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The role of consonant/vowel organization in perceptual discrimination

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Abstract

According to a recent hypothesis, the CV pattern (i.e., the arrangement of consonant and vowel letters) constrains the mental representation of letter strings, with each vowel or vowel cluster being the core of a unit. Six experiments with the same/different task were conducted to test whether this structure is extracted prelexically. In the mismatching trials, the targets were pseudowords built by the transposition of two adjacent letters from base words. In one condition, the pseudowords had the same number of vowel clusters as the base word, whereas in another condition, the transposition modified the number of vowel clusters (e.g., *poirver*: 2 vowel clusters vs. *povirer*: 3 vowel clusters , from *POIVRER*: 2 vowel clusters). In Experiment 1, pseudowords with a different number of vowel clusters were more quickly processed than pseudowords preserving the CV structure of their base word. Experiment 2 further showed that this effect was not due to changes in syllabic structure. In Experiment 3, the pattern of results was also replicated when the category (consonant or vowel) of the transposed letters was strictly equated between conditions. Experiments 4 to 5 confirmed that the effects were not attributable to lexical processing, to differences in letter identity, or to the position of transpositions. The results suggest that the orthographic representation of letter strings is influenced by the CV pattern at an early, prelexical processing stage.

Key-words: CV pattern, same/different task, orthographic parsing, visual word recognition

One fundamental issue in visual word recognition concerns the nature and structure of the mental representations that are extracted from the sensory input. In the recent years, a large part of the research has focused on the processes through which letter identity and positional information are obtained and how they are encoded (see Davis & Bowers, 2006; Frost, 2012, for reviews). An earlier line of attack on this issue has taken the form of a quest for the units of perception, and numerous proposals have been put forward over the course of years (e.g., Carreiras, Alvarez, & de Vega, 1993; Shallice & McCarthy, 1985; Spoehr & Smith, 1973; Treiman, 1986). Most theories presuppose that words need to be parsed into multiletter groups during the identification process, but neither the precise delimitation of the resulting units nor the nature of cues controlling the parsing mechanism are established. In the present study, we examine the hypothesis that the CV pattern, that is, the organization of consonant and vowel symbols in the letter strings, constrains their perceptual structure with each vowel or cluster of adjacent vowel letters constituting the core of one perceptual unit.

This hypothesis was tested in previous studies with a metalinguistic syllable counting task as well as with tasks requiring lexical processing. Readers were asked to count the number of syllables in written words and they were biased by the number of vowel clusters. Thus, syllabic length was overestimated in words with one vowel cluster more than the number of syllables (e.g., *biberon*, /bi.bʀɔ̃/: three clusters but two syllables, Chetail & Content, 2013) and it was underestimated when words exhibited one vowel cluster less than the number of syllables (e.g., *pharaon*, /fa.ʀa.ɔ̃/: two vowel clusters but three syllables, Chetail & Content, 2012)[1]. We argued that the effect ensues from a conflict between the phonological syllabic structure and the orthographic structure derived from the distribution of vowel and consonant letters in the stimulus string. Naming and lexical decision experiments further showed that the CV pattern also affects word recognition (Chetail & Content, 2012). In the naming task, pronunciation was delayed for words exhibiting one vowel cluster less than the number of syllables, presumably due to the structural mismatch between the orthographic word form and the phonological word form to be produced. In the lexical decision task, the direction of the effect varied as a function of word length, from facilitatory for trisyllabic words to inhibitory for four-syllable items. Based on the assumption that the identification of long words involves sequential processes (Ans, Carbonnel, & Valdois, 1998; Carreiras, Ferrand, Grainger, & Perea, 2005), the facilitatory effect may be explained by the fact that words including fewer vowel clusters need fewer sequential steps. However, for longer words, the lexical identification process would take more time, thus increasing the likelihood that phonological assembly processes noticeably influence performance in a similar way as in the naming task, yielding a net inhibitory effect.

The notion of "perceptual unit" is widely used in psycholinguistics and refers to different concepts in different contexts. As noted by Lupker, Acha, Davis, and Perea (2012), in the domain of visual word recognition, many authors have argued for the perceptual reality of various linguistic elements, such as graphemes, syllables, or syllable constituents, to characterize the mental representations that are activated during processing, but the exact function of these units has not been fully specified. According to a common framework, perceptual processing can be viewed as the simultaneous activity of a complex hierarchy of detectors (e.g., Dehaene, Cohen, Sigman, & Vinckier, 2005; McClelland & Rumelhart, 1981), each one being responsible for the coding of a certain element of information, from the simplest sensory properties to more abstract and composite characteristics. We take a "perceptual unit" to be any element of information for which a detector exists in the hierarchy, and we assume that one level in the hierarchy is shaped by the CV pattern, so that higher-order elements in the hierarchy, which we henceforth label vowel-centered units, correspond to groups of contiguous letters, centered on a vowel or vowel cluster (see Figure 1).

One important aspect of our hypothesis is that the perceptual analysis based on the CV pattern occurs at a prelexical level of processing. However, the tasks used in previous studies involved metalinguistic processes (syllable counting) or were oriented towards word recognition. Whereas the latter findings confirmed that the CV pattern affects lexical processing, neither data set directly demonstrates that the effects hinge upon earlier, prelexical processing stages. The fact that an effect was found for both words and pseudowords (Chetail & Content, 2012, Experiment 6) could suggest that the CV pattern plays a role prelexically but more direct evidence would be required to support this claim. In the present paper, we report a series of experiments aimed at examining whether the CV pattern influences the perceptual organization of letter strings at a prelexical level. This requires to use a task that relies on orthographic processing while being sensitive to the perceptual structure extracted during the encoding of the letter string. The cross-case sequential matching task in which participants have to decide whether two letter strings are identical or different was deemed to meet this goal but we exploited it in a slightly different manner than in previous research.

The same-different task was initially conceived as a tool for the chronometric investigation of processing stages in classification (Posner & Mitchell, 1967) and it has also been exploited under various guises in reading and word recognition research. In the 1980's, the task has served to investigate the relative influence of letter identity versus letter position (Proctor & Healy, 1985, 1987) and to support the existence of abstract letter identity coding (Besner, Coltheart, & Davelaar, 1984). Using a physical match condition, Besner et al. showed that 'different' responses to letter strings sharing the same letters but differing in case (e.g., *HILE/hile*) require more time than 'different' responses to one-letter-different strings. This suggests that an abstract case-independent letter code is extracted early and automatically, and interferes with the mismatch decision. Further, as no difference was found between homophone (e.g., *HILE/hyle*) and non-homophone (e.g., *HILE/hule*) strings, the task appears immune to the influence of phonology (see also Pollatsek, Well, & Schindler, 1975). In more recent years, the same-different task has been used to investigate orthographic encoding. In the contemporary version of the paradigm, the referent and the target are presented successively in different cases, and longer polysyllabic words are employed (see Kinoshita & Norris, 2009; Norris & Kinoshita, 2008). Interestingly, the sequential version of the task shows limited influence of lexicality, particularly in the mismatch condition (Marmurek, 1989), which is also the critical condition in the present study.

In line with the idea that the same/different paradigm is particularly suited to examine early visuo-orthographic processes, it has reappeared in the context of the recent discussions about models of orthographic coding (e.g., Davis, 2010; Davis & Bowers, 2006; Gomez, Ratcliff, & Perea, 2008; Grainger & Van Heuven, 2003; Norris, Kinoshita, & van Casteren, 2010; Whitney, 2001). One important empirical source to this debate stems from letter transposition effects. It has been known for a long time that letter transpositions can easily go unnoticed. Thus, Bruner and O'Dowd (1958; see also Chambers, 1979) showed that pseudowords built from words by a transposition of two adjacent letters (e.g., *gadren* from *garden*) were frequently misperceived as the corresponding base words in word detection and lexical decision tasks. More recently, experiments based on letter transposition have provided further evidence against a strict letter position coding scheme. For example, Forster, Davis, Schoknecht, and Carter (1987) and Perea and Lupker (2003, 2004) reported that a word (e.g., *JUDGE*) is processed more rapidly when it is preceded by a transposed-letter pseudoword prime such as *jugde* than by a replaced-letter prime like *jupte*. Norris and Kinoshita (2008) pointed out that transposed-letter priming effects are generally weak or absent for pseudowords in the lexical decision task, and argued that their origin remains ambiguous. To determine whether the effects stem from a lexical or prelexical source, they introduced a new paradigm combining masked orthographic priming with letter transposition manipulations in the same-different task. They reported equivalent facilitation on both word and pseudoword targets, and concluded that the effects arise from the prelexical encoding of orthographic information (see also Kinoshita & Norris, 2009; Norris et al., 2010).

Beside the use of transposed letter manipulations to study letter position coding, several studies have started exploiting the same technique in a slightly different way to assess the perceptual structure of letter strings. Thus, Lupker et al. (2012) used transposed letter stimuli in the primed lexical decision task to evaluate the reality of graphemic units. They reasoned that if graphemes constitute perceptual units in visual word processing, disturbing the letters corresponding to a single grapheme in the prime (e.g., *anhtem - ANTHEM*, *th* is a single grapheme) should yield a different cost than disturbing letters corresponding to two distinct graphemes (e.g., *emlbem - EMBLEM*, *b* and *l* are two graphemes). In none of their experiments did the two critical conditions yield different performance patterns, thus suggesting that graphemes do not constitute primary units in orthographic encoding. Taft and colleagues (Lee and Taft, 2009, 2011; Taft & Krebs-Lazendic, 2013) similarly capitalized on the principle that letter transpositions that break the perceptual structure of the stimuli should be discriminated more easily than letter transposition that preserve the structure to provide evidence supporting the perceptual reality of subsyllabic constituents.

The present study

Following the same logic as Lupker et al. (2012) and Lee and Taft (2009, 2011), we used the transposed letter manipulation to determine whether the distribution of consonant and vowel letters in the stimulus string influences same/different performance. We conducted six experiments aimed at examining whether mismatch decisions on stimuli derived from words or pseudowords by a single letter transposition varied according to whether the transposition preserves or modifies the CV pattern. We used the sequential matching task (e.g., Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002; Duñabeitia, Dimitropoulou, Grainger, Hernández, & Carreiras, 2012; Ratcliff, 1981) as it is supposed to assess prelexical stages of orthographic encoding (see Besner et al., 1984; Marmurek, 1989). Importantly, we did not use the exact same design as in previous letter transposition experiments aimed at assessing letter position coding. As our hypothesis was that letter transpositions would cause differential performance effects as a function of the CV pattern they induce, the central contrast was the comparison of structure-preserving and structure-modifying letter transpositions rather than the more usual comparison between letter transposition and letter substitution (but see Experiment 5b).

More concretely, based on our previous findings, we expected transposed-letter pseudowords to be judged as different from the referent base word more easily when the transposition leads to an extra vowel cluster than when the transposition does not modify the number of vowel clusters. For example, from the word *POIVRER,* which comprises two vowel clusters (CVVCCVC), the transposition of *i* and *v* produces the pseudoword *povirer* (CVCVCVC, three clusters), whereas the transposition of *v* and *r* produces the pseudoword *poirver*, (CVVCCVC) which has the same number of vowel clusters as the referent. In the former case, we predict that the discrepancy between the base word and the derived pseudoword would be more salient because the two stimuli do not share the same number of vowel clusters. This was tested in Experiment 1. In Experiment 2, we ensured that the effect was not due to phonological differences resulting from the letter transposition and Experiment 3 was designed to test an alternative account of the effect in terms of the type of letter transposition involved. Experiment 4 used pseudoword referents to rule out a lexical explanation of the effects, and finally, Experiments 5a and 5b were conducted to ensure that the effects were not due to confounds with letter identity and position. In all experiments, we included a baseline condition in which the transposed pseudoword was not derived from the referent base word (e.g., *batsion* for *POIVRER*). This enabled us to ensure that the participants performed appropriately as they were expected to be more rapid and accurate in this condition than in any other. In Experiment 5b, we also used the more traditional letter substitution condition as baseline.

Experiment 1

To test the hypothesis that written words are orthographically structured according to their CV pattern, we devised transposed-letter stimuli which had either the same number of vowel clusters as their base word or not. In both conditions, we expected longer decision latencies than in a baseline condition, and latencies should be longer for stimuli with the same number of vowel clusters as the base word than for stimuli with one more vowel cluster because of the orthographic structure mismatch in the latter condition. In addition, given that transpositions disturbing the CV pattern more often led to break a vowel grapheme (e.g., *oi* in *POIVRER*), a fourth condition was added in which the grapheme was also disrupted but the CV pattern was preserved (e.g., *POIVRER- piovrer*).

Method

Participants. Thirty students participated in the experiment. They were all native French speakers and reported having normal or corrected-to-normal vision.

Stimuli. One hundred and twenty referent words were selected from the Lexique database (New, Pallier, Brysbaert, & Ferrand, 2004). All the referents included a –VVCC– or –CCVV– internal letter sequence (e.g., *POIVRER*, /pwa.vʀe/, *oivr* being a –VVCC– sequence) so that transposing adjacent consonant or vowel letters enabled to devise two targets with the same number of vowel clusters as the referent (*poirver*, /pwaʀ.ve/: CC transposition, *piovrer*, /pjɔ.vʀe/: VV transposition), whereas a transposition of the medial consonant and vowel created a target with one vowel cluster more than the referent (*povirer*, /pɔ.vi.ʀe/: CV transposition). In the fourth baseline condition, targets were derived by analogous letter transpositions from unrelated words (e.g., *bastion,* /bas.tjɔ̃/). Targets were matched on number of letters, summed bigram frequency, and did not include any silent *e* (Table 1 and Appendix A). For task requirements, 120 additional referents with the same characteristics were included (e.g., *VALSEUR,* /val.sœʀ/), associated to the same targets (*valseur*). Four lists of stimuli were used with every referent appearing once in each list and an equal number of trials of the four target conditions.

Procedure. Participants performed a cross-case same-different task programmed in Matlab using the Psychtoolbox extension (Brainard, 1997). Each trial began with a centered fixation cross for 500 ms, followed by the referent in uppercase for 500 ms. After a blank of 500 ms, the target appeared and remained on the screen until the response. Participants were instructed to decide as rapidly and accurately as possible whether the referent and the target comprised the same sequence of letters (response ‘same’) or not (response ‘different’), by pressing the rightShift or leftShift key. They had to ignore the difference in case. Reaction times were measured from target onset until the keypress. All participants performed practice trials before receiving the 240 trials in a variable random order.

Results and Discussion

The mean correct reaction times and mean error rates averaged over participants are presented in Table 2. The data were submitted to separate oneway analyses of variance on the participant ($F1$) and item ($F2$) means with Target Type (baseline, CC, VV, CV) as factor. In item analyses, one word was discarded because the corresponding error rate was 100% in one condition.

For reaction times, there was a main effect of target type, $F1(3, 87) = 44.31$, $p < .001$, $F2(3, 354) = 92.91$, $p < .001$. Planned orthogonal comparisons showed that related targets (CC, VV, CV) were processed more slowly than unrelated ones (baseline), $F1(1, 29) = 41.59$, $p < .001$, $F2(1, 118) = 202.35$, $p < .001$. Critically, CV transposed targets were responded more quickly than CC and VV transposed targets, $F1(1, 29) = 54.97$, $p < .001$, $F2(1, 118) =$

58.77, $p < .001$. In addition, VV transposed targets were processed more quickly than CC transposed targets, $F1(1, 29) = 45.58$, $p < .001$, $F2(1, 118) = 44.39$, $p < .001$.

The same pattern was found for error rates. The effect of target type was significant, $F1(3, 87) = 56.92$, $p < .001$, $F2(3, 357) = 62.06$, $p < .001$. Related targets (CC, VV, CV) produced more errors than unrelated ones (baseline), $F1(1, 29) = 63.56$, $p < .001$, $F2(1, 119) = 109.95$, $p < .001$. CV transposed targets produced fewer errors than CC and VV transposed targets, $F1(1, 29) = 40.64$ $p < .001$, $F2(1, 119) = 43.42$, $p < .001$. VV transposed targets produced fewer errors than CC transposed targets, $F1(1, 29) = 62.28$ $p < .001$, $F2(1, 119) = 56.90$, $p < .001$.

Although the three letter-transposition conditions were processed more slowly than the baseline condition, there were not equivalent to each other. As expected, pseudowords were classified as different from their referent more quickly in the CV transposition condition than in the CC and VV conditions. Additionally, judgments were also faster in the VV condition than in the CC condition.

The fact that CV transpositions yield faster reaction times than CC or VV transpositions is consistent with the hypothesis that the comparison is based on a representation structured according to vowel clusters, as CV transpositions systematically lead to a pseudoword with a different number of vowel clusters than the referent word. Because the referent and target stimuli differ in orthographic structure and not only in letter order, the discrepancy is more salient than in transpositions that do not alter orthographic structure (CC and VV conditions). The results provide further indications that the effect genuinely stems from the salience of the CV pattern. First, although it was not possible to strictly control for the position of transpositions in this experiment, the results do not fit with an explanation assuming a left-to-right scan of letter strings. The average position of letter transpositions for the CC, VV, and CV conditions was respectively 3.53, 4.37, and 3.97. Therefore, if the participants used a left-to-right scanning strategy, they should have been faster in the CC condition than in the VV condition, with the CV condition falling in between. This does not correspond to the pattern of results, as mismatch decisions were faster in the CV than in the VV condition, and faster in the VV than in the CC condition. Additionally, the advantage for the CV condition cannot be accounted for in terms of graphemic structure either. Although graphemes were systematically disrupted in both CV and VV conditions, responses were still more rapid in the former than in the latter condition, $F1(1, 29) = 9.42, p = .005$, $F2(1, 118) = 9.55, p = .003$.

Although not directly related to the main issue of the present study, it is worth noting that VV-transposed targets were processed more rapidly than CC-transposed ones, despite the fact that the CV structure was similarly preserved in both conditions. This finding suggests that VV transpositions are perceived as less similar to their base word than CC transpositions. It fits with prior results in the lexical decision task but not in the same/different task. Thus, Perea & Lupker (2004) found that VV-transposed pseudowords were easier than CC-transposed pseudowords to reject in a lexical decision task, even though both kinds of stimuli were more difficult to reject than unrelated control pseudowords. In the same vein, VV transposed-letter pseudowords (e.g., *cisano,* from *casino*) yielded a smaller facilitation effect than CC transposed-letter pseudowords (e.g., *caniso*) in the primed lexical decision task (e.g., Perea & Lupker, 2004; Lupker, Perea, & Davis, 2008). In this study, however, the transpositions involved non-adjacent letters, which may not be fully comparable to the present manipulation. In a follow-up study, Perea and Acha (2009) specifically compared adjacent VV transposition (e.g., *craota, from CROATA*) and CC transposition (e.g., *catrel, from CARTEL*) to a baseline letter substitution condition (respectively, *crieta*, and *cafnel).* They also obtained a stronger priming effect in the CC condition in the lexical decision task, but not in the same-different task. Based on these findings, they argued that letter category effects are related to late, lexical processing stages, and do not affect early orthographic encoding. Given the present finding of a reaction time difference between the CC and the VV conditions, the question of the locus of letter category effects remains open, and would deserve further investigation as the two studies are not directly comparable (i.e., different baseline conditions, primed vs. unprimed task). In any case, CC and VV transpositions do not modify the CV pattern (which is the reason why we used both as control conditions), and the possibility that they yield differential effects does not call into question the conclusion that the distribution of consonant and vowel letters determines the perceived structure of letter strings.

Experiment 2

In Experiment 1, mismatch decisions were faster when pseudowords involved a letter transposition that modified the number of vowel clusters (e.g., *LOINTAIN* – *loinatin*). However, this change in orthographic structure was systematically associated with a change in phonological structure, as the resulting pseudoword had one more syllable than its base word (/lwɛ̃.tɛ̃/ – /lwa.na.tɛ̃/). Experiment 2 was designed to assess whether the advantage for CV transposition was caused by the change induced in orthographic structure or in syllabic structure. To do so, we used hiatus words. Hiatus words include two contiguous vowel graphemes mapping onto two different vowel phonemes (e.g., *RÉACTION*, /ʀe.ak.sjɔ̃/). For such words, it is possible to produce a CV transposition that leads to a pseudoword with one additional vowel cluster without changing the number of syllables (e.g., *récation*, /ʀe.ka.sjɔ̃/). As in Experiment 1, this condition was compared to a CC transposed-letter condition and a baseline condition. The VV condition could not be included due to the other constraints in stimulus selection.

Method

Participants. Forty-four new students participated in the experiment. They were all native French speakers and reported having normal or corrected-to-normal vision.

Stimuli. Forty-five referent words with two contiguous vowel graphemes (hiatus words) were selected from Lexique (New et al., 2004). All the referents were trisyllabic and included an internal –VVCC– or –CCVV– letter sequence (e.g., *PEUPLIER*, /pœ.pli.je/) so that transposing adjacent letters enabled to devise a pseudoword target with the same number of vowel clusters as the referent (*peulpier*, /pœl.pje/: CC transposition), and a target of identical syllabic length than the referent, but with one more vowel cluster (*peupiler*, /pœ.pi.le/: CV transposition)[2]. As in Experiment 1, an unrelated baseline condition (*gourmand*, /guʀ.mɑ̃/) was also included (Table 3 and Appendix B). Forty-five trials eliciting ‘same’ responses were added (e.g., *CRUAUTÉ – cruauté*, /kʀy.o.te/). Three lists of stimuli were used so that every referent appeared once in each list with an equal number of trials of the three target conditions.

Procedure. The procedure was identical to that of Experiment 1.

Results and Discussion

The mean correct reaction times and mean error rates averaged over participants are presented in Table 4. The data were submitted to separate analyses of variance on the participant ($F1$) and item means ($F2$) with Target Type (baseline, CC, CV) as factor.

For reaction times, there was a main effect of target type, $F1(2, 86) = 84.34, p < .001$, $F2(2, 88) = 156.43, p < .001$. Planned comparisons showed that related targets (CC, CV) were processed more slowly than unrelated ones (baseline), $F1(1, 43) = 116.85, p < .001$, $F2(1, 44) = 296.52, p < .001$. Critically, CV transposed targets were processed more quickly than CC transposed targets, $F1(1, 43) = 28.42, p < .001$, $F2(1, 44) = 33.75, p < .001$.

The same pattern was found on error rates. The effect of target type was significant, $F1(2, 86) = 29.97, p < .001$, $F2(2, 88) = 31.40, p < .001$. Planned comparisons showed that related targets (CC, CV) produced fewer errors than unrelated ones (baseline), $F1(1, 43) =$

35.51, $p < .001$, $F2(1, 44) = 59.23$, $p < .001$. Critically, CV transposed targets produced fewer errors than CC transposed targets, $F1(1, 43) = 21.85$, $p < .001$, $F2(1, 44) = 14.99$, $p < .001$.

The pattern of results is identical to that of Experiment 1. Both CV and CC transposed-letter conditions were processed more slowly than the baseline condition, and the CV condition yielded faster and more accurate responses than the CC condition. In addition to providing a replication of the CV-transposition advantage observed in Experiment 1, the results show that the effect is not due to a change in syllabic structure. This is consistent with previous studies indicating that the transposed-letter effect is not influenced by syllabic boundaries (e.g., Perea & Acha, 2009; Perea & Carreiras, 2006). Perea and Carreiras (2006) examined negative responses in the lexical decision task for two types of transposed-letter pseudowords, pseudowords created by transposing two internal syllables (e.g., *privemara*, from the transposition of *ma* and *ve* in *primavera*) and pseudowords created by transposing two adjacent bigrams that do not form a syllable (e.g., *primerava*, coming from the transposition of the bigrams *av* and *er*). They found that the transposed-letter effect was similar in both conditions, and concluded that transposed-letter effects occur at an early orthographic level, rather than at a syllable level.

Experiment 3

In Experiments 1 and 2, the critical comparison was between mismatch judgments on items with a CC letter transposition preserving the CV structure of the base word (e.g., *poirver*) and items with a CV letter transposition altering the CV structure relative to the base word (e.g., *povirer*). As the category of the transposed letters is not the same in the two conditions, the effect could ensue from the nature of the letters involved in the manipulation. Especially, the fact that the CV condition led to faster responses could be due to the transposition of a vowel, given previous evidence that transpositions involving vowels may be detected faster (Lupker et al., 2008). To avoid this potential confound, we selected two sets of words such that a CV transposition would either preserve or alter the number of vowel clusters. This design presented the additional advantage that the position of the letter transposition could be strictly equated across the two conditions.

Method

Participants. Thirty-six new students participated in the experiment. They were all native French speakers and reported having normal or corrected-to-normal vision.

Stimuli. Thirty triplets of bisyllabic words with two vowel clusters were selected from Lexique (New et al., 2004). One word included a –VVCC– or –CCVV– internal sequence so that transposing a consonant and a vowel created an additional vowel cluster (e.g., *POIVRER – povirer*, /pwa.vʀe/-/pɔ.vi.ʀe/: structure-modifying transposition). The second word included a –VVCV– or –VCVV– sequence, so that transposing a consonant and a vowel did not alter the number of vowel clusters (e.g., *PLUMIER – pluimer*, /ply.mje/-/plwi.me/: structure-preserving transposition). The third word had the same characteristics and was followed by an unrelated target (e.g., *POIREAU – drouger*, /pwa.ʀo/-/dʀu.ʒe/: baseline). In the three conditions, referent words were carefully matched on lexical frequency, number of letters, and summed bigram frequency. The position of the transposition was also controlled for in the structure-preserving and the structure-modifying conditions (Table 5 and Appendix C). Ninety trials eliciting a 'same' response were added (e.g., *FOIREUX – foireux*, /fwa.ʀø/).

Procedure. The procedure was identical to that of Experiment 1.

Results and Discussion

The mean correct reaction times and mean error rates averaged over participants are presented in Table 6. The data were submitted to separate analyses of variance on the participant (*F*1) and item means (*F*2) with Target Type (baseline, structure-modifying transposition, structure-preserving transposition) as factor.

For reaction times, there was a main effect of target type, $F1(2, 70) = 81.51$, $p < .001$, $F2(2, 87) = 60.53$, $p < .001$. Planned orthogonal comparisons showed that related targets were processed more slowly than baseline targets, $F1(1, 35) = 99.45$, $p < .001$, $F2(1, 87) = 107.99$, $p < .001$. Critically, structure-modifying transposed targets were processed more quickly than structure-preserving transposed targets, $F1(1, 35) = 32.27$, $p < .001$, $F2(1, 87) = 13.08$, $p < .001$.

A similar pattern was found on error rates. The effect of target type was significant, $F1(2, 70) = 27.10$, $p < .001$, $F2(2, 87) = 15.98$, $p < .001$. Planned comparisons showed that related targets produced fewer errors than unrelated ones (baseline), $F1(1, 35) = 39.86$ $p < .001$, $F2(1, 87) = 29.25$, $p < .001$. Structure-modifying transposed targets produced fewer errors than structure-preserving targets, $F1(1, 35) = 6.09$, $p = .02$, but $F2(1, 87) = 2.71$, $p = .10$.

The results are clear-cut. When two adjacent letters –namely a consonant and a vowel– were transposed within a word, the resulting stimuli led to faster mismatch decision if the transposition modified the number of orthographic units based on the CV pattern (e.g., *POIVRER* – *povirer*) than if this number remains unchanged (e.g., *PLUMIER* – *pluimer*). These results provide a further replication of the effect observed in the previous experiments and confirm that the effect is not due to the category of the letters that are transposed but rather to the structural change that the transposition induces in the orthographic representation.

Experiment 4

In the three previous experiments the referents were always words. As a consequence, the lexicality of the targets was confounded with the response. In ‘same’ trials, the targets were words because they needed to be identical to the referent. In ‘different’ trials, targets were pseudowords because they were systematically derived from the referent by transposition of two letters. Responses could therefore be determined by evaluating the lexicality of the target, rather than the orthographic similarity between the target and the referent. This confound does not undermine the results as their interest do not lie in a comparison of ‘same’ and ‘different’ trials, but in a comparison between several conditions of ‘different’ trials. The effects we found cannot therefore be attributed to lexicality. However, the fact that the participants could rely on target lexicality to discriminate same and different trials could have led them to use a lexical decision strategy, and would obviously challenge any claim that the effects are prelexical. One way to avoid such a confound is to use pseudoword referents so that all the stimuli are pseudowords and participants cannot rely on lexicality anymore. We therefore conducted a new experiment following the same design as Experiment 3 but with pseudowords as referents. If the effects stem from prelexical processes, targets in the structure-modifying transposition condition should be responded to more quickly and accurately than in the structure-preserving transposition condition.

Method

Participants. Thirty-nine new students participated in the experiment. They were all native French speakers and reported having normal or corrected-to-normal vision.

Stimuli. Thirty triplets of bisyllabic pseudowords with two vowel clusters were devised. One pseudoword included a –VVCC– or –CCVV– internal sequence so that transposing a consonant and a vowel created an additional vowel cluster (e.g., *POUGNET – pogunet*, /pu.ɲɛ/-/pɔ.gy.nɛ/: structure-modifying transposition). The second pseudoword included a –VVCV– or –VCVV– sequence, so that transposing a consonant and a vowel did not alter the number of vowel clusters (e.g., *FARIEUX – faireux*, /fa.ʀjø/-/fɛ.ʀø/: structure-preserving transposition). The third pseudoword had the same characteristics and was followed by an unrelated target (e.g., *GLATIAL – plouson*, /gla.tjal/-/plu.zɔ̃/: baseline). In the three conditions, items were matched on number of letters, summed bigram frequency, and transposition position (Table 7 and Appendix D). Ninety trials eliciting a ‘same’ response were added (e.g., *NAIRAUX* – *nairaux*, /nɛ.ʀo/).

Procedure. The procedure was identical to that of Experiment 1.

Results and Discussion

The mean correct reaction times and mean error rates averaged over participants are presented in Table 8. We performed the same analyses as in Experiment 3. Seven extreme reaction times above 6,500 ms or below 250 ms were removed from the analyses. One triplet of pseudowords was removed because one of the items contained an incorrect transposition.

For reaction times, there was a main effect of target type, $F1(2, 76) = 111.42$, $p < .001$, $F2(2, 84) = 156.48$, $p < .001$. Planned orthogonal comparisons showed that related targets were processed more slowly than baseline targets, $F1(1, 38) = 202.60$, $p < .001$, $F2(1, 84) = 298.94$, $p < .001$. Critically, structure-modifying transposed targets were treated more quickly than structure-preserving transposed targets, $F1(1, 38) = 8.94$, $p = .005$, $F2(1, 84) = 14.03$, $p < .001$.

A similar pattern was found on error rates. The effect of target type was significant, $F1(2, 76) = 35.78$, $p < .001$, $F2(2, 84) = 39.80$, $p < .001$. Planned comparisons showed that related targets produced fewer errors than unrelated ones (baseline), $F1(1, 38) = 55.15$, $p < .001$, $F2(1, 84) = 71.15$, $p < .001$. Structure-modifying transposed targets produced fewer errors than structure-preserving targets, $F1(1, 38) = 5.03$, $p = .005$, $F2(1, 84) = 8.44$, $p = .005$.

In sum, as in Experiment 3, transpositions were detected more rapidly and more accurately if they modified the number of vowel clusters. The fact that the results tightly mirror those of Experiment 3 suggests that the participants genuinely performed a same/different task rather than a lexical decision task and therefore confirms our interpretation of the effects in terms of prelexical processing.

A last point that needs to be examined is the possibility that the difference between the structure-modifying transposition condition and the structure-preserving transposition condition is due to the fact that different letters and different positions were involved in the two conditions. To rule out this possibility, we conducted two additional experiments. Experiment 5a was a replication of Experiment 4 with more stringent matching criteria, and Experiment 5b used the more traditional comparison between transposition and substitution.

Experiment 5a

In Experiment 5a, the referent and target pseudowords were devised so that both the position of the letter transposition and the identity of the manipulated letters were strictly identical between the two critical conditions (e.g., *FOUDEIL-fodueil* and *BOUDLET-bodulet*: U and D transposed in both conditions). Thus any difference between the two conditions could not be attributed to a confound in letter identity or position.

Method

Participants. Twenty-nine new students participated in the experiment. They were all native French speakers and reported having normal or corrected-to-normal vision.

Stimuli. The pseudowords were devised in the same way as in Experiment 4 except that the two transposed letters were identical in the structure-modifying condition (e.g., *MIEDRAR-miderar*) and in the structure-preserving condition (e.g., *FIEDURT-fideurt*). As in Experiments 3 and 4, the position of the transposition was strictly matched between the two conditions (see Table 9 and Appendix E).

Procedure. The procedure was identical to that of Experiment 1.

Results and discussion

The mean correct reaction times and mean error rates averaged over participants are presented in Table 10. One triplet of pseudowords was removed because one of the items was a pseudohomophone. We performed the same analyses as in Experiment 3.

For reaction times, there was a main effect of target type, $F1(2, 56) = 87.56$, $p < .001$, $F2(2, 84) = 110.54$, $p < .001$. Planned orthogonal comparisons showed that related targets were processed more slowly than baseline targets, $F1(1, 28) = 136.53$, $p < .001$, $F2(1, 84) = 214.92$, $p < .001$. Critically, structure-modifying transposed targets were treated more quickly than structure-preserving transposed targets, $F1(1, 28) = 7.35$, $p = .01$, $F2(1, 84) = 6.15$, $p = .02$.

For error rates, the effect of target type was significant, $F1(2, 56) = 15.46$, $p < .001$, $F2(2, 84) = 19.14$, $p < .001$. Planned comparisons showed that related targets produced fewer errors than unrelated ones (baseline), $F1(1, 28) = 35.57$, $p < .001$, $F2(1, 84) = 38.05$, $p < .001$. There was no significant difference between the structure-modifying transposed targets and the structure-preserving targets, $F1 < 1$, $F2 < 1$.

In sum, Experiment 5a clearly showed that even though the position of the transposition and the identity of the transposed letters were strictly identical across the two critical conditions, responses in the structure-modifying transposition condition were still faster than in the structure-preserving transposition condition. The effect cannot therefore be attributed to potential confounds with letter identity or position.

Experiment 5b

As a complementary attempt to ensure that letter position and identity could not explain the pattern of results found in the previous experiments, we used the substitution manipulation that has been traditionally employed in transposed-letter studies. Each of the transposition conditions (e.g., *TARIEUX-taireux*, *GUISSON-gusison*) was compared to a control substitution condition in which the two transposed letters were replaced by two other letters (e.g., *TARIEUX-tauceux*, *GUISSON-gureson*). It should be easier to decide that referents and targets are different in the substitution conditions than in the transposition conditions, because fewer letters are shared between the referents and targets in the former case (Duñabeitia et al., 2012). More importantly, the effect of structure should manifest itself by the presence of an interaction, with a smaller RT difference between transposition and substitution in the modified structure condition than in the preserved structure condition.

Method

Participants. Thirty-five new students participated in the experiment. They were all native French speakers and reported having normal or corrected-to-normal vision.

Stimuli. Forty pairs of referent pseudowords were devised in the same way as in Experiment 4. For one of the pseudowords, transposing a consonant and a vowel led to an additional vowel cluster (e.g., *BOUDLET-bodulet*, modified structure), whereas for the other pseudoword it led to the same number of vowel clusters (e.g., *FOUREIL-forueil*, preserved structure). For each referent, two target pseudowords were created, one corresponding to the transposition of two letters, as in the previous experiments (e.g., *bodulet*, *foureil*), and one for which the two transposed letters were replaced by two other letters (e.g., *bofalet, foviel*). The referents were matched on number of letters, summed bigram frequency, and transposition position (Table 11 and Appendix F). Forty baseline trials and 120 trials eliciting a 'same' response were added (e.g., *NAIRAUX – nairaux*, /nɛ.ʀo/). Two counterbalanced lists of stimuli were created so that each participant was exposed to the full list of referents, followed either by a substituted-letter target or a transposed-letter target. The baseline trials and those eliciting a 'same' response were identical for all the participants.

Procedure. The procedure was identical to that of Experiment 1.

Results and discussion

The mean correct reaction times and mean error rates averaged over participants are presented in Table 12. One participant was excluded from the analyses due to a high error rate, as well as five extreme reaction times above 6,500 ms or below 250 ms. The data were submitted to separate analyses of variance with structure (preserved or modified) and condition (transposition vs. substitution) as main factors.

In the reaction time analyses, there was a significant effect of structure, *F*1(1, 33) = 7.64, *p* = .009, *F*2(1, 78) = 4.52, *p* = .04, and of condition, *F*1(1, 33) = 206.74, *p* < .001, *F*2(1, 78) = 296.09, *p* < .001. The interaction was significant by participants, *F*1(1, 33) = 4.36, *p* = .04, and marginally significant by items, *F*2(1, 78) = 3.40, *p* = .07. Critically, the interaction was due to the fact that modified-structure items were processed more rapidly than preserved-structure items in the transposition condition, *F*1(1, 33) = 7.01, *p* = .01, *F*2(1, 78) = 6.83, *p* = .01, but not in the substitution condition, *F*s < 1.

The same pattern was found on error rates. There were significant effects of structure, *F*1(1, 33) = 26.41, *p* < .001, *F*2(1, 78) = 11.08, *p* = .001, and of condition, *F*1(1, 33) = 88.42, *p* < .001, *F*2(1, 78) = 173.14, *p* < .001, as well as an interaction, *F*1(1, 33) = 15.45, *p* < .001, *F*2(1, 78) = 6.83, *p* = .01, indicating that modified-structure items led to more errors than preserved-structure items in the transposition condition, *F*1(1, 33) = 26.85, *p* < .001, *F*2(1, 78) = 5.00, *p* = .03, but not in the substitution condition, *F*1(1, 33) = 1.09, *p* = .30, *F*2(1, 78) = 1.05, *p* = .31.

To sum up, Experiment 5b once again confirmed the influence of orthographic structure. As expected, the results showed an interaction between structure (preserved, modified) and type of modification (transposition, substitution), indicating that it was easier to detect a mismatch if the number of orthographic units was modified by a letter transposition than if this number remains unchanged, whereas no such difference was observed for the substitution conditions.

Complementary analyses

Taken together, the present experiments clearly demonstrate the influence of orthographic CV structure on mismatch detection performance, both on RTs and on error rates. In the following analyses, we present post-hoc analyses of RT distributions as a first step towards a more precise specification of the process of structure extraction.

In studies using chronometric tasks, analyses of reaction time distributions have been proposed has a complement to analyses on central tendency (e.g., Andrews & Heathcote, 2001; Andrews & Lo, 2013; Balota & Yap, 2011; Balota, Yap, Cortese, & Watson, 2008). Indeed, a difference between two condition means can be due to several distinct underlying differences in the distributions (Balota et al., 2008): a shift of the modal portion of the distribution (actually reflected by a difference in means), an increase in the tail of the distribution, or both. Previous studies have shown that indications of changes in the distribution parameters for stable and well-documented effects (e.g., lexical frequency) can sometimes lead to refine the interpretation of the processes underlying the effects (see Andrews & Heathcote, 2001; Balota et al., 2008; Yap & Balota, 2007, for extensive demonstrations).

Concerning the present study, we considered three possible scenarii which might account for the CV pattern effect: (1) The CV structure is extracted during the earliest stages of perceptual processing, namely, before all letters are identified, (2) The CV structure constitutes an intrinsic component of the gradual activation of elements taking place in the perceptual system; (3) The CV structure is extracted through a late orthographic parsing mechanism which is taking place after letters have been identified and a perceptual code incorporating them has been built (but before it makes contact with long term lexical storage). In this case, as the perceptual code entails all the necessary information for the same/different decision, the effect of a structural mismatch should only emerge on the slowest trials.

The first hypothesis seems incompatible with the results already presented. Indeed, as the targets in the baseline condition shared the structure of the referent even though they completely diverged in terms of letter identities, the hypothesis would predict a radically different pattern of results, with longer reaction times for baseline as well as structure-preserving targets than for structure-modifying targets. Similarly, the fact that substitution targets were processed faster than transposition targets and were not affected by structure (Experiment 5b) indicates that at least some letter identity information must be available earlier than structural information. To disentangle the other views, we considered the baseline reaction times distribution as a depiction of the time needed to make a “different” decision based on one single comparison between the referent and the target. In contrast, in the letter transposition conditions, most letter comparisons between the referent and the target would indicate a match and several comparisons would thus be required to reach the correct decision. The reaction times distribution should thus reflect the time needed to accumulate mismatch information and reach a negative decision.

Because the number of trials per condition was limited and insufficient to fit a theoretical distribution and to estimate its parameters, we used descriptive vincentile plot analyses (e.g., Ratcliff, 1979; Yap & Balota, 2007). For each participant, we rank-ordered the observations from fastest to slowest in each condition using ten quantile bands and we averaged correct reaction times for each bin. We then computed the reaction time difference between the baseline condition, the structure-preserving condition, and the structure-modifying condition per participant and per bin. Figure 2 displays the three effects for each of the fifth first experiments (there were too few observations per participants per conditions in Experiment 5b to conduct the analysis). The black line represents the CV structure effect, obtained in averaging the difference across participants between the structure-preserving and structure-modifying letter transposition condition. The two grey lines represent the mean difference between each of these two conditions and the baseline condition.

In all five experiments, the difference between the two transposition conditions and the baseline condition (grey lines) is clearly visible for all vincentiles, and it is similar for the fastest vincentiles although the two transposition conditions gradually diverge. The difference between the structure-preserving and baseline condition tends to increase, in line with the hypothesis that the structure-preserving condition requires numerous comparisons before a decision criterion is reached. By contrast, the difference between the structure-modifying and baseline condition (dashed line) appears relatively stable across vincentiles (except perhaps for Experiment 2 and Experiment 5a). This pattern is compatible with the idea that when it becomes available, the structural information preempts over letter information and determines a mismatch decision. The nearly constant ~100 ms difference between the baseline and the structure-modifying condition would then reflect the time required for the structural information to become available.

As a consequence, the CV structure effect (black line) builds up gradually from the earliest vincentiles. Despite a restricted number of observations (maximum 3 per bin per participant), the confidence intervals indicate that the effect was present from the first (Experiment 2), second (Experiments 1 and 5a), third (Experiment 3), or fourth (Experiment 4) bin. One firm conclusion is thus that the CV structure effect does not primarily emerge only for the slowest section of the RT distribution. We take this to constitute evidence against the hypothesis that the CV structure effect results from a late parsing mechanism taking place after the perceptual code is built and in support of the view that the orthographic structure driving the present effects is built concurrently with the extraction of letter identity and positional coding.

General discussion

The present study aimed at testing the hypothesis that the organization of vowels and consonants within letter strings, the CV pattern, determines their perceptual structure. We reasoned that if a letter transposition modifies the number of vowel-centered units stemming from the CV pattern, the resulting stimulus should look more distinguishable from its referent than when the letter transposition does not alter the number of units. Hence, ‘different’ responses should be faster in the former case. The findings of Experiment 1 supported this prediction. Pseudowords like *povirer* were more quickly judged as different from *POIVRER* than pseudowords like *poirver* or *piovrer*. Further, the effect was still present when the number of syllables (Experiment 2), the category of the transposed letters (Experiments 3 and 4) as well as letter identity and position (Experiments 5) were controlled for. Thus, consistent with our proposal, letter transpositions were more salient and discernible when they produced a change in the number of vowel-centered units relative to their referent. If the configuration of consonants and vowels did not matter in letter string perception, no difference should have been found between the transposition conditions, especially in Experiments 3 to 5 in which the transposition applied to a consonant-vowel or vowel-consonant sequence for all conditions and stimuli.

Taken together, the results demonstrate that readers are sensitive to the organization of letter strings as determined by the alternation of consonant and vowel letters. The fact that these effects were obtained in the sequential same/different matching task permits to conclude that the organization of consonants and vowels constrains letter string processing at a prelexical level of processing. At the stage of orthographic encoding, we hypothesize that letter strings are parsed into a number of letter groups corresponding to the number of vowel clusters, with each vowel cluster underlying a distinct slot. Hence, two slots would be required when the referent word (e.g., *POIVRER*) is displayed, whereas three would be needed for targets with a different structure (e.g., *povirer*). Detecting a difference between the referent and the target would therefore be faster and easier than when they share the same number of slots.

Several indications support the view that the observed response time difference is not caused by phonological or morphological characteristics. First, the influence of CV structure was observed in Experiment 2 even though the number of syllables was kept constant. This is consistent with previous findings suggesting that transposed-letter similarity effects are not related to syllabic organization (see Perea & Acha, 2009; Perea & Carreiras, 2006). Second, despite the fact that the letter transposition in the VV condition of Experiment 1 did systematically break a multiletter vowel grapheme (e.g., *OI* in *RACLOIR* leading to *RACLIOR*), it still produced longer response times than the corresponding CV condition. The faster decision times for the CV condition cannot therefore be attributed to grapheme disruption (see also Lupker et al., 2012). A third potential phonological explanation is in terms of a phonological parsing mechanism following an onset-nucleus-coda scheme (e.g., Perry, Ziegler, & Zorzi, 2007, 2010; Lee & Taft, 2009, 2011; Taft & Krebs-Lazendic, 2013). According to Taft and Krebs-Lazendic (2013), orthographic lexical representations of bisyllabic words are structured in units with slots corresponding to onset, nucleus, and coda (ONC) constituents. In our experiments, the letter transpositions sometimes modify the ONC structure. However in Experiment 2, the two contrasted manipulations produced similar numbers of ONC structure changes (41 and 45 changes). Thus, ONC structure cannot account for the effect observed here. Fourth, post-hoc analyses indicated that the effects of structure cannot be explained by an artefactual difference in phonological structure that would induce differential ease of access to the pronunciation. Targets in the two critical conditions did not differ in average biphone frequency in five out of six experiments. We also checked that the effects could not be explained by the morphemic structure of words, as previous studies showed that morphological units are activated during visual word recognition (e.g., Duñabeitia, Perea, & Carreiras, 2007; Rastle, Davis, & New, 2004). In Experiment 1, there were more morphologically complex words in the CC and VV conditions than in the CV condition, but in Experiments 2 and 3, the proportion of morphologically complex words for which the letter transposition occurred within or between morphemes was similar across conditions[3]. Moreover, even when the morphologically complex words were removed from the analyses, response times to the structure-modifying transposition condition were still faster than those in the structure-preserving condition, $F1(1, 35) = 31.28$, $p < .001$, $F2(1, 71) = 11.64$, $p = .001$ (Experiment 3). This rules out an interpretation of the effects in terms of morphemic structure.

The present data are in line with prior research demonstrating that the CV pattern determines the perceptual structure of polysyllabic letter strings, each vowel cluster serving as the core of a perceptual unit (Chetail & Content, 2012, 2013). The previous evidence which we reported was mainly obtained with metalinguistic tasks such as syllable counting for words with a different number of vowel clusters and of syllables. Basically, this occurs when words entail either a hiatus pattern (e.g., *chaos* - /keɪ.ɒs/ in English, two syllables but only one vowel cluster) or a silent E (the so-called 'schwa pattern' in French, e.g., *biberon*, /bi.bʀɔ̃/, two syllables, but three vowel clusters). Hiatus words comprise one orthographic unit less than their number of syllables due to two adjacent vowel graphemes (Chetail & Content, 2012). Conversely, schwa words include one orthographic unit more than the number of syllables because of the presence of the E letter in the orthographic form (but not in the phonological form), leading to one supplementary vowel cluster (Chetail & Content, 2013).

The results are also consistent with evidence from case studies of dysgraphic patients, which suggest the existence of an abstract orthographic CV representation distinct from the phonological CV skeleton (e.g., Buchwald & Rapp, 2006; Caramazza & Miceli, 1990). For example, the dysgraphic patient in Caramazza and Miceli's study produced deletions of consonant and vowel letters within consonant or vowel clusters respectively (e.g., *sfondo* → *sondo*), but never for singleton consonants or vowels (e.g., *tirare* ↛ *trare*). In other words, the patient's spelling responses most often preserved the number of vowel clusters. Moreover, Buchwald and Rapp (2006) analyzed substitutions errors in the written production of two dysgraphic patients, and showed that they were sensitive to the orthographic CV structure of words rather than to the phonological CV skeleton. For example, for words like *thigh* (/θ-aɪ/, phonological CV skeleton: CV; *t-h-i-g-h*, orthographic CV pattern: CCVCC), the two patients made more errors preserving the orthographic structure (e.g., *thich*) than the phonological structure.

The respective role of consonants and vowels in lexical organization, lexical representation and word recognition has been an issue of major interest in psycholinguistics over the last decades. Among the various strands of investigation, some recent studies have examined the impact of consonant and vowel information on visual word recognition, by selectively modifying and preserving either kind of letters (e.g., Carreiras & Price, 2008; Lee, Rayner, & Pollatsek, 2001, 2002; New, Araújo, & Nazzi, 2008; Lupker et al., 2008; Perea & Acha, 2009; Perea & Lupker, 2004; Vergara-Martínez, Perea, Marín, & Carreiras, 2010). The main conclusion of this line of research is that consonants provide stronger constraints on lexical selection than vowels, probably because the former carry more information than the latter. In spite of the surface similarity between those studies and the present experiments – both in terms of objects and methods–, the underlying issues are distinct. We aimed at assessing whether the CV pattern, that is the arrangement of consonant and vowel letters, determines the perceptual structure of letter strings. In other words, the underlying question was whether a disruption of the CV pattern obtained by letter transposition –be it consonants or vowels– affects discrimination*,* rather than whether transposing consonants versus vowels produces different performance. The two questions are independent and the evidence shows that the answer to both may be positive. On one hand, the CV pattern contributes to orthographic parsing at a prelexical level, with each vowel cluster underlying one perceptual unit. On the other hand, consonants appear to play a predominant role during lexical access. The two statements are not incompatible, and may even mirror the differential roles of consonant and vowel phonemes in speech processing and language acquisition, with consonants being more important for lexical selection, and vowels supporting prosodic and morphosyntactic processing (see Nazzi, 2005; Nespor, Peña, & Mehler, 2003).

One might be tempted to assimilate the proposal that vowel clusters determine orthographic units to the notion of orthographic syllables. There is no consensual definition of ‘orthographic syllable’ in the literature, and many studies ambiguously use the term ‘syllable’ to refer to units within written words as well as within spoken words. The dominant definition assumes that orthographic syllables are groups of letters that correspond to phonological syllables (e.g., Chetail & Mathey, 2010; Conrad, Grainger, & Jacobs, 2007). According to this view, even though the number of vowel clusters is identical to the number of orthographic syllables in many words, the two terms cannot be used as synonyms since the correspondence is not complete. For example, hiatus words will systematically differ in orthographic and phonological structure (i.e., *congruent*: two vowel clusters and three syllables).

However, orthographic syllables have also been defined on the basis of morphological and orthographic structure (BOSS; e.g., Taft, 1979) or as units emerging from orthotactic or statistical regularities (Prinzmetal, Treiman, & Rho, 1986; Seidenberg, 1987). To make it even more complex, the term ‘graphosyllable’ is sometimes preferred, referring either to groups of letters coding for syllables (e.g., Colé, Magnan, & Grainger, 1999) or to groups of letters centered on graphemic vowels (Caramazza & Miceli, 1990). Although the latter definition is close to our proposal, we prefer to avoid this terminology to prevent the ambiguity it conveys. According to us, one cause of the lack of consensus about the nature of orthographic units is that a major part of the research effort has consisted in searching evidence in favor of predefined linguistic units. In contrast, we favor an approach focusing on the information and cues that subserve perceptual parsing.

Together with other recent findings (e.g., Lee and Taft, 2009, 2011; Perea, abu Mallouh, & Carreiras, 2010; Taft & Krebs-Lazendic, 2013; Velan & Frost, 2009), the present results suggest that models of orthographic coding should take the internal structure of words into consideration. Based on letter transposition similarity effects, current models have abandoned the hypothesis of strict letter positional coding in favor of open-bigram schemes (e.g., Grainger & Van Heuven, 2003; Whitney, 2001), spatial gradient (Davis, 2010; Davis & Bowers, 2006), or noisy positional coding (e.g., Gomez et al., 2008; Norris et al., 2010). For example, in open-bigram models (e.g., Grainger & Van Heuven, 2003; Whitney, 2001), stimuli activate bigrams corresponding to adjacent and non-adjacent letters (e.g., FO, FR, FM, OR, OM, and RM for FORM, and FR, FO, FM, RO, RM, and OM for FROM). Due to the high overlap of activated bigrams (5/6 in the FORM/FROM example), a prime created by the transposition of two letters can be as good as the base word itself. According to the spatial gradient hypothesis (Davis, 2010; Davis & Bowers, 2006), the orthographic representation depends on a specific pattern of activation of its component letters, with activation decreasing from left to right as a function of letter position within the string. Hence, in both FORM and FROM, the letters F and M are the most and the least activated respectively, and O is more activated than R in FORM whereas it is the opposite in FROM. Again, both letter strings are therefore coded by relatively similar patterns of letter activation. Finally, according to the noisy positional coding scheme (e.g., Gomez et al., 2008; Norris et al., 2010), the activation of each letter extends to adjacent positions, so that the representation of FORM is strongly activated by R in the third position but also by R in the second position.

In these models, the only perceptual units playing a role in early orthographic processing are letters and bigrams. Because they observed differences between consonant and vowel transpositions in the primed lexical decision task but not in the primed same-different task, Perea and Acha (2009) argued that the consonant/vowel distinction affects lexical processing and does not impinge on early encoding stages, so that current models need no adjustment. On the contrary, the present results show that not all adjacent letter transpositions have the same effect on discrimination performance, and that the effect is modulated by the preservation or disruption of the CV structure. Future models of orthographic coding and word recognition should thus take these findings into account. Indeed, we conducted further analyses to assess whether current orthographic coding models could account for the present results. For each critical referent-target pair, we computed orthographic similarity indexes (i.e., weighted proportion of shared letters or bigrams) according to the coding schemes of the open bigram model (Grainger & van Heuven, 2004), the SOLAR model (Davis, 2006), and the overlap model (Gomez et al., 2008)[4]. If the present findings are due to letter or bigram structure, targets with a modified number of units based on the CV pattern should have a lower index of orthographic similarity than those with a preserved number. The difference would thus explain why the former were perceived as less similar to their referents than the latter. As can be seen in Table 13, none of the models fits with this explanation. In the SOLAR and Overlap models, the two critical conditions did not differ in terms of orthographic similarity in five experiments out of six while we found a significant effect of CV structure in the six ones. In the open bigram model, items with a modified CV structure tended to have a lower orthographic similarity index in one experiment, but a higher index in three others, which is thus clearly inconsistent with the experimental data. It therefore seems that models of orthographic coding would need to be modified, potentially by incorporating an intermediate level of orthographic representations based on vowel clusters.

The idea of an intermediate level of representations between letters and word form is far from new (e.g., Patterson & Morton, 1985; Shallice & McCarthy, 1985; Taft, 1991; Conrad, Tamm, Carreiras, & Jacobs, 2010). The specificity of the current proposal is that the grouping strictly ensues from orthographic characteristics, namely, the arrangement of consonant and vowel letters, and not from phonological properties. In this view, a minimal perceptual hierarchy might include four levels of representation: features, letters, vowel-centered units (i.e., orthographic units based on the CV pattern of words), and orthographic word forms (see Figure 3). Vowel-centered units would thus both serve to contact lexical representations and to encode the identity and spatial position of substrings from the sensory stimulation. Furthermore, the number of active vowel-centered nodes or the summed activity in that layer might provide a useful cue to string length and structure. This hypothesis is consistent with empirical evidence suggesting that the activation of lexical competitors is modulated by their similarity in length with the stimulus, measured as the number of large units (Chetail & Mathey, 2011). This is also consistent with recent evidence showing that the number of vowel-centered units influences the perceived length of words (Chetail & Content, in press), even with short presentation duration such that stimuli could scarcely be completely identified.

One question that arises is how to reconcile the present proposal with the possible role of graphemic parsing in phonological transcoding. One possibility in such a multiple level framework is that the mapping with phonology is assumed to occur in parallel at all levels (Figure 1A) through the activation and synthesis of associated phonological counterparts, and there is thus no separate grapheme-phoneme conversion procedure. We further believe that there is no strong argument to incorporate grapheme units in between the letter and vowel-centered unit levels. Lupker et al. (2012) reasoned that, if graphemes are perceptual units, disturbing letters in a multiletter grapheme (e.g., *TH*) should produce a larger effect on word processing than when letters that constitute two graphemes are disturbed (e.g., *BL*). Using transposed-letter masked priming, they found no difference between the two conditions in a lexical decision study in either English or Spanish. Both *anhtem* and *emlbem* facilitated lexical decisions for the target words *ANTHEM* and *EMBLEM* respectively, compared to a control condition. This led the authors to conclude that multiletter graphemes are not perceptual units involved in early stages of visual word identification. Interestingly, other experiments favouring a role of graphemes as reading units can be accounted for in terms of effects of the CV pattern. In the letter detection task, Rey, Ziegler, and Jacobs (2000) showed that is was more difficult to detect the letter A in a complex grapheme (e.g., *BEACH*) than as a simple grapheme (e.g., *PLACE*), which led them to conclude that graphemes are processed as perceptual units. The alternative interpretation we propose is that the letter A was more slowly detected in *BEACH* because it was part of a vowel cluster, core of an orthographic unit, rather than part of a grapheme. Similarly, the better detection of the letter O in weakly cohesive graphemes (e.g., *thon*, ON corresponding either to one phoneme /ɔ̃/ in /tɔ̃/ or two phonemes such as /ɔn/ in *bonne*, /bɔn/ in French) than in strongly cohesive graphemes (e.g., *flou*, OU systematically corresponding to one phoneme /u/ in /flu/) (Spinelli, Kandel, Guerassimovitch, & Ferrand, 2012) can also be accounted for in terms of vowel clusters. The letter O would be more difficult to detect in OU because the two vowel letters form a cohesive chunk, core of an orthographic unit, while the O in ON is not part of a vowel cluster. Hence, this kind of effects, accounted in terms of graphemic units may merely reflect CV pattern effects.

It remains however possible that graphemes are extracted and serve as the basis of a separate phonological conversion procedure (Figure 1B). In that case, graphemic units may be inserted in a grapho-syllabic structure with onset, nucleus and coda slots (as in the CDP++ model, Perry et al., 2007, 2010). In this context, the vowel-centered structure might provide a clue to help the system set up the adequate number of grapho-syllabic and phonological structure. Indeed, although a detailed analysis of orthographic consonant attachment is beyond the scope of the present study, it is likely that vowel-centered units most of the time correspond to graphosyllables. One advantage of vowel-centered units would be to code the orthographic structure of letter strings according to a definite and fixed scheme, independent of ortho-phonological mapping inconsistencies. In French for example, the E in *atelier* and *cadenas* would be the kernel of an orthographic units whether it has a direct phonological counterpart (as in *atelier*, /atəlje/) or not (as in *cadenas*, /kadna/).

To conclude, the present study provides strong evidence that all letter transpositions are not equivalent with respect to discriminability. More specifically, transpositions that disrupt higher order structure are more distant from their base word in terms of perceptual similarity than transpositions that preserve structure. We further propose that the relevant structure determining perceptual similarity is orthographic and not phonological in nature, and that it is primarily based on the information provided by the CV orthographic pattern, that is, the configuration of consonant and vowel class elements in the letter string.

Footnotes

[1] Although for most words the number of vowel clusters would correspond to the number of orthographic syllables, the two notions are distinct. For instance, there are three orthographic syllables in hiatus words such as *stereo* or *congruent,* but only two vowel clusters. This point is discussed in further details in the general discussion.

[2] The CC transposition condition sometimes led to pseudowords with one syllable less than the base word. Note however that this runs against the predicted effect. Indeed, if it is the number of syllables that drives the CV-transposition advantage, such items should therefore be perceived as less similar to their base word and yield shorter reaction times than in the CV condition (for which there is systematically the same number of syllables between the referent and the target), which is the opposite of our prediction.

[3] We used the morphological structures of words provided in the database DérifF of the Centre National de Ressources Textuelles et Lexicales (http://www.cnrtl.fr/outils/DeriF/)

[4] Orthographic similarity measures were computed with the Match Calculator software created by Colin Davis and available at http://www.pc.rhul.ac.uk/staff/c.davis/Utilities/MatchCalc/

Authors' notes

Fabienne Chetail is a postdoctoral researcher of the F.R.S.-FNRS. Virginie Drabs is a research fellow of the F.R.S.-FNRS. The authors thank Julie Le Berre for collecting the data of Experiment 4 during her research internship.

Appendix A

Stimuli used in Experiment 1

(BASE WORD/baseline – CC transposition –VV transposition – CV transposition)

PEIGNÉ/ortiel-peingé-piegné-peginé

PEUPLÉ/epsion-peulpé-pueplé-pepulé

TIERCÉ/absuos-tiecré-teircé-tirecé

FIERTÉ/goubri-fietré-feirté-fireté

HEURTÉ/optoin-heutré-huerté-heruté

FIESTA/entuor-fietsa-feista-fiseta

NOIRCIR/vuclain-noicrir-niorcir-noricir

MEUBLER/santaig-meulber-muebler-mebuler

BEUGLER/virtail-beulger-buegler-beguler

MEUGLER/pafrait-meulger-muegler-meguler

PEUPLER/martail-peulper-puepler-pepuler

FAIBLIR/pantios-failbir-fiablir-fabilir

PEIGNER/cobmien-peinger-piegner-peginer

BEIGNET/anlgais-beinget-biegnet-beginet

PEIGNÉE/gardein-peingée-piegnée-peginée

VAUTRER/cordail-vaurter-vuatrer-vaturer

FEUTRER/cangeux-feurter-fuetrer-feturer

POIVRER/batsion-poirver-piovrer-povirer

BIOPSIE/contuor-biospie-boipsie-biposie

FEINTER/cicruit-feitner-fienter-feniter

TEINTER/partail-teitner-tienter-teniter

POINTER/betsiau-poitner-pionter-poniter

CUISTOT/bosnoir-cuitsot-ciustot-cusitot

BEUGLANT/friasier-beulgant-bueglant-begulant

CRAIGNOS/foiuller-craingos-criagnos-craginos

CHAUDRON/poucrent-chaurdon-chuadron-chaduron

FROUFROU/tounrois-frourfou-fruofrou-frofurou

FIÉVREUX/buidling-fiérveux-fiévruex-fiéverux

FEIGNANT/boubreux-feingant-fiegnant-feginant

GEIGNANT/duobleur-geingant-giegnant-geginant

PIERCING/sounrois-piecring-peircing-pirecing

GLOUGLOU/scarbeux-gloulgou-gluoglou-glogulou

PLAINTIF/doirtier-plaitnif-pliantif-planitif

CRAINTIF/mouchior-craitnif-criantif-cranitif

POITRAIL/nuonours-poirtail-poitrial-poitaril

LOINTAIN/perchior-loitnain-lointian-loinatin

LOURDAUD/pluevoir-loudraud-lourduad-louradud

NOIRCEUR/mendaint-noicreur-noircuer-noirecur

LOURDEUR/mueblant-loudreur-lourduer-louredur

COUPLEUR/baurdoie-coulpeur-coupluer-coupelur

BAIGNEUR/scorpoin-baingeur-baignuer-baigenur

SAIGNEUR/coutrois-saingeur-saignuer-saigenur

SEIGNEUR/concuors-seingeur-seignuer-seigenur

TEIGNEUX/questoin-teingeux-teignuex-teigenux

SOIGNEUR/papraing-soingeur-soignuer-soigenur

SOIGNEUX/cuorrier-soingeux-soignuex-soigenux

POUDREUX/siognant-pourdeux-poudruex-pouderux

MAIGREUR/doulbard-mairgeur-maigruer-maigerur

CUIVREUX/roulbard-cuirveux-cuivruex-cuiverux

COUVREUR/piognard-courveur-couvruer-couverur

FEINTEUR/poutrant-feitneur-feintuer-feinetur

POINTEUR/suproids-poitneur-pointuer-poinetur

BOURBIER/cerfueil-boubrier-bourbeir-bouriber

COURTIER/bliareau-coutrier-courteir-couriter

PEIGNOIR/poucreau-peingoir-peignior-peigonir

HONGROIS/driotier-honrgois-hongrios-hongoris

HEURTOIR/tuojours-heutroir-heurtior-heurotir

COURTOIS/gionfrer-coutrois-courtios-courotis

POURVOIR/fuabourg-pouvroir-pourvior-pourovir

POURTOUR/chértien-poutrour-pourtuor-pourotur

URBAIN/piovré-ubrain-urbian-urabin

ADROIT/piontu-ardoit-adriot-adorit

BERCAIL/diagner-becrail-bercial-beracil

FORFAIT/gagnuer-fofrait-forfiat-forafit

HARNAIS/ampluer-hanrais-harnias-haranis

PORTAIL/havrias-potrail-portial-poratil

COSTAUD/versoin-cotsaud-costuad-cosatud

TOMBEUR/gestoin-tobmeur-tombuer-tomebur

FARCEUR/consiel-facreur-farcuer-farecur

BERCEUR/huoblon-becreur-bercuer-berecur

MANGEUR/fibruex-magneur-manguer-manegur

VENGEUR/dértoit-vegneur-venguer-venegur

SONGEUR/patriel-sogneur-songuer-sonegur

LARGEUR/piovron-lagreur-larguer-laregur

AIGREUR/caclium-airgeur-aigruer-aigerur

PISTEUR/endriot-pitseur-pistuer-pisetur

MENDIER/fictoin-mednier-mendeir-menider

SENTIER/gourdon-setnier-senteir-seniter

DENTIER/sutrout-detnier-denteir-deniter

RENTIER/patseur-retnier-renteir-reniter

POSTIER/bubleux-potsier-posteir-positer

BUSTIER/patrout-butsier-busteir-busiter

DICTION/congeur-ditcion-dictoin-diciton

MENTION/barbeir-metnion-mentoin-meniton

PORTION/tabluer-potrion-portoin-poriton

TAMBOUR/sufrait-tabmour-tambuor-tamobur

FORTUIT/pelvein-fotruit-fortiut-forutit

QUATRAIN/princeir-quartain-quatrian-quatarin

CHARGEUR/siagnant-chagreur-charguer-charegur

RONFLEUR/beinfait-ronlfeur-ronfluer-ronfelur

GONFLEUR/fautueil-gonlfeur-gonfluer-gonfelur

JONGLEUR/emprient-jonlgeur-jongluer-jongelur

TRACTEUR/poingant-tratceur-tractuer-tracetur

PARCOURS/bougreon-pacrours-parcuors-parocurs

ÉCLAIR/coubré-élcair-écliar-écalir

SURFEUR/moulfet-sufreur-surfuer-surefur

ONCTION/ronguer-ontcion-onctoin-onciton

REFRAIN/bilgeux-rerfain-refrian-refarin

ENTRAIN/hurluer-enrtain-entrian-entarin

MALSAIN/modreur-maslain-malsian-malasin

HERBEUX/captuer-hebreux-herbuex-herebux

PERCEUR/moingon-pecreur-percuer-perecur

FORCEUR/bestail-focreur-forcuer-forecur

GARDEUR/cetrain-gadreur-garduer-garedur

VERDEUR/poinget-vedreur-verduer-veredur

FORGEUR/martein-fogreur-forguer-foregur

SABLEUX/guordin-salbeux-sabluex-sabelux

TORPEUR/fatcion-topreur-torpuer-torepur

VIBREUR/duoblet-virbeur-vibruer-viberur

CADREUR/tesnion-cardeur-cadruer-caderur

VITREUX/dortior-virteux-vitruex-viterux

LIVREUR/pensoin-lirveur-livruer-liverur

OUVREUR/morpoin-ourveur-ouvruer-ouverur

LECTEUR/soucril-letceur-lectuer-lecetur

PULSION/porteir-puslion-pulsoin-pulison

SECTION/morteir-setcion-sectoin-seciton

RACLOIR/testuer-ralcoir-raclior-racolir

OUVROIR/lérpeux-ourvoir-ouvrior-ouvorir

PLONGEUR/courvant-plogneur-plonguer-plonegur

CAMBOUIS/chanrier-cabmouis-cambuois-camobuis

Appendix B

Stimuli used in Experiment 2

(BASE WORD /baseline -CC transposition- CV transposition)

ÉBLOUIR/passoin-élbouir-éboluir

DÉCLOUER/coutrois-délcouer-décoluer

COOPTER/terrian-cootper-copoter

PROACTIF/huisseir-proatcif-procatif

ÉBLOUI/clatré-élboui-ébolui

OUBLIÉ/boéral-oulbié-oubilé

OUVRIER/palfond-ourvier-ouvirer

SABLIER/cevreau-salbier-sabiler

PUBLIER/chargin-pulbier-pubiler

FÉVRIER/prafait-férvier-févirer

VITRIOL/ronlfer-virtiol-vitirol

SANGLIER/predreau-sanlgier-sangiler

TABLIER/chabron-talbier-tabiler

SUCRIER/porfond-surcier-sucirer

BOUCLIER/piotrail-boulcier-bouciler

POIVRIER/saoudein-poirvier-poivirer

VITRIER/floéral-virtier-vitirer

PEUPLIER/guormand-peulpier-peupiler

GAUFRIER/bliareau-gaurfier-gaufirer

POUDRIER/plasiant-pourdier-poudirer

PUBLIEUR/craétion-pulbieur-pubileur

RÉCRIER/coruant-rércier-récirer

OUBLIER/luaréat-oulbier-oubiler

LÉVRIER/réunoin-lérvier-lévirer

COUDRIER/nuaséeux-courdier-coudirer

REPLIER/prévais-relpier-repiler

DÉPLIER/talbeau-délpier-dépiler

DÉCRIER/purdent-dércier-décirer

PROPRIO/giuchet-prorpio-propiro

DÉPLIANT/quatrier-délpiant-dépilant

MAUGRÉER/gloireux-maurgéer-maugérer

MÉCRÉANT/distriat-mércéant-mécérant

RHÉOSTAT/fianéant-rhéotsat-rhésotat

AGRÉER/parton-argéer-agérer

RÉACTION/champoin-réatcion-récation

RÉACTEUR/pressoin-réatceur-récateur

RÉACTIF/drouger-réatcif-récatif

PROCRÉER/flargant-prorcéer-procérer

GÉORGIEN/chaileur-géogrien-gérogien

BÉARNAIS/pleuvior-béanrais-béranais

NUCLEUS/vainder-nulceus-nucelus

RENFLOUER/craossant-renlfouer-renfoluer

RECRÉER/daiment-rercéer-recérer

MALSÉANT/suplpéer-masléant-malésant

MAIGRIOT/pouvroir-mairgiot-maigirot

Appendix C

Stimuli used in Experiment 3

Condition					
Baseline		Structure-preserving transposition		Structure-modifying transposition	
Referent	Target	Referent	Target	Referent	Target
POIREAU	drouget	FOIRAIL	foriail	DOUBLET	dobulet
GLACIER	blauger	CUISANT	cusiant	POIVRER	povirer
ROUTIER	drouger	FAISEUR	fasieur	MEUGLER	meguler
BOITEUX	spaital	FOUTOIR	fotuoir	POIVRON	poviron
MOITEUR	briuger	LAINEUX	lanieux	COUVRIR	covurir
PEINARD	graicer	RAIDEUR	radieur	SOIGNER	soginer
RADIEUX	stauter	LAIDEUR	ladieur	FOURNIR	forunir
GLACIAL	blosuon	FURIEUX	fuireux	POIGNET	poginet
SOUCIER	covuent	CURIEUX	cuireux	POISSON	posison
GRAVIER	foluard	DOULEUR	dolueur	DAIGNER	daginer
PATIENT	chavuin	FLUVIAL	fluival	JUILLET	julilet
STATION	brotuer	MEUNIER	meuiner	TOURNER	toruner
GRENIER	povuoir	PLUMIER	pluimer	DOSSIER	dosiser
PRODUIT	mavuais	CREUSET	cresuet	REFRAIN	refarin
SUIVANT	coluoir	PRUNIER	pruiner	POSTIER	positer
MOUSSON	dobulon	CROUPIR	cropuir	PARTIAL	parital
NOURRIR	rosusir	CRUCIAL	cruical	MORPION	moripon
JOURNAL	forubir	FLAIRER	flarier	RENTIER	reniter
TEINTER	coridal	FREINER	frenier	MENSUEL	menusel

FONCIER	monidal	PLURIEL	pluirel	FERMOIR	feromir
DICTION	bisucit	CLAIRON	clarion	TERROIR	terorir
TANGUER	palimer	PLAIDER	pladier	CONDUIT	conudit
VITRAIL	moriter	CROISER	crosier	MENDIER	menider
FACTION	haranis	LUISANT	lusiant	PARLOIR	parolir
SENSUEL	conifer	CLOISON	closion	FICTION	ficiton
CORBEAU	penison	CHINOIS	chionis	PORTION	poriton
MENTION	poratil	TRAITER	tratier	PORTIER	poriter
FERMIER	bonosir	PROUVER	provuer	CIRCUIT	cirucit
FALLOIR	bariber	LIAISON	liasion	VERSION	verison
JANVIER	nupital	TROUVER	trovuer	MISSION	misison

Appendix D

Stimuli used in Experiment 4

Condition					
Baseline		Structure-preserving transposition		Structure-modifying transposition	
Referent	Target	Referent	Target	Referent	Target
PAIREUX	drauget	FOUREIL	forueil	BOUDLET	bodulet
PLACIER	bloucée	CAUSINT	casuint	VOIPRAL	vopiral
ROUTIOR	dronget	FEUSAIR	fesuair	MAUGLER	maguler
BAITOUX	spoital	TOUFIOR	tofuior	COIPRON	copiron
MOITONT	brauget	LEINAUT	leniaut	POUCRIR	pocurir
POINARD	groicer	RAUDOIR	raduoir	SOUGNET	sogunet
DARIEUX	stonter	LOUVEUR	lovueur	DOUTRIR	doturir
GLATIAL	plouson	FARIEUX	faireux	POUGNET	pogunet
SONCIER	coinaut	TARIEUX	taireux	GUISSON	gusison
TRAVIER	doulart	LEUDOUR	leduour	DOINGER	doniger
PATIEUX	plauvin	FRIVOUL	friovul	JUISTER	jusiter
STAPION	vroutir	MOUNIER	mouiner	TOUCRER	tocurer
VRENIER	gouvoil	PLAMIET	plaimet	RESTOIL	resotil
PRADUIX	pavuais	CROUSER	crosuer	FERRAIN	ferarin
SOIVANT	voluoir	PRINEUR	prienur	PESTION	pesiton
NOUTRIR	rousoir	CROICUL	crociul	MARPOIN	maropin
JOURNAR	moribir	BRAIRER	brarier	NANTIER	naniter
TEINPER	voridan	PREINET	preniet	MANSEIL	manesil
TONCIOR	mouidor	PLARIOL	plairol	PEVROIR	pevorir

LICTION	pisucir	CROIRAN	crorian	RETROIR	retorir
TONGEUR	ploimec	PLOUDER	ploduer	TOMPUIS	tomupis
VITRAIN	varitet	CRAISER	crasier	DANMIER	danimer
MACTION	taramil	LAUSINT	lasuint	LAPROIS	laporis
TROSEUL	ponifer	CLOISAN	closian	MECTION	meciton
CIRBAUX	panison	VRINOIS	vrionis	RUPROIL	ruporil
VENTION	paratil	TRARIET	trairet	PONTIER	poniter
FERNIAR	tousoir	VROUPER	vropuer	CIRCOIT	cirocit
MALLOIR	boribel	LOISAIN	losiain	REVROIN	revorin
JONVIEN	mupitan	TRAUVET	travuet	MISSAIN	misasin

Appendix E

Stimuli used in Experiment 5a

Condition					
Baseline		Structure-preserving transposition		Structure-modifying transposition	
Referent	Target	Referent	Target	Referent	Target
PAIREUX	drauget	FOUDEIL	fodueil	BOUDLET	bodulet
PLACIER	bloucée	CAUPINT	capuint	VOUPRAS	vopuras
ROUTIOR	dronget	FIEDURT	fideurt	MIEDRAR	miderar
BAITOUX	spoital	COUFERT	cofuert	COUFRON	cofuron
MOITONT	brauget	LEICAUR	leciaur	PUICROS	puciros
POINARD	groicer	RUAGINT	rugaint	SUAGNET	suganet
DARIEUX	stonter	LOUTEUR	lotueur	DOUTRIF	doturif
GLATIAL	plouson	SAUGEIR	sagueir	POUGNET	pogunet
SONCIER	coinaut	TOISEUX	tosieux	GUISSON	gusison
TRAVIER	doulart	LIONIRS	linoirs	DIONGET	dinoget
PATIEUX	plauvic	FAISOUL	fasioul	JUISTER	jusiter
STAPION	vroutir	COITEUR	cotieur	COITRER	cotirer
MOUSSIN	gouvoil	PAINOUR	paniour	POINDOR	ponidor
FERNIAR	pavuais	TOISERT	tosiert	VAISSUL	vasisul
JONVIEN	voluoir	VROPIER	vroiper	DOSPIEN	dosipen
VRENIER	pobuloc	PLATION	plaiton	RESTIOL	resitol
PRADUIX	fousoir	CRITAUL	criatul	VERTAIF	veratif
SOIVANT	moribir	PROTIUL	proitul	PESTIOC	pesitoc
NOUTRIR	voridan	TRIPOIN	triopin	GARPOIN	garopin

JOURNAR	mouidor	BRATIER	braiter	NANTIER	naniter
TEINPER	pisucir	PRISEIL	priesil	MANSEIL	manesil
TONCIOR	ploimec	PLARUIR	plaurir	PEVRUIF	pevurif
LICTION	varitet	STUROIR	stuorir	RUTROIF	rutorif
TONGEUR	taramil	CLOPUEL	cloupel	TOMPUIS	tomupis
VITRAIN	ponifet	CRALIER	crailer	DANLIER	daniler
MACTION	panison	CLIROUL	cliorul	JAPROIS	japoris
TROSEUL	varatil	PLATIAN	plaitan	MECTIOR	mecitor
CIRBAUX	tousoil	GLIROIS	glioris	RUPROIL	ruporil
VENTION	boribel	TRARIER	trairer	PONRIER	ponirer

Appendix F

Stimuli used in Experiment 5b

Type of structure					
Preserved			Modified		
Referent	Transposition	Substitution	Referent	Transposition	Substitution
FOUREIL	forueil	fovieil	BOUDLET	bodulet	bofalet
CAUSINT	casuint	caneint	VOIPRAL	vopiral	vojoral
FEUSAIR	fesuair	feriair	MAUGLER	maguler	mapiler
TOUFIOR	tofuior	todaior	COIPRON	copiron	coguron
LEINAUT	leniaut	legeaut	POUCRIF	pocurif	povarif
RAUDOIR	raduoir	rageoir	SOUGNET	sogunet	sopenet
LOUVEUR	lovueur	lorieur	DOUTRIL	doturil	dolaril
FARIEUX	faireux	fauteux	POUGNET	pogunet	popinet
TARIEUX	taireux	tauceux	GUISSON	gusison	gureson
LEUDOUR	leduour	letiour	DOINGER	doniger	dovuger
FRIVOUL	friovul	friecul	JUISTER	jusiter	jurater
MOUNIER	mouiner	mouacer	TOUCREL	tocurel	tovirel
PLAMIET	plaimet	plauret	RESTOIL	resotil	resedil
CROUSER	crosuer	cronier	FERRAIN	ferarin	feruvin
PRINEUR	prienur	priasur	PESTION	pesiton	pesalon
PROUCER	procuer	prorier	PASSOIN	pasosin	pasuvon
CROICUL	crociul	croneul	MARPOIN	maropin	maregin
BRAIRER	brarier	bramuer	NANTIER	naniter	nanofer
PREINET	preniet	presuet	MANSEIL	manesil	manucil

PLARIOL	plairol	plaucol	PEVROIR	pevorir	pevasir
CROIRAN	crorian	crovuan	RETROIR	retorir	retuvir
PLOUDER	ploduer	plotier	TOMPUIS	tomupis	tomagis
CRAISER	crasier	cranuer	DANMIER	danimer	danover
LAUSINT	lasuint	lameint	NAPROIS	naporis	napinis
CLOISAN	closian	clonuan	VECTION	veciton	vecalon
VRINOIS	vrionis	vriacis	RUPROIL	ruporil	rupucil
TRARIET	trairet	trauvet	PONTIER	poniter	ponaler
VROUPER	vropuer	vrogier	CIRCOIT	cirocit	ciranit
LOISAIN	losiain	loruain	REVROIN	revorin	revucin
TRAUVET	travuet	traciet	MISSAIN	misasin	minorin
NOISORD	nosiord	nocuord	NOICLON	nocilon	novulon
FRONUAN	frounan	froiran	RONSUAN	ronusan	ronivan
GEUSOIR	gesuoir	gemioir	BEURPOL	berupol	besipol
RIALURC	rilaurc	ritourc	NIATRUR	nitarur	niborur
TRENUAL	treunal	treimal	JERTUAR	jerutar	jeridar
DRASUAN	drausan	drailan	JASPUAN	jasupan	jasigan
BRODIEL	broidel	broutel	RONVIEL	ronivel	ronusel
FRASIAL	fraisal	fraucal	NARCIAL	narical	naruval
GUEJURC	gujeurc	gupaurc	GUENFUL	guneful	guriful
BLEVIEN	bleiven	bleuren	GEPRIEL	gepirel	gepusel

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Table 1. *Characteristics of the items used in Experiment 1*

	'Same' responses	'Different' responses				
		Referent	Baseline	CC	VV	CV
Example	*VALSEUR*	*POIVRER*	*batsion*	*poirver*	*piovrer*	*povirer*
Number	120	120	120	120	120	120
Lexical frequency	7.24	4.23	-	-	-	-
Number of letter	7.49	7.31	7.31	7.31	7.31	7.31
Summed bigram frequency	24,243	23,492	22,195	21,736	21,332	21,348
Transposition position	-	-	3.71	3.53	4.37	3.97

Note. 78% and 22% of the referent words included a –VVCC– and –CCVV– sequence respectively.

Table 2. *Mean reaction times (in ms) and percentage of errors on target words in Experiment 1*

	Examples	RTs	Error rates
'Same' responses	VALSEUR-valseur	617	3.3
'Different' responses			
Baseline	POIVRER-batsion	576	1.2
CC transposition	POIVRER-poirver	763	19.8
VV transposition	POIVRER-piovrer	679	5.4
CV transposition	POIVRER-povirer	651	5.1

Table 3. Characteristics of the items used in Experiment 2

	‘Same’ responses	‘Different’ responses			
		Referent	Baseline	CC	CV
Example	*CRUAUTÉ*	*PEUPLIER*	*guormand*	*peulpier*	*peupiler*
Number	120	120	120	120	120
Lexical frequency	7.24	4.23	-	-	-
Number of letter	7.49	7.31	7.31	7.31	7.31
Summed bigram frequency	24,243	23,492	22,195	21,736	21,332
Transposition position	-	-	3.71	3.53	4.37

Note. 20% and 80% of the referent words included a –VVCC– and –CCVV– sequence respectively.

Table 4. *Mean reaction times (in ms) and percentage of errors on target words in Experiment 2*

	Examples	RTs	Error rates
‘Same’ responses	CRUAUTÉ-cruauté	677	3.6
‘Different’ responses			
Baseline	PEUPLIER-guormand	598	2.4
CC transposition	PEUPLIER-peulpier	842	19.4
CV transposition	PEUPLIER-peupiler	755	10.2

Table 5. Characteristics of the items used in Experiment 3

	'Same' responses	'Different' responses					
		Baseline		Preserved structure		Modified structure	
		Referent	Target	Referent	Target	Referent	Target
Example	*FOIREUX*	*POIREAU*	*drouger*	*PLUMIER*	*pluimer*	*POIVRER*	*povirer*
Number	90	30	30	30	30	30	30
Lexical frequency	11.01	13.91	-	17.10	-	12.32	-
Number of letters	7	7	7	7	7	7	7
Summed bigram fq.	25,847	25,847	16,312	22,443	17,585	27,433	18,383
Transposition position	-	-	-	-	3.63	-	3.60

Notes. 63% and 37% of the referent words in the preserved structure condition included a –VVCV– and –VCVV– sequence respectively. 40% and 60% of the referent words in the modified structure condition included a –VVCC– and –CCVV– sequence respectively.

Table 6. *Mean reaction times (in ms) and percentage of errors on target words in Experiment 3*

	Examples	RTs	Error rates
'Same' responses	FOIREUX-foireux	589	2.6
'Different' responses			
Baseline	POIREAU-drouger	583	1.3
Structure-preserving transposition	PLUMIER-pluimer	713	11.2
Structure-modifying transposition	POIVRER-povirer	670	8.2

Table 7. Characteristics of the items used in Experiment 4

	'Same' responses	'Different' responses					
		Baseline		Preserved structure		Modified structure	
		Referent	Target	Referent	Target	Referent	Target
Example	*NAIRAUX*	*ROUTIOR*	*dronget*	*FEUSAIR*	*fesuair*	*MAUGLER*	*maguler*
Number	90	30	30	30	30	30	30
Number of letters	7	7	7	7	7	7	7
Summed bigram fq.	23,942	21,936	19,278	21,186	19,030	27,441	20,015
Transposition position	-	-	-	-	3.60	-	3.60

Notes. 73% and 27% of the referent pseudowords in the preserved structure condition included a –VVCV– and –VCVV– sequence respectively. 40% and 60% of the referent pseudowords in the modified structure condition included a –VVCC– and –CCVV– sequence respectively.

Table 8. *Mean reaction times (in ms) and percentage of errors on target words in Experiment 4*

	Examples	RTs	Error rates
‘Same’ responses	NAIRAUX-nairaux	619	8.7
‘Different’ responses			
Baseline	ROUTIOR-dronget	597	6.1
Structure-preserving transposition	FEUSAIR-fesuair	762	24.8
Structure-modifying transposition	MAUGLER-maguler	728	18.6

Table 9. Characteristics of the items used in Experiment 5a

	'Same' responses	'Different' responses					
		Baseline		Preserved structure		Modified structure	
		Referent	Target	Referent	Target	Referent	Target
Example	*NAIRAUX*	*VENTION*	*boribel*	*FIEDURT*	*fideurt*	*MIEDRAR*	*miderar*
Number	90	30	30	30	30	30	30
Number of letters	7	7	7	7	7	7	7
Summed bigram fq.	23,942	25,158	20,937	22,009	15,749	28,294	19,754
Transposition position	-	-	-	-	3.53	-	3.53

Notes. In both the preserved structure and the modified structure conditions, 47% of the referent pseudowords included a –VVCC– sequence and 53% included a–CCVV– sequence.

Table 10. *Mean reaction times (in ms) and percentage of errors on target words in Experiment 5a*

	Examples	RTs	Error rates
'Same' responses	NAIRAUX-nairaux	661	6.0
'Different' responses			
Baseline	VENTION-boribel	623	2.1
Structure-preserving transposition	FIEDURT-fideurt	839	11.9
Structure-modifying transposition	MIEDRAR-miderar	798	11.1

Table 11. Characteristics of the items used in Experiment 5b for the ‘different’ responses

	Example	Number	Number of letters	Summed bigram fq.	Transposition position
Preserved structure					
Referent	FOUREIL	40	7	22 277	-
Target: Transposed letters	forueil	40	7	18 264	3.6
Target: Substituted letters	fovieil	40	7	16 339	-
Modified structure					
Referent	BOUDLET	40	7	26 544	-
Target: Transposed letters	bodulet	40	7	18 165	3.6
Target: Substituted letters	bofalet	40	7	18 074	-
Baseline					
Referent	PAIREUX	40	7	22 988	-
Target	drauget	40	7	18 977	-

Table 12. *Mean reaction times (in ms) and percentage of errors (brackets) on target words in Experiment 5b*

	Preserved structure	Modified structure	*Differences*
Transposition	903 (29.7)	863 (20.6)	*40 ms (9.1)*
Substitution	691 (5.3)	686 (4.3)	*5 ms (1.0)*

Notes. Mean reaction times for the 'same' responses and the 'different' responses in the baseline condition were 655 ms and 648 ms respectively (8.5 and 3.5% in error rates respectively).

Table 13. Indices of orthographic similarity in the five experiments

	Model used for the computation of orthographic similarity		
	SOLAR (Davis, 2006)	Open bigram (Grainger & van Heuven, 2004)	Overlap (Gomez, Perea, Ratcliff, 2008)
Experiment 1			
CC	0.91	0.90	0.39
VV	0.91	0.88	0.39
CV	0.91	0.88	0.38
p value (CC vs. CV)	-	*< .001*	*.01*
p value (VV vs. CV)	-	*.60*	*.001*
Experiment 2			
CC	0.92	0.88	0.41
CV	0.91	0.87	0.41
p value	*.01*	*.09*	*.57*
Experiment 3			
Preserved structure	0.91	0.88	0.36
Modified structure	0.91	0.90	0.38
p value	-	*.054*	*0.22*
Experiment 4			
Preserved structure	0.91	0.88	0.37
Modified structure	0.91	0.90	0.37
p value	-	*.03*	*.77*
Experiment 5a			
Preserved structure	0.91	0.87	0.37
Modified structure	0.91	0.89	0.37
p value	-	*.10*	*.86*
Experiment 5b			
Preserved structure	0.91	0.88	0.37
Modified structure	0.91	0.89	0.38
p value	-	*.04*	*.33*

Notes. Scores of orthographic similarity range from 0 to 1, with 0 indicating no similarity between the two items (e.g., *paireux-clongot*) and 1 a perfect match (e.g., *paireux-paireux*).

Figure captions

Figure 1. *Example of hierarchy of detectors involved in visual word processing (features, letters, vowel-centered units, words)*

Figure 2. *Effects of orthographic structure (black line) and of letter similarity (grey lines) across quantiles in the four experiments. Transparent grey spaces around the lines represent the confident intervals*

Figure 3. *Schematic representations of orthographic coding models including vowel-centered units (highlighted in bold). See text for explanations*

Figure 1

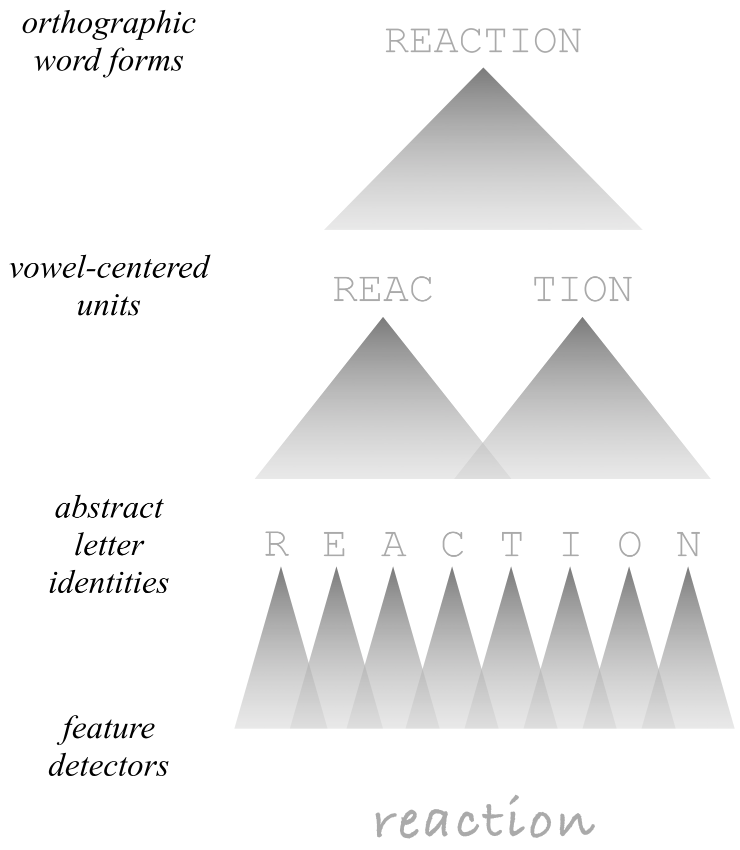

orthographic word forms
REACTION
vowel-centered units
REAC
TION
abstract letter identities
R E A C T I O N
feature detectors
reaction

Figure 2

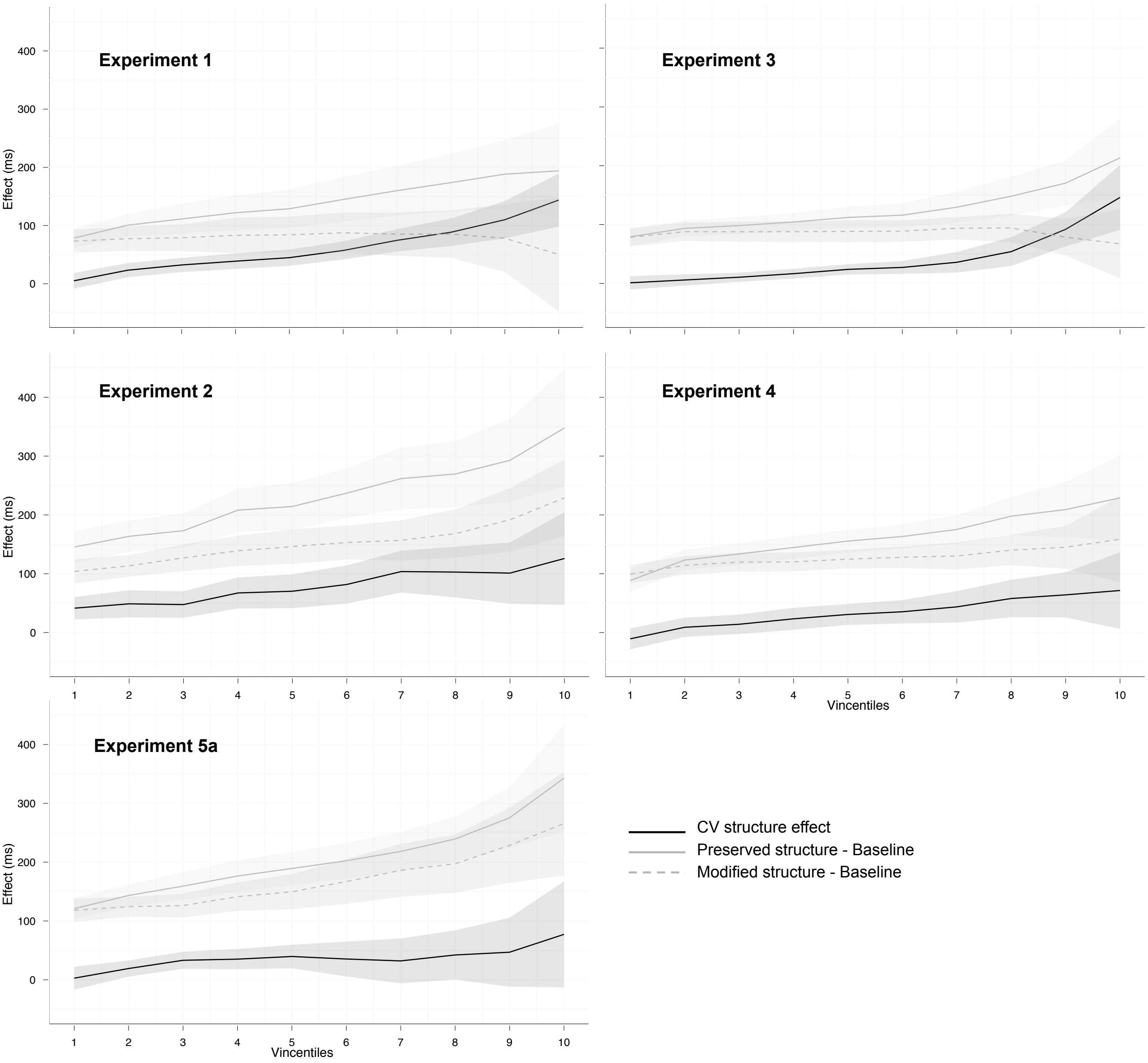
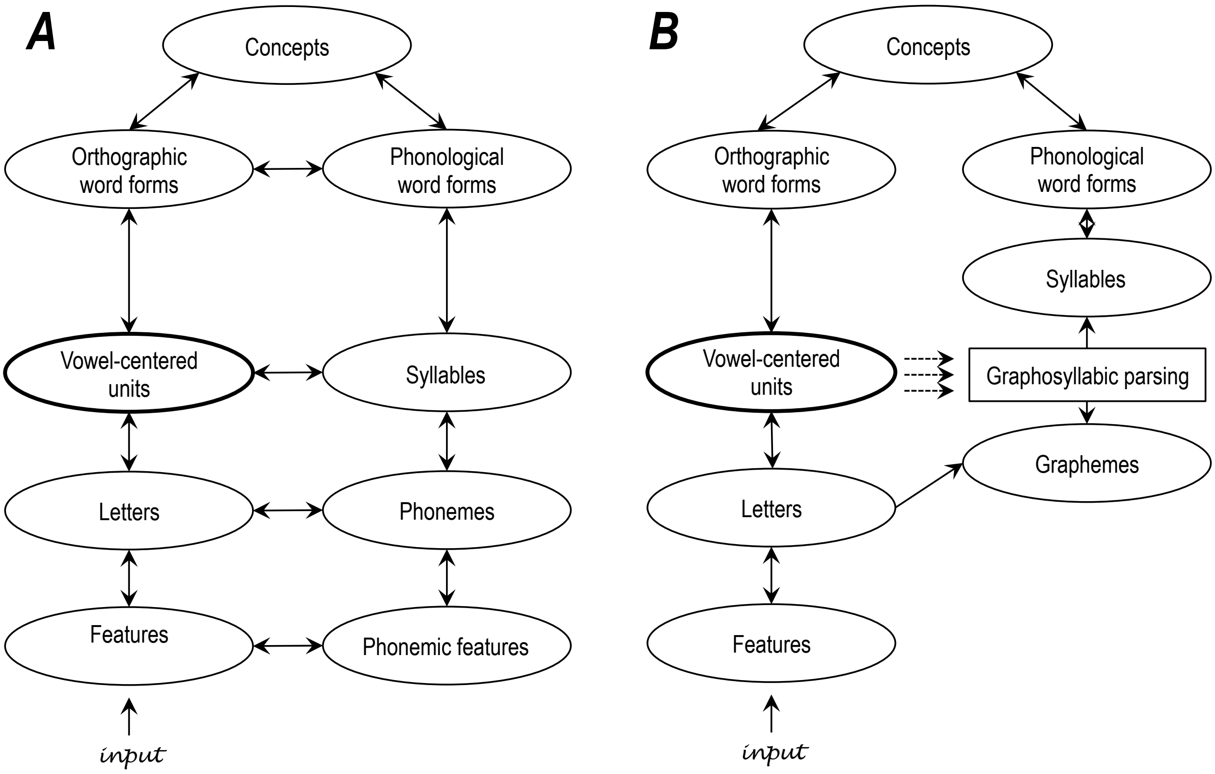

Experiment 1
Experiment 3
Experiment 2
Experiment 4
Experiment 5a
Effect (ms)
400
300
200
100
0
1
2
3
4
5
6
7
8
9
10
Vincentiles
CV structure effect
Preserved structure - Baseline
Modified structure - Baseline

Figure 3


A
Concepts
Orthographic word forms
Phonological word forms
Vowel-centered units
Syllables
Letters
Phonemes
Features
Phonemic features
input
B
Concepts
Orthographic word forms
Phonological word forms
Syllables
Vowel-centered units
Graphosyllabic parsing
Graphemes
Letters
Features
input