealed that the words were processed more accu- rately than the pseudowords (error rates were 7% vs. 15%, respectively), $F_1(1,74) = 39.21$, $p < 0.001$, MSE = 44; $F_2(1,77) = 17.84$, $p < 0.001$, MSE = 47, while the one-feature phoneme mismatch pseudowords were processed less accurately than the multiple-feature phoneme mismatch pseudowords (error rates 14% vs. 10%, respectively), $F_1(1,74) = 83.48$, $p < 0.001$, MSE = 110; $F_2(1,77) = 25.24$, $p < 0.001$, MSE = 109.

The analyses on RTs were conducted in exactly the same way as those on error percentages. The ANOVA revealed a main effect of type of item ($F_1(2,146) = 70.12$, $p < 0.001$, $\eta_p^2 = 0.49$; $F_2(2,152) = 56.33$, $p < 0.001$, $\eta_p^2 = 0.43$) and a main effect of grade, with fifth graders responding faster (67 ms) than third graders ($F_1(1,73) = 4.24$, $p = 0.043$, $\eta_p^2 = 0.05$; $F_2(1,76) = 52.53$, $p < 0.001$, $\eta_p^2 = 0.41$). In contrast, the interaction between type of items and grade was not significant (Fs < 1). Planned comparisons made with all children taken together showed that the words were processed faster (138 ms) than the pseudowords ($F_1(1,74) = 104.99$, $p < 0.001$, MSE = 12,683; $F_2(1,77) = 107.40$, $p < 0.001$, MSE = 13,979), while the one-feature phoneme mismatch pseudowords were processed more slowly (42 ms) than the multiple-feature phoneme mismatch pseudowords ($F_1(1,74) = 12.26$, $p < 0.001$, MSE = 876; $F_2(1,77) = 9.03$, $p = 0.004$, MSE = 1239).

3.2. Results in visual modality

The overall error rate was 12%. Analyses were performed exactly as in the auditory modality. The ANOVA on error percentages revealed a main effect of type of item ($F_1(2,146) = 13.71$, $p < 0.001$, $\eta_p^2 = 0.16$; $F_2(2,152) = 17.41$, $p < 0.001$, $\eta_p^2 = 0.19$) and a main effect of grade, with fifth graders responding more accurately than third graders (error rates 10% vs. 15%, respectively), $F_1(1,73) = 4.85$, $p = 0.031$, $\eta_p^2 = 0.06$; $F_2(1,76) = 7.64$, $p = 0.007$, $\eta_p^2 = 0.09$. In contrast, the interaction between type of item and grade was not significant (Fs < 1). Planned comparisons, made with all children taken together showed that the words were processed more accurately than the pseudowords (error rates 9% vs. 14%, respectively), $F_1(1,74) = 8.11$, $p = 0.006$, MSE = 17; $F_2(1,77) = 14.19$, $p < 0.001$, MSE = 19 while the one-feature phoneme mismatch pseudowords were processed less accurately than the multiple-feature phoneme mismatch pseudowords (error rates 18% vs. 10%, respectively), $F_1(1,74) = 20.68$, $p < 0.001$, MSE = 35; $F_2(1,77) = 19.88$, $p < 0.001$, MSE = 36.

The ANOVA on RTs revealed a main effect of type of item ($F_1(2,146) = 86.09$, $p < 0.001$, $\eta_p^2 = 0.54$; $F_2(2,152) = 47.31$, $p < 0.001$, $\eta_p^2 = 0.38$) and a main effect of grade, with fifth graders responding faster (225 ms) than third graders ($F_1(1,73) = 9.24$, $p = 0.003$, $\eta_p^2 = 0.11$; $F_2(1,76) = 64.79$, $p < 0.001$, $\eta_p^2 = 0.46$). The interaction between type of item and grade was significant only by participant ($F_1(1,146) = 4.06$, $p = 0.019$, $\eta_p^2 = 0.05$; $F_2 < 1$), indicating that third and fifth graders did not process the different types of item in the same way. An additional analysis (2 (third grade vs. fifth grade) × 2 (words vs. pseudowords taken together)) indicated that this difference in processing was due to the lexicality of the items. The interaction between grade and words vs. pseudowords indicated that fifth graders rejected pseudowords faster (compared to words, 227 ms) than third graders (352 ms), $F_1(1,73) = 5.70$, $p = 0.020$, $\eta_p^2 = 0.07$; $F_2(1,76) = 2.88$, $p = 0.093$. Planned comparisons were therefore made by group. Third graders processed words faster (352 ms) than pseudo- words ($F_1(1,36) = 78.12$, $p < 0.001$, MSE = 82,596; $F_2(1,38) = 63.68$, $p < 0.001$, MSE = 63,325). In contrast, the one-feature phoneme mismatch pseudowords and the multiple-feature phoneme mismatch pseudowords did not show any significant difference ($F_S < 1$). Planned comparisons showed that fifth graders processed words faster (227 ms) than pseudowords ($F_1(1,37) = 43.53$, $p < 0.001$, MSE = 34,253; $F_2(1,38) = 101.40$, $p < 0.001$, MSE = 35,842). On the other hand, there was no significant difference between one-feature phoneme mismatch pseudowords and multiple-feature phoneme mismatch pseudowords ($F_S < 1$).

4. Discussion

The aim of the present study was to investigate whether phonemic features typically used in spoken language processing (e.g., Gerken et al., 1995; Schild et al., 2011) are involved in phonological lexicon activation during visual word recognition (Lukatela et al., 2001) in children. To investigate this issue, we performed a lexical decision task in a visual modality with third and fifth graders. Two types of pseu- dowords were created from the French basewords (e.g., *piano* [piano]). The phonologically close pseudowords varied in only one phonemic feature (e.g., *tiano*) while the phonologically distant pseudowords varied in multiple phonemic features (e.g., *liano*). These pseudowords were used as marker of phonemic feature involvement in visual word recognition. Additionally, we made sure that processing of spoken items was at phonemic feature level in both grades by conducting an auditory lexical decision task using the same material. Our main prediction was that the phonological lexicon is activated more by the (visual and au- ditory) phonologically close pseudowords than by the (visual and au- ditory) phonologically distant pseudowords, making it harder to reject one-feature phoneme mismatch pseudowords (e.g., *tiano*) than mul- tiple-feature phoneme mismatch pseudowords (e.g., *liano*) in both the visual and auditory lexical decision tasks.

In the auditory lexical decision task, the main finding was a pho- nemic feature effect in both grades: children were less accurate and slower at rejecting the one-feature phoneme mismatch pseudowords than the multiple-feature phoneme mismatch pseudowords. Therefore, the activation of the phonological lexical representation was stronger with the one-feature phoneme mismatch pseudowords than with the multiple-feature phoneme mismatch pseudowords. This means that phonemic features are involved in lexical access during speech pro- cessing by children of both grades (e.g., Schild et al., 2011). This is congruent with the phonemic feature effect found by Connine et al. (1993) in adults (see also Andruski et al., 1994; Cole, 1973; Connine et al., 1997; Friedrich et al., 2009; Marslen-Wilson & Welsh, 1978; Milberg et al., 1988; Schild et al., 2012) and with Schild et al. (2011) who found that phonological lexical access in children aged 8 years was sensitive to phonemic features. In the present study, children aged 9 and 10 years did not show any developmental effect in phonemic fea- tures. Schild et al. (2011) showed that spoken language processing is modulated during the time children start learning to read and write: spoken word recognition was more precise in beginning readers than in pre-readers (see also Hoonhorst et al., 2010). In a recent study, Medina, Hoonhorst, Bogliotti, and Serniclaes (2010) did not find any effect of age on categorical perception of sounds (voicing) between 9-year-old children and 17-year-old adolescents. However, they showed that the precision of boundaries between categories still changed after nine years of age. They asked participants to identify and discriminate sounds within a voicing continuum composed of eight synthetic stimuli. In the present study, we did not find any developmental effect probably because (1) the task did not focus on one phoneme but on the whole pseudoword and (2) the auditory lexical decision task was not suffi- ciently sensitive to detect any difference between 9- and 11-year-old children.

Interestingly, we also found a phonemic feature effect in both grades on the visual lexical decision task. It was harder to reject the one-feature phoneme mismatch pseudowords than the multiple-feature phoneme mismatch pseudowords. Therefore, we show for the first time in children that phonological lexical activation triggered by written processing depends on phonemic features. The probable explanation for this effect is that the one-feature phoneme mismatch pseudowords ac- tivated the lexical entry of the basewords in the phonological lexicon more than the multiple-feature phoneme mismatch pseudowords be- cause they were phonologically very similar to the basewords. This strong activation of phonological lexical representations tended to- wards a strong signal the presence of a real word (see results in auditory lexical decision task), whereas the orthographic information does not match to any word and therefore signaled the absence of a real word. We assume that this conflict led to more errors being made in the one- feature phoneme mismatch pseudoword condition. In the framework of the BIAM model, this finding also suggests that phonological activation from print has a sub-lexical component: the activation from print spreads in central interface between graphemes and phonemes re- presentations. Indeed, given that the two types of written pseudowords were orthographically equidistant from the baseword (all letters, ex- cepted one, were shared), the orthographic lexical activation was the same for both types of pseudowords. This means that the influence of the orthographic lexical representation activated by both types of pseudowords on the phonological lexical representation should be identical. If phonological activation occurred only at the lexical level, a phonemic feature effect on error rates would not be observed.

Our results reveal no developmental effect in phonemic feature while the lexical effect (fifth graders rejected pseudowords faster than third graders) indicates that the efficiency of orthographic processing increases with age. This means that the phonemic effect does not de- pend on the development of orthographic processing. It seems that the involvement of phonemic features in visual word recognition occurs early in the course of learning to read. It is therefore possible that this involvement in visual word recognition is more a trace of phonological recoding used when children begin to read rather than the marker of the development of a deep relationship between the written processing system and the speech processing system. Phonological recoding en- ables children to translate the orthographic string into its corresponding spoken string. In this way, beginning readers can read each new written word by accessing its spoken form. It is likely that phonemic features play a role at this very first stage of learning to read (Laing & Hulme, 1999; Rack et al., 1994; Ross, Treiman, & Bick, 2004), a hypothesis that requires further studies.

A limitation of our study is that we used pseudowords as critical items. The visual lexical decision task does not require the spoken phonological code and the pseudoword form was very close to the baseword. However, it is possible that children partly used phonolo- gical recoding so it would be interesting to investigate this issue in a priming experiment using primes sharing more or less phonemic fea- tures with the target words (e.g., Connine et al., 1993).

Considering the BIAM framework (e.g., Diependaele et al., 2010; Grainger et al., 2006; Grainger & Ferrand, 1994; Grainger & Ziegler, 2011), our results suggest that phoneme representations activated by grapheme representations spread activation to the phonological lexical representations as well as excitatory feedback to phonemic feature re- presentations. As in spoken word processing (see note[1] for more de- tails), the activation from phonemic feature representations is sent to the phoneme representations characterized by these phonemic features, then to the lexical representations. Given that the one-feature phoneme mismatch pseudowords shared more phonemic features with the lexical representation of the basewords, they sent more activation to the phonological lexical representations than the multiple-feature phoneme mismatch pseudowords. This would explain the phonemic feature effect on the error rates in both grades. In the BIAM, phonological re- presentations and orthographic representations are also inter-connected at the lexical level, thereby influencing visual pseudoword processing. However, in the present study, the orthographic lexical representation *piano* was activated equally by the pseudowords *tiano* and *liano*. Con- sequently, the interactions at the lexical level should not affect differ- ently the processing of both types of pseudowords. To accommodate the present findings, the BIAM would have to include the processing of phonemic features in visual word recognition because the activation of feature representations seems to have an impact on the level of acti- vation of phonological lexical representations.

In summary, the present study shows that the involvement of the phonological code in written word processing in third and fifth graders occurs at a detailed level as fine as phonemic features. This suggests that the written word recognition system is deeply inter-connected with the speech processing system early in the course of learning to read. Future research is needed to determine whether these findings can be generalized and to ascertain the sensitivity of the written word re- cognition system to phonemic features.

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Appendix A

Baseword	O-pseudoword	M-pseudoword
première	bremière	vremière
bonjour	ponjour	fonjour
dehors	tehors	fehors
depuis	tepuis	fepuis
jeudi	zeudi	teudi
toujours	doujours	voujours
besoin	pesoin	fesoin
bientôt	pientôt	fientôt
jugement	zugement	tugement
pauvre	tauvre	lauvre
samedi	zamedi	ramedi
siècle	ziècle	rièclе
vitesse	fitesse	kitesse
docteur	tocteur	focteur
fantôme	vantôme	lantôme
jardin	zardin	tardin
période	tériode	lériode
piano	tiano	liano
prochain	brochain	vrochain
propre	bropre	vropre
séjour	zéjour	réjour
témoin	démoin	jémoin
victoire	fictoire	kictoire
voisin	foisin	koisin
culture	gulture	rulture
fragile	vragile	dragile
journal	zournal	tournal
pantalon	tantalon	lantalon
portrait	tortrait	lortrait
précieux	brécieux	vrécieux
premier	bremier	vremier
principe	brincipe	vrincipe
problème	broblème	vroblème
puisque	buisque	luisque
sensible	zensible	rensible
solitude	zolitude	rolitude
système	zystème	rystème
terrible	derrible	jerrible
trésor	drésor	vrésor
victime	fictime	kictime
camarade	gamarade	ramarade
parvenir	tarvenir	larvenir
poitrine	toitrine	loitrine

Note. O-pseudoword: one-feature phoneme mismatch pseudoword; M-pseudoword: multiple-feature phoneme mismatch pseudoword.

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