Parafoveal letter-position coding in reading

Joshua Snell^{1,2} · Daisy Bertrand¹ · Jonathan Grainger^{1,3}

Published online: 8 January 2018
© Psychonomic Society, Inc. 2018

Abstract

The masked-priming lexical decision task has been the paradigm of choice for investigating how readers code for letter identity and position. Insight into the temporal integration of information between prime and target words has pointed out, among other things, that readers do not code for the absolute position of letters. This conception has spurred various accounts of the word recognition process, but the results at present do not favor one account in particular. Thus, employing a new strategy, the present study moves out of the arena of *temporal*- and into the arena of *spatial* information integration. We present two lexical decision experiments that tested how the processing of six-letter target words is influenced by simultaneously presented flanking stimuli (each stimulus was presented for 150 ms). We manipulated the orthographic relatedness between the targets and flankers, in terms of both letter identity (same/different letters based on the target's outer/inner letters) and letter position (intact/reversed order of letters and of flankers, contiguous/noncontiguous flankers). Target processing was strongly facilitated by same-letter flankers, and this facilitatory effect was modulated by both letter/flanker order and contiguity. However, when the flankers consisted of the target's inner-positioned letters alone, letter order no longer mattered. These findings suggest that readers may code for the relative position of letters using words' edges as spatial points of reference. We conclude that the flanker paradigm provides a fruitful means to investigate letter-position coding in the fovea and parafovea.

Keywords Orthographic processing · Reading · Parallel processing · Letter-position coding · Flanker task

There is general consensus that the process of visual word recognition is largely driven by orthographic processing—that is, the coding of letter identity and letter position and the consequent activation of lexical representations. However, decades of reading research have made it clear that the cognitive mechanisms underlying letter-position coding are not easy to pinpoint, and today's researchers are still faced with the challenge of “cracking the orthographic code” (Grainger, 2008). Nonetheless, the development of good, testable theoretical models and experimental paradigms fit to put those models to the test has advanced our understanding of the recognition process considerably.

The masked-priming lexical decision task, pioneered by Forster and Davis (1984, 1987), has arguably made the strongest impact. In this task, participants make lexical decisions (*word*,

nonword) about target words that are preceded by briefly presented (sometimes unnoticed) prime words. Manipulating the way in which prime words relate to target words—for example, in terms of orthography, phonology, or semantics—has allowed researchers to gain insight into whether and how these types of information are processed and integrated over time.

Concerning orthographic processing, masked priming has revealed at least three things. Firstly, orthographic information can be integrated across multiple stimuli, such that same-letter primes lead to faster target recognition than do different-letter primes (e.g., Forster & Davis, 1984; Forster, Davis, Schoknecht, & Carter, 1987). Secondly, this integration process may be carried on to the lexical level, such that orthographically related word pairs (orthographic neighbors: e.g., *rock–rack*) compete for recognition by exerting mutual inhibition, leading to slower recognition than for unrelated word pairs (e.g., *stop–rack*) (e.g., Davis & Lupker, 2006; De Moor & Brysbaert, 2000; De Moor, Van der Herten, & Verguts, 2007; Segui & Grainger, 1990). Thirdly, evidence suggests that readers do not code for the absolute positions of letters. For instance, it has been shown that target words are recognized faster after a transposed-letter prime (e.g., *mohter–mother*) than after a prime with different letters at the same

✉ Joshua Snell
joshua.snell@hotmail.com

¹ Aix-Marseille Université, Marseille, France

² Brain & Language Research Institute, Aix-en-Provence, France

³ Centre Nationale de Recherche Scientifique, Marseille, France

positions (e.g., *monder–mother*) (Perea & Lupker, 2004; Schoonbaert & Grainger, 2004). Additionally, Peressotti and Grainger (1999) found that the processing of six-letter target words was facilitated by four-letter relative-position primes (e.g., *mtmr–mother*), as compared to unrelated primes (e.g., *lndn–mother*) (see also Bowers, Davis, & Hanley, 2005; Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006; Van Assche & Grainger, 2006).

The conception that readers do not code for the absolute position of letters has led researchers to argue against the seminal interactive-activation model (IAM) of McClelland and Rumelhart (1981; Rumelhart & McClelland, 1982), wherein letters are processed in a rigid, slot-based fashion (e.g., *rock* would strictly activate a detector for *r* at Position 1, a detector for *o* at Position 2, etc.), and the search for theoretical alternatives has since spurred at least three modeling approaches: noisy slot-based coding, spatial coding, and relative-position coding. *Noisy slot-based coding* refers to the addition of Gaussian noise to the slot-based scheme of the IAM (Gomez, Ratcliff, & Perea, 2008; Norris & Kinoshita, 2012), meaning that each letter of a stimulus would activate the node representing that letter not only at its specific slot (*n*), but also at slots $n - 2$, $n - 1$, $n + 1$, $n + 2$, and so forth, with increasing eccentricity from the letter's true position leading to weaker activation. This Gaussian noise renders the system less efficient but more flexible, and allows it to account for the effects of transposed-letter primes and relative-position primes (although some extreme cases of relative-position priming might be problematic for noisy slot coding).

Spatial coding (Davis, 1999, 2010) implements flexibility in a fairly similar way, by adding letter-position uncertainty to a spatial code of letter representations. The SOLAR model additionally assumes a certain amount of length-independent flexibility, such that the word *backstop* would activate the representations for *back* and *stop*, as well (Davis, 2010).

The third modeling approach, *relative-position coding*, assumes that orthographic input activates location-invariant nodes that represent the relative positions of within-word letter pairs (e.g., the stimulus *rock* would activate nodes for *ro*, *rc*, *rk*, *oc*, *ok*, and *ck*; see Grainger & van Heuven, 2003; Whitney, 2001). These so-called *open-bigram* units in turn activate all lexical representations that they belong to. The unit *ro*, for example, would activate *rock*, but also *rose* and *ribbon*. Accounting for the transposed-letter priming effect (e.g., *rock* is primed more strongly by *rcok* than by *rdok*), the lexical representation of *rock* would be activated by a larger subset of the open-bigram units with the former prime (*rc*, *ro*, *rk*, *ck*, and *ok*) than with the latter (*rk* only) (Grainger & Whitney, 2004).

Beyond the isolated word

The three modeling approaches seem to do equally well in explaining results obtained with the masked-priming paradigm (e.g., Grainger, 2008, for a review), suggesting that the question of which account of orthographic processing is the most plausible cannot be answered by the masked-priming paradigm alone. In the present article, we therefore shift focus away from temporal information integration as revealed by masked-priming, and instead build on evidence suggesting that readers can also integrate information across spatially distinct stimuli.

Using a paradigm in which participants had to identify two words that were briefly presented together (e.g., *sand lane*), McClelland and Mozer (1986) showed that letter migration errors can occur (e.g., *land sane*). Davis and Bowers (2004) showed that such illusory identifications do not have to respect position: Given a word pair such as *step soap*, participants could also respond “stop,” indicating a migration of the letter *o* from Position 2 to Position 3.

In sentence reading, fixation durations on word *n* are found to be shorter when *n* is orthographically related to word $n + 1$ (Angele, Tran, & Rayner, 2013; Dare & Shillcock, 2013; Inhoff, Radach, Starr, & Greenberg, 2000; Kennedy & Pynte, 2005; Snell, Vitu, & Grainger, 2017), indicating that orthographic information from multiple words is simultaneously processed and integrated. Furthermore, using the novel flanking-letters lexical decision (FLLD) task, Dare and Shillcock (2013) found that lexical decisions about foveal target words were made faster when the target letters were repeated as flankers on each side (e.g., *ro rock ck*), as compared to when the flanker letters were unrelated (*st rock ep*). Crucially, the same facilitatory effect was obtained when the order of the flanker bigrams was reversed (*ck rock ro*). As was pointed out by Grainger, Mathôt, and Vitu (2014), this particular finding is in line with the open-bigram model of Grainger and van Heuven (2003), which operates on the principle that open-bigram nodes (representing the relative position of within-word letter pairs) are location-invariant. In a similar experiment, Grainger et al. went on to replicate the absence of an effect of bigram order, but at the same time found that letter order did matter (i.e., *or rock kc* led to longer RTs than did *ro rock ck*), confirming the importance of relative as opposed to absolute letter position.

Indeed, it is difficult to conceive how noisy slot-based coding could account for these findings, since the greater distance between letter occurrences in the switched bigram condition should have led to less activation and therefore longer RTs (e.g., the parafoveal *k* is only three slots away from the target's *k* in *ro rock ck*, whereas it is five slots away in *ck rock ro*). The only solution to this problem would be to assume that the target and flankers were processed as three separate units, such that the *k* in the flanker *ck* was coded for Position 2,

irrespective of the position of the flanker relative to the target. The *k* in the target *rock* would as such receive additional activation from a *k* that was only two slots away, in both the original and the switched bigram condition.

The letter-order effect reported by Grainger et al. (2014) suggests that both the coding of parafoveal letters and the spatial integration of this information is quite fine-grained. However, more research needs to be done in order to gain full understanding of the mechanisms underlying (parafoveal) letter-position coding. For instance, according to the open-bigram model of Grainger and van Heuven (2003), similar facilitatory parafoveal-on-foveal effects should be obtained with contiguous flankers (e.g., *ro rock ck*) and noncontiguous flankers (e.g., *rc rock ok*). Furthermore, it can be argued that the stimuli used in the aforementioned FLLD studies were within the limits of what readers can process in a single glance, and it would be worthwhile to see whether the presence of a letter-order effect and the absence of a bigram-order effect (i.e., location invariance) persist in a setting using longer targets and flankers. Finally, previous research has suggested that outer-positioned letters may have a special role in orthographic processing, due to reduced crowding effects for these letters as compared to inner-positioned letters, and it has been argued that the edges of a word may be used as anchoring points during letter-position coding (e.g., Fischer-Baum, Charny, & McCloskey, 2011; Fischer-Baum, McCloskey, & Rapp, 2010; Jacobs, Rey, Ziegler, & Grainger, 1998). The FLLD paradigm would be suited to put this conception to the test, for instance by comparing intact- versus reversed-letter flankers using only inner-positioned letters (e.g., *ar barrel re* vs. *ra barrel er*).

Below we report two experiments that address these issues. Experiment 1 was designed as a test of the importance of letter order and contiguity, in a setting using six-letter targets and three-letter flankers. Experiment 2 provides a further test of the open-bigram scheme of Grainger and van Heuven (2003) by comparing intact versus switched flankers in a setting using six-letter targets and three-letter flankers. Additionally, Experiment 2 compares intact versus reversed-letter flankers using inner-positioned letters, to test an account of letter-position coding according to which the word's edges are used as spatial points of reference.¹

Experiment 1

Method

Participants Twenty students volunteered to participate in this study, carried out at Aix-Marseille Université in Aix-en-Provence, France. All students reported being nondyslexic

and native to the French language and had normal or corrected-to-normal vision. All students were naïve to the purpose of the experiment.

Stimuli and design From the French Lexicon Project lexicon and its pseudoword lexicon counterpart (Ferrand et al., 2010), we retrieved 150 six-letter word targets and 150 six-letter pseudoword targets (the latter of which were used as filler stimuli). These targets were selected from a lexical decision time (LDT) range of 500–700 ms (the mean frequency of the word targets was 4.79 Zipf; see Van Heuven, Mandera, Keuleers, & Brysbaert, 2014, for more on the Zipf scale). The word targets were nouns, adjectives, or nonconjugated verbs. The targets contained no diacritics (e.g., *á, î, û, ç*), since although these marks are quite typical in the French orthography, their effects are not well-documented in word recognition research.

In every trial, the target was flanked by three letters on the left and three letters on the right. We manipulated these flanking letters across five conditions, as can be seen in Table 1. Four of the five conditions had flankers that were orthographically related to the target, whereas the fifth condition served as a control with unrelated flankers. For this control condition we retrieved a word from the lexicon for each target, such that the LDT values were equal (difference < 50 ms) and there was no orthographic overlap (the mean frequency of the control words was 4.83 Zipf). The pseudoword targets were coupled to an unrelated pseudoword in a similar way. The unrelated words were split into two halves that were used as left- and right-sided flankers, respectively (e.g., the target *laptop* and unrelated word *sprint* would become *spr laptop int*). The four related conditions followed a 2×2 factorial design, with letter order (intact/reversed) and contiguity (contiguous/noncontiguous) as factors. The same conditions were also implemented for the pseudoword trials. We used a Latin-square design to ensure that all targets were seen across all conditions, but only once per participant. The experiment thus consisted of 300 experimental trials, which were presented in randomized order.

Apparatus and software The stimuli and experimental design were implemented with OpenSesame (Mathôt, Schreij, & Theeuwes, 2012) and presented on a 17-in., $1,024 \times 768$ pixel, 150-Hz display. Participants were seated at a 60-cm distance from the display, so that each character space subtended 0.30° of visual angle.

Procedure Participants were seated in a comfortable office chair in a dimly lit room. Centrally positioned vertical fixation bars, separated from one another by 0.60° of visual angle, were shown throughout each trial. At 500 ms after the start of every trial, a target stimulus with flankers (separated from the target by one character space) was shown for 150 ms

¹ All data from the present work are available at <https://osf.io/y2vj8/>.

Table 1 Experiment 1 conditions

	Intact Letter Order				Reversed Letter Order			
Contiguous letters	123	123456	456	321	123456	654		
Noncontiguous letters	135	123456	246	531	123456	642		
Control (unrelated letters)	ddd	123456	ddd					

The target's letters are indicated by the digits 123456. The flanker digits indicate letter identities based on their respective locations in the target. Unrelated letters, used in the control condition, are indicated with *ds*.

between the fixation bars, after which participants had a maximum of 2,000 ms to respond. Responses were given by means of a right- or a left-handed button press to indicate “word” or “nonword,” respectively. In the case of a correct button response, a green fixation dot was shown at the center of the screen for 700 ms. In the case of an incorrect- or of no response, a red fixation dot was shown for 700 ms. The display then returned to the beginning state, and after 500 ms a new trial would commence. Participants were offered a short break after every block of 100 trials. They would start every block with three practice trials, for which we did not collect data. The experiment lasted approximately 20 min.

Results

Only correctly answered trials with a word target² were included in the analysis of response times (RTs). Trials with an RT beyond 2.5 *SDs* from the grand mean (2.8%) were discarded. We used linear mixed-effect models (LMMs) with items and participants as crossed random effects (Baayen, 2008; Baayen, Davidson & Bates, 2008). We followed Barr, Levy, Scheepers, and Tily (2013) in determining the maximal random-effects structure permitted by the data. This led us to include by-item and by-participant random slopes alongside random intercepts.³ The models were fitted with the lmer function from the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) in the R statistical computing environment. We report regression coefficients (*b*), standard errors (*SE*), and *t* values. Fixed effects

² In pseudoword trials, no significant effects were observed in RTs (relative to the control condition: $b = 10.69$, $SE = 12.96$, $t = 0.83$, for contiguous intact-letter-order flankers; $b = 0.26$, $SE = 13.06$, $t = 0.02$, for contiguous reversed-letter-order flankers; $b = 0.73$, $SE = 13.09$, $t = 0.06$, for noncontiguous intact-letter-order flankers; and $b = -7.76$, $SE = 13.05$, $t = -0.59$, for noncontiguous reversed-letter-order flankers). No main effects of letter order ($b = 10.25$, $SE = 9.41$, $t = 1.09$) and contiguity ($b = 9.91$, $SE = 9.31$, $t = 1.06$) were observed. Similar nonsignificant values were observed in the error rates.

³ It should be noted that there is as of yet no consensus on the most appropriate random-effects structure of LMMs, with some researchers being in favor of the maximal random-effects structure (e.g., Barr et al., 2013), while others prefer models with fewer parameters (e.g., Baayen et al., 2008). Indeed, one may argue that the models used in the present study were over-parameterized, since the correlations between the random slope and intercept were 1.0 for participants and .8 for items. Importantly, the patterns of effects reported in this work persisted with a simpler model.

were deemed reliable if $|t| > 1.96$. Logistic LMMs were used to analyze the error rates.

Prior to the analyses, we determined for each of the 3,000 trials whether the flankers were in themselves words, as well as whether the flankers were pronounceable. The rationale here was that the lexicality and pronounceability of flankers may have biased participants toward a certain response (e.g., nonword flankers and/or unpronounceable flankers might have induced a “nonword” response). In a similar vein, we determined the flanker bigram frequency, considering that flankers with a low bigram frequency could have been experienced as more unusual, again biasing participants toward the “nonword” response. Flanker bigram frequencies represent the average frequency of all bigrams (as indicated by the Lexique bigram database of New and Pallier⁴) that occur in the flanker (e.g., *ye*, *ys*, and *es* in *yes*). These variables were not taken into consideration during stimulus selection, but their potential relevance was realized at a later stage. Hence, to exclude the possibility that our results would be (partially) driven by these variables, flanker lexicality, pronounceability, and bigram frequency (log ppm) were included in the LMMs for all analyses. These variables are also listed in Table 2.

As will be seen below, none of our effects of interest were influenced by flanker lexicality, pronounceability, or bigram frequency. Note that one might nonetheless also attempt to control these variables in the stimulus selection phase,⁵ rather than in the analyses.

Response times Table 3 shows the mean RTs and error rates across conditions. There were significantly lower RTs in all conditions with target-related flankers, as compared to the control condition (Table 4). Meanwhile, no significant influence of flanker lexicality ($b = -10.78$, $SE = 10.67$, $t = -1.01$), pronounceability ($b = 4.20$, $SE = 4.94$, $t = 0.85$), or bigram frequency ($b = 0.70$, $SE = 3.18$, $t = 0.22$) was established.

We observed a significant main effect of flanker letter order, such that RTs in trials with intact-letter-order flankers were lower than RTs in trials with reversed-letter-order flankers, with $b = 14.00$, $SE = 3.90$, $t = 3.59$. This effect of letter order was not modulated by flanker lexicality ($b = -4.42$, $SE = 8.76$, $t = -0.51$), pronounceability ($b = 3.75$, $SE = 9.86$, $t = 0.38$), or bigram frequency ($b = 3.31$, $SE = 5.47$, $t =$

⁴ www.lexique.org/listes/liste_bigrammes.php

⁵ To control for the lexicality and pronounceability of flankers, we checked whether the flankers occurred in the word and pseudoword lexicons of Ferrand et al. (2010). All flankers occurring in either lexicon were marked as *pronounceable*; all flankers specifically occurring in the word lexicon were marked as *word*. All other flankers were marked as *nonword* and/or *unpronounceable*. One might apply the same procedure to filter out stimuli during the stimulus selection phase. As for flanker bigram frequency, one would have to delete stimuli until the average flanker bigram frequencies were equal across conditions.

Table 2 Numbers of word target trials with word flankers or pronounceable flankers in Experiment 1

	<i>Trials With Word Flankers</i>	<i>Trials With Pronounceable Flankers</i>	<i>Average Bigram Frequency (log ppm)</i>
<i>Contiguous intact</i>	0	180	3.78
<i>Contiguous reversed</i>	132	213	3.72
<i>Noncontiguous intact</i>	0	70	3.72
<i>Noncontiguous reversed</i>	0	33	3.64
<i>Control (unrelated letters)</i>	0	186	3.87

0.61) (these variables did not produce main effects in either this analysis or subsequent analyses).

We also found a significant main effect of contiguity, with contiguous-letter flankers yielding shorter RTs than noncontiguous-letter flankers: $b = 7.39$, $SE = 3.31$, $t = 2.23$. Like letter order, the effect of contiguity was not modulated by flanker lexicality ($b = -4.42$, $SE = 8.76$, $t = -0.51$), pronounceability ($b = 8.14$, $SE = 11.76$, $t = 0.69$), or bigram frequency ($b = -3.16$, $SE = 6.71$, $t = 0.47$). There was also no significant interaction between letter order and contiguity: $b = 2.46$, $SE = 6.61$, $t = 0.37$.

Error rates As compared to the control condition, the error rates were significantly lower in the contiguous bigram conditions (Table 4). Again, flanker lexicality ($b = -0.46$, $SE = 0.68$, $z = -0.67$), pronounceability ($b = -0.35$, $SE = 0.32$, $z = -1.10$), and bigram frequency ($b = -0.02$, $SE = 0.21$, $z = -0.08$) had no influences here. Letter order produced no main effect ($b = 0.13$, $SE = 0.28$, $z = 0.46$) or interaction with flanker lexicality ($b = -0.24$, $SE = 0.56$, $z = -0.42$), pronounceability ($b = 0.20$, $SE = 0.33$, $z = 0.60$), or bigram frequency ($b = 0.49$, $SE = 0.29$, $z = 1.67$) on the error rate.

There was a marginally significant effect of contiguity, with contiguous flankers leading to fewer errors than noncontiguous flankers ($b = 0.50$, $SE = 0.29$, $z = 1.76$). This effect again was not modulated by flanker lexicality ($b = -0.69$, $SE = 0.59$, $z = -1.17$), pronounceability ($b = 0.28$, $SE = 0.31$, $z = 0.88$), or bigram frequency ($b = 0.53$, $SE = 0.34$, $z = 1.57$). As with the RTs, no significant interaction between letter order

and contiguity was found in the error rates: $b = 0.30$, $SE = 0.57$, $z = 0.52$.

Discussion

Experiment 1 replicated the letter-order effect reported by Grainger et al. (2014), this time with six-letter targets and three-letter flankers, suggesting that even at the greater eccentricities implicated by the use of longer stimuli in Experiment 1, parafoveal orthographic processing is sensitive to letter-position information. The fact that the reversed letter-order flankers nonetheless yielded considerably shorter RTs than the control flankers suggests that readers also code for separate letter identities, irrespective of position, and that the coding of letter identity and position may thus be represented by two distinct cognitive components (e.g., Grainger et al., 2014, argued for the presence of a “bag-of-letters” alongside a “bag-of-bigrams”; see also Peressotti & Grainger, 1995, for an earlier proposal). We also found an effect of contiguity, with contiguous flankers (e.g., 123 123456 456) yielding shorter RTs than noncontiguous flankers (e.g., 135 123456 246).

Within the open-bigram scheme of Grainger and van Heuven (2003), the effect of contiguity may be explained by the idea that bigrams are only formed between letters that are not too far apart from each other in the stimulus, meaning that the target 123456 would activate bigrams for 12, 13, and 14, but not for 15 or 16 (see also Hannagan & Grainger, 2012; Whitney, 2001). Similarly, the same target would activate bigrams for 56, 46, and 36, but not for 26. However, the

Table 3 Condition means

<i>Condition</i>	<i>Flanker Letters</i>		<i>RT (ms)</i>	<i>Error Rate</i>
<i>Contiguous intact</i>	123	456	562 (110)	.019 (.025)
<i>Contiguous reversed</i>	321	654	575 (120)	.024 (.031)
<i>Noncontiguous intact</i>	135	246	572 (121)	.032 (.033)
<i>Noncontiguous reversed</i>	531	642	579 (113)	.031 (.009)
<i>Control (unrelated letters)</i>	ddd	ddd	605 (124)	.040 (.010)

Values presented between parentheses indicate standard deviations.

Table 4 Analysis of response times and error rates (relative to the control condition)

<i>Condition</i>	<i>Response Time</i>			<i>Error Rate</i>		
	<i>b</i>	<i>SE</i>	<i>t</i>	<i>b</i>	<i>SE</i>	<i>z</i>
<i>Intercept</i>	594.80	30.72	14.48	-3.80	0.30	12.60
<i>Contiguous intact</i>	-42.03	5.31	-7.92	-0.81	0.39	-2.11
<i>Contiguous reversed</i>	-28.18	5.83	-4.84	-0.77	0.39	-1.99
<i>Noncontiguous intact</i>	-34.58	5.61	-6.16	-0.17	0.33	-0.52
<i>Noncontiguous reversed</i>	-20.96	5.78	-3.62	-0.43	0.35	-1.23

Significant values are shown in bold.

contiguous flankers 123 and 456 would activate the bigrams 12, 13, 23, 45, 46, and 56, all of which belong to the target's set of bigrams. In contrast, the noncontiguous flankers 135 and 246 would activate the bigrams 15 and 26, which are not among the target's set of bigrams, thus leading to increased RTs (however, see the Discussion section of Experiment 2 below for an alternative explanation). Importantly, the letter-order effect persisted in the noncontiguous flanker trials, in line with a relative-position coding scheme.

Our aim for Experiment 2 was twofold. Firstly, since we had replicated the letter-order effect reported by Grainger et al. (2014) using six-letter targets, we now wanted to provide a further test of the second claim of their study—that is, that bigram order does *not* matter. We thus compared the condition with intact flanker order (123 123456 456) against one with a switched flanker order (456 123456 123). Secondly, according to the relative-position coding approach, a letter-order effect should also be obtained when using inner-positioned letters in the flankers (e.g., comparing 23 123456 45 vs. 32 123456 54). However, it has been argued that outer-positioned letters may play an important role in letter-position coding (e.g., Fischer-Baum et al., 2011; Fischer-Baum et al., 2010; Jacobs et al., 1998), and this alternative account would predict no letter-order effect when using inner-positioned letters alone. We thus included these conditions in Experiment 2 as well. It should therefore be noted that Experiment 2 did not follow a 2×2 factorial design, but rather tested two pairs of conditions in isolation. We also included a control condition with unrelated flanker letters in order to evaluate overall effects of flanker relatedness.

Experiment 2

Method

Twenty-six students volunteered to participate in this study, carried out at Aix-Marseille Université in Aix-en-Provence, France. The experimental conditions for Experiment 2 are shown in Table 5. Other than that, the entire methodology for Experiment 2 was left unchanged from Experiment 1.

Results

We again included only correctly answered trials in the analysis of RTs. The 2.5-*SD* cutoff led to the exclusion of 2.94% of trials. The data were analyzed using LMMs in the same way as in Experiment 1. Flanker lexicality, pronounceability, and bigram frequency (Table 6) were again included as factors in all analyses.

We again found decreased RTs in all conditions with orthographically related flankers as compared to the control

Table 5 Experiment 2 conditions

<i>Intact flanker order</i>	123	123456	456
<i>Switched flanker order</i>	456	123456	123
<i>Intact inner letters</i>	23	123456	45
<i>Reversed inner letters</i>	32	123456	54
<i>Control (unrelated letters)</i>	ddd	123456	ddd

Targets' constituent letters are indicated by the digits 123456. The flanker digits indicate letter identities based on their respective locations in the target. Unrelated letters, used in the control condition, are indicated with *ds*.

condition (Tables 7 and 8), with no significant contribution of flanker lexicality ($b = -2.97$, $SE = 7.35$, $t = -0.40$), pronounceability ($b = 0.81$, $SE = 5.01$, $t = 0.16$), and bigram frequency ($b = 0.48$, $SE = 3.09$, $t = 0.15$).⁶

Flanker order Unlike Grainger et al. (2014) and Dare and Shillcock (2013), who found that bigram order (flanker order, in the present study) does not matter, here RTs were significantly decreased in the intact-flanker condition as compared to the switched-flanker condition: $b = 10.04$, $SE = 4.66$, $t = 2.16$. Flanker order did not interact with flanker lexicality (neither condition contained trials with word flankers), pronounceability ($b = 15.01$, $SE = 10.22$, $t = 1.47$), or bigram frequency ($b = -0.36$, $SE = 11.46$, $t = -0.03$).

It could have been the case that the bigram frequency of flankers consisting of Letters 1, 2 and 3 differed from that of the flankers consisting of Letters 4, 5 and 6, and that asymmetrical processing of the flankers drove our flanker order effect. Investigating this scenario, we found that the flankers 123 had a higher bigram frequency than did the flankers 456 (respectively, 3.93 and 3.69 log ppm). Interestingly, however, we also found that higher bigram frequencies of *rightward* flankers significantly reduced RTs ($b = -11.87$, $SE = 5.90$, $t = -2.01$), whereas the bigram frequency of leftward flankers had no influence ($b = 2.66$, $SE = 5.90$, $t = 0.45$). If the bigram frequency of rightward flankers played a crucial role, then we would expect shorter RTs in the switched-flanker-order condition. Given that we found the opposite result, it is safe to assume that our flanker-order effect was not confounded with differences in flanker bigram frequency combined with asymmetrical processing (note also that there was no interaction of flanker order and left- or rightward flanker bigram frequency: $b = 11.07$, $SE = 12.13$, $t = 0.91$, and $b = 4.93$, $SE = 12.01$, $t = 0.41$, respectively).

Flanker order did not influence the error rate: $b = 0.02$, $SE = 0.35$, $z = 0.06$. Nevertheless, the switched-flanker condition did lead to faster RTs and lower error rates than did the unrelated-flanker condition, in line with

⁶ As in Experiment 1, no significant effects were observed for pseudoword trials.

Table 6 Numbers of word target trials with word flankers or pronounceable flankers in Experiment 2

	<i>Trials With Word Flankers</i>	<i>Trials With Pronounceable Flankers</i>	<i>Average Bigram Frequency (log ppm)</i>
<i>Intact flanker order</i>	0	180	3.78
<i>Switched flanker order</i>	0	180	3.78
<i>Intact inner-letter flankers</i>	343	426	4.18
<i>Reversed inner-letter flankers</i>	238	293	4.08
<i>Control (unrelated letters)</i>	0	186	3.87

the findings of Dare and Shillcock (2013) and Grainger et al. (2014) for bigram flankers.

Inner-positioned letter order RTs and error rates did not differ significantly between the intact- versus the reversed-letter-order flankers when these flankers consisted of the target's inner-positioned letters alone: for RTs, $b = 4.25$, $SE = 4.68$, $t = 0.91$ (no modulation of flanker lexicality, $b = 13.33$, $SE = 10.91$, $t = 1.22$; pronounceability, $b = 13.33$, $SE = 10.91$, $t = 1.22$; or bigram frequency, $b = 11.62$, $SE = 6.92$, $t = 1.68$); for errors, $b = 0.04$, $SE = 0.31$, $z = 0.14$ (again no modulation of flanker lexicality, $b = -0.58$, $SE = 0.70$, $z = -0.82$; pronounceability, $b = -0.58$, $SE = 0.70$, $z = -0.82$; or bigram frequency, $b = -0.11$, $SE = 0.43$, $z = -0.26$).

Discussion

The results from Experiment 2 are quite clear-cut. The key finding of Dare and Shillcock (2013) and Grainger et al. (2014), that flanker order does not modulate the effect of related flankers, could not be confirmed in a setting using six-letter targets and three-letter flankers, since the switched-flanker condition yielded significantly longer RTs than the intact-flanker condition. Thus, these results argue against the idea that the absolute position of letters does not matter at all, at least concerning the integration of orthographic information across spatially distinct stimuli. Instead, taking the present results and the work of Grainger et al. together, it seems that location invariance only persists within certain spatial limits (see the General Discussion). Nonetheless, the fact that the switched-bigram flankers yielded lower RTs than the control

flankers indicates that the integration of orthographic information is, at least to a considerable degree, location-invariant.

Experiment 2 further showed that when flankers do not involve the target's outer-positioned letters, the effect of letter order disappears. This points to the importance of outer-positioned letters with respect to letter-position coding, in line with the proposals of Fischer-Baum et al. (2011) and Jacobs et al. (1998). According to their *both-edges* account of letter-position coding (Fischer-Baum et al., 2011), the location of an inner-positioned letter would be represented by its distances from the first (β) as well as the last (γ) letter of the word. Thus, the *r* in *target* would have the position representations $\beta + 2$ and $\gamma - 3$, whereas the *e* would have the position representations $\beta + 4$ and $\gamma - 1$. Combining this approach with a relative-position coding account, it may be that words only activate bigrams that consist of an outer-positioned letter: *target*, for instance, would activate *ta*, *tr*, *tg*, *rt*, *gt*, and *et*, but not *ar*, *rg*, or *ge*. Such a type of letter-position coding could take on more importance in peripheral vision, where position information becomes more noisy (Chung & Legge, 2009), while outer-positioned letters remain highly visible (e.g., Chanceaux & Grainger, 2012).

This approach to relative-position coding, using the word's edges as anchoring points, raises the question of how readers would be able to distinguish words (e.g., *target*) from their jumbled counterparts (*tgerat*), considering that these stimuli would activate the same set of bigrams. Here the answer would be that an increasing distance between a bigram's constituent letters should lead to increased activation of the

Table 7 Condition means

<i>Condition</i>	<i>Flanker Letters</i>		<i>RT (ms)</i>	<i>Error Rate</i>
<i>Intact flanker order</i>	123	456	600 (111)	.019 (.025)
<i>Switched flanker order</i>	456	123	612 (115)	.024 (.031)
<i>Intact inner-letter order</i>	23	45	605 (111)	.032 (.033)
<i>Reversed inner-letter order</i>	32	54	609 (112)	.031 (.009)
<i>Control (unrelated letters)</i>	ddd	ddd	645 (129)	.040 (.010)

Values presented between parentheses indicate standard deviations.

Table 8 Analysis of response times and error rates (relative to the control condition)

<i>Condition</i>	<i>Response Time</i>			<i>Error Rate</i>		
	<i>b</i>	<i>SE</i>	<i>t</i>	<i>b</i>	<i>SE</i>	<i>z</i>
<i>Intercept</i>	638.56	29.55	16.54	-3.30	1.43	2.32
<i>Intact flanker order</i>	-44.10	4.74	-9.30	-0.80	0.29	-2.75
<i>Switched flanker order</i>	-31.60	4.76	-6.64	-0.60	0.28	-2.18
<i>Intact inner-letter order</i>	-36.18	5.72	-6.32	-0.34	0.30	-1.13
<i>Reversed inner-letter order</i>	-31.86	5.72	-5.57	-0.35	0.30	-1.17

Significant values are shown in bold.

bigram. The rationale behind this assumption is that there should be more certainty about the relative positions of two objects when those objects are farther apart from each other. Lexical representations would be activated by specific bigram activity patterns. The representation for *target*, for example, would correspond to a highly active bigram node representing *te* and a less active node representing *ta*. This mechanism would then also account for the flanking-letter contiguity effect obtained in Experiment 1. Comparing the flankers 123 and 135, the distances between the letters in the former flanker matched those in the target, thus leading to a similar pattern of bigram activity. The latter flanker, in contrast, causes a different pattern of bigram activity, leading to slower target word recognition.

The concept of lexical activation through bigram pattern activation bears resemblance to spatial coding, as employed in Davis's (1999, 2010) SOLAR model. In the SOLAR model, location-specific letter detectors respond to the orthographic input in a quick, sequential, left-to-right fashion—meaning, for instance, that the visual input *target* will lead to the activation of a node coding for *t*, followed by the activation of a node coding for *a*, and so forth (the level of activation over time for each node follows a Gaussian function, meaning that multiple letters can be active at once, accounting for letter-position uncertainty). This dynamic activation pattern is coined the *spatial code*. Word nodes, in turn, are tuned to specific spatial codes, and the degree of similarity between the “learned” spatial code (i.e., the lexical representation) and the incoming signal pattern determines whether the word is recognized. In a both-edges bigram coding scheme, word nodes would be tuned to bigram node activities rather than letter node activities. The theoretical advantage of this approach is that multiple letters—or indeed, multiple stimuli—would be processed in parallel, rather than sequentially, in line with the kind of parallel processing that is revealed by the flanker paradigm.

It should not be forgotten that flankers without outer-positioned letters nonetheless led to lower RTs than did the control flankers. In this light, it must be stressed that a both-edges bigram coding scheme would serve to account for letter-position coding more than for letter-identity coding. As we argued in the Discussion of Experiment 1, letter identity and letter position may be encoded by two distinct cognitive mechanisms. As a consequence, letters would always to some degree activate lexical representations, irrespective of the absolute position of those letters.

General discussion

Previous work aiming to “crack the orthographic code” has predominantly employed the masked-priming paradigm (Forster & Davis, 1984), and results obtained with this

paradigm have led to the development of various cognitive accounts of the word recognition process. However, the bulk of masked-priming data, which mostly pertains to the temporal integration of orthographic information, does not favor any model in particular. In light of this, the present article builds on recent evidence that information about letter identity and position is integrated not only in the temporal dimension, but also in the spatial dimension (e.g., Dare & Shillcock, 2013; Grainger et al., 2014; Snell et al., 2017). Exploiting this principle, the FLLD paradigm pioneered by Dare and Shillcock provides an important novel approach to pinpointing the mechanisms underlying letter-position coding in reading.

The two experiments reported in this work tested the processing of six-letter target words, when those targets were flanked by two or three letters on each side. In both experiments we found that readers processed target words considerably faster when these were flanked by related as compared to unrelated letters. This effect continued to be quite strong ($b = 31.52$ ms) when the target's right- and left-sided letters were used as left- and right-sided flankers, respectively (e.g., *get target tar*; Exp. 2). Harmonizing this finding with a noisy slot-based account is not so straightforward, considering that each of the targets letters is seven positions away from its repetition in the flankers in this condition. Allowing letters to influence one another at such a distance would impair a noisy slot-based models performance greatly (e.g., Davis, 2010). On the other hand, as we have argued in this article, it is likely that letter identities are to some extent activated irrespective of the position of these letters in the visual input (see also Grainger et al., 2014). Yet, although this assumption would allow a noisy slot-based model to account for general effects of flanker relatedness, it would not allow such a model to account for the letter order effect reported here and in Grainger et al. (2014).

Although relative-position coding accounts for these findings quite effectively, we did find a difference between the aforementioned switched-flanker condition (*get target tar*) and the intact-flanker condition (*tar target get*), contrasting with Dare and Shillcock (2013) and Grainger et al. (2014), who found that flanker order did not matter when using four-letter targets and two-letter flankers (e.g., *ck rock ro*). Taking these results together, factors may be at play that cause orthographic information to be tied to specific spatial locations more strongly under certain conditions. For instance, the three-letter flankers in the present experiments may have borne more processing weight than the two-letter flankers in the studies of Dare and Shillcock (2013) and Grainger et al. (2014), causing increased lateral activation at early visual-processing stages, consequently allowing higher processing levels to make a stronger distinction between information stemming from the left and right visual hemifields. Alternatively, it might be that the flanker-order effect is driven by differences in processing of the initial versus the final

letters in the target word, combined with a difference in the impacts of left- versus rightward flankers. It must be acknowledged that such explanations are at this point speculative but worthy of investigation in future research.

Experiment 1 replicated the flanker letter-order effect reported by Grainger et al. (2014), suggesting that both the processing of parafoveal information and the parafoveal–foveal integration of this information are sensitive to letter-position information—even at the greater eccentricities implicated by the use of six-letter targets and three-letter flankers in the present work. Although numerically reduced in size, the letter-order effect persisted in conditions using noncontiguous-letter flankers (e.g., 531 123456 642), underlining the importance of relative rather than absolute position.

The results from Experiment 2 suggest that the word's edges (i.e., outer-positioned letters) play an important role with respect to letter-position coding, since there was no effect of flanker-letter order when using the target's inner-positioned letters alone (23 123456 45 vs. 32 123456 54). It is conceivable that outer-positioned letters act as spatial points of reference, in relation to which the location of inner-positioned letters is determined. Such a scheme is much in line with the both-edges account of letter-position coding proposed by Fischer-Baum et al. (2011; Fischer-Baum et al., 2010)—with, however, the important difference that readers would code for the relative positions of, rather than the absolute distance between, outer- and inner-positioned letters. At the same time, this both-edges bigram coding scheme bears a resemblance to spatial coding (Davis, 1999, 2010), in that word nodes would be tuned to specific activation patterns. In Davis's SOLAR model, these patterns consist of letter node signals that are ordered in the temporal dimension. In both-edges bigram coding, the activation pattern consists of combined bigram activities (e.g., the word *target* corresponds to a highly active bigram node for *tg* and a less active node for *ta*). The theoretical difference between these two approaches is that letter processing takes place in a serial fashion in the SOLAR model, whereas it takes place in parallel in the scheme proposed here, in line with evidence for parallel processing during reading (e.g., Dare & Shillcock, 2013; Grainger et al., 2014; Snell et al., 2017). It should be noted that this type of letter-position coding could take on more importance in peripheral vision, where position information becomes more noisy (Chung & Legge, 2009), while outer-positioned letters remain highly visible (e.g., Chanceaux & Grainger, 2012).

Finally, it must be stressed that a both-edges bigram coding scheme would serve to account for letter-position coding more than for letter-identity coding. Indeed, the switched-flanker conditions and the conditions using flankers without outer-positioned letters yielded considerably shorter RTs than in the control condition, suggesting that a portion of the word recognition process is driven by the coding of letters

irrespective of their absolute position (e.g., similarly, Grainger et al., 2014, have argued for the presence of a “bag-of-letters” alongside a “bag-of-bigrams”; see also Peressotti and Grainger's, 1995, proposal for position-independent letter detectors).

A question that remains is whether the present findings speak to the reading system in general, and thus whether the cognitive mechanisms underlying letter-position coding and spatial integration would operate similarly in more natural reading settings such as sentence reading. In regard to this question, it is noteworthy that Snell et al. (2017) employed both the FLLD paradigm and sentence reading to investigate parafoveal-on-foveal effects of orthographic neighbors, and found similar patterns of effects in the two settings. Furthermore, as we mentioned in the introduction, various other studies have shown that orthographic information is integrated across spatially distinct words in sentence reading (e.g., Angele et al., 2013; Dare & Shillcock, 2013; Inhoff et al., 2000). Hence, given that the mechanisms underlying spatial integration seem to operate similarly in natural reading settings, we at this point see no reason why the mechanisms underlying letter-position coding would operate differently. Additionally, one might argue that the FLLD paradigm may be unveiling task-specific processes rather than word recognition processes, and that the locus of the flanker effects established here would be at the decision level rather than at the level of orthographic processing. Our argument against this is that if our flanker effects concerned task-specific processes, then we would have expected to find an effect of flanker lexicality, given that the task at hand was a lexical decision task. This was not the case, however. Considering that we established flanker letter-order and -identity effects but no effects of flanker lexicality, pronounceability, or bigram frequency, the most straightforward conclusion is that our flankers affected the cognitive stages of letter-position and -identity coding—that is, orthographic processing.

In conclusion, the novelty of the FLLD paradigm is attested by the fact that many flanker configurations are still to be tested. The claims raised in this article provide a tentative explanation for the results obtained so far, but they will need to be further consolidated—for instance, by testing flanker order in a setting using four-letter targets and three-letter flankers (e.g., *roc rock ock* vs. *ock rock roc*), as well as a setting using six-letter targets and two-letter flankers (e.g., *sp sprint nt* vs. *nt sprint sp*). A further test of the both-edges relative-position scheme, discussed above, may be provided by a setting comparing “edge flankers” (e.g., *rk rock rk*) to “nonedge flankers” (e.g., *oc rock oc*). With respect to the mechanisms underlying spatial integration rather than letter-position coding, it would further be worth investigating possible asymmetries between the influences from leftward and rightward flankers in the FLLD paradigm. Future implementations of the FLLD paradigm should reveal how

much benefit the investigation of spatial information integration may have in cracking the orthographic code.

Author note This research was supported by Grants ANR-11-LABX-0036 and ANR-15-CE33-0002-01 from the French National Research Agency (ANR).

References

- Angele, B., Tran, R., & Rayner, K. (2013). Parafoveal–foveal overlap can facilitate ongoing word identification during reading: Evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, 39, 526–538.
- Baayen, R. (2008). *Analyzing linguistic data: A practical introduction to statistics using R*. Cambridge, UK: Cambridge University Press.
- Baayen, R., Davidson, D., & Bates, D. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language*, 59, 390–412. doi:<https://doi.org/10.1016/j.jml.2007.12.005>
- Barr, D. J., Levy, R., Scheepers, C., & Tily, H. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, 68, 255–278. doi:<https://doi.org/10.1016/j.jml.2012.11.001>
- Bates, D. J., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 67, 1–48.
- Bowers, J. S., Davis, C. J., & Hanley, D. A. (2005). Automatic semantic activation of embedded words: Is there a “hat” in “that”? *Journal of Memory and Language*, 52, 131–143.
- Chanceaux, M., & Grainger, J. (2012). Serial position effects in the identification of letters, digits, symbols, and shapes in peripheral vision. *Acta Psychologica*, 141, 149–158.
- Chung, S. T. L., & Legge, G. E. (2009). Precision of position signals for letters. *Vision Research*, 49, 1948–1960. doi:<https://doi.org/10.1016/j.visres.2009.05.004>
- Dare, N., & Shillcock, R. (2013). Serial and parallel processing in reading: Investigating the effects of parafoveal orthographic information on nonisolated word recognition. *Quarterly Journal of Experimental Psychology*, 66, 417–428.
- Davis, C. J. (1999). The self-organizing lexical acquisition and recognition (SOLAR) model of visual word recognition. Unpublished doctoral dissertation, University of New South Wales, Australia.
- Davis, C. J. (2010). SOLAR versus SERIOL revisited. *European Journal of Cognitive Psychology*, 22, 695–724.
- Davis, C. J., & Bowers, J. S. (2004). What do letter migration errors reveal about letter position coding in visual word recognition? *Journal of Experimental Psychology: Human Perception and Performance*, 30, 923–941. doi:<https://doi.org/10.1037/0096-1523.30.5.923>
- Davis, C. J., & Lupker, S. J. (2006). Masked inhibitory priming in English: Evidence for lexical inhibition. *Journal of Experimental Psychology: Human Perception and Performance*, 32, 668–687. doi:<https://doi.org/10.1037/0096-1523.32.3.668>
- De Moor, W., & Brysbaert, M. (2000). Neighborhood-frequency effects when primes and targets are of different lengths. *Psychological Research*, 63, 159–162.
- De Moor, W., Van der Herten, L., & Verguts, T. (2007). Is masked neighbor priming inhibitory? Evidence using the incremental priming technique. *Experimental Psychology*, 54, 113–119. doi:<https://doi.org/10.1027/1618-3169.54.2.113>
- Ferrand, L., New, B., Brysbaert, M., Keuleers, E., Bonin, P., Méot, A., . . . Pallier, C. (2010). The French Lexicon Project: Lexical decision data for 38,840 French words and 38,840 pseudowords. *Behavior Research Methods*, 42, 488–496. doi:<https://doi.org/10.3758/BRM.42.2.488>
- Fischer-Baum, S., Charny, J., & McCloskey, M. (2011). Both-edges representation of letter position in reading. *Psychonomic Bulletin & Review*, 18, 1083–1089.
- Fischer-Baum, S., McCloskey, M., & Rapp, B. (2010). The representation of grapheme position: Evidence from acquired dysgraphia. *Cognition*, 115, 466–490.
- Forster, K., & Davis, C. (1984). Repetition priming and frequency attenuation in lexical access. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 10, 680–698. doi:<https://doi.org/10.1037/0278-7393.10.4.680>
- Forster, K., Davis, C., Schoknecht, C., & Carter, R. (1987). Masked priming with graphemically related forms: Repetition or partial activation? *Quarterly Journal of Experimental Psychology*, 39, 211–251. doi:<https://doi.org/10.1080/14640748708401785>
- Gomez, P., Ratcliff, R., & Perea, M. (2008). The overlap model: A model of letter position coding. *Psychological Review*, 115, 577–600. doi:<https://doi.org/10.1037/a0012667>
- Grainger, J. (2008). Cracking the orthographic code: An introduction. *Language and Cognitive Processes*, 23, 1–35. doi:<https://doi.org/10.1080/01690960701578013>
- Grainger, J., Granier, J.-P., Farioli, F., Van Assche, E., & van Heuven, W. J. B. (2006). Letter position information and printed word perception: The relative-position priming constraint. *Journal of Experimental Psychology: Human Perception and Performance*, 32, 865–884. doi:<https://doi.org/10.1037/0096-1523.32.4.865>
- Grainger, J., Mathôt, S., & Vitu, F. (2014). Test of a model of multi-word reading: Effects of parafoveal flanking letters on foveal word recognition. *Acta Psychologica*, 146, 35–40.
- Grainger, J., & van Heuven, W. J. B. (2003). Modeling letter position coding in printed word perception. In P. Bonin (Ed.), *The mental lexicon: Some words to talk about words* (pp. 1–23). Hauppauge, NY: Nova Science.
- Grainger, J., & Whitney, C. (2004). Does the human mind read words as a whole? *Trends in Cognitive Sciences*, 8, 58–59. doi:<https://doi.org/10.1016/j.tics.2003.11.006>
- Hannagan, T., & Grainger, J. (2012). Protein analysis meets visual word recognition: A case for string kernels in the brain. *Cognitive Science*, 36, 575–606.
- Inhoff, A. W., Radach, R., Starr, M., & Greenberg, S. (2000). Allocation of visuo-spatial attention and saccade programming during reading. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 221–246). Amsterdam, The Netherlands: Elsevier.
- Jacobs, A., Rey, A., Ziegler, J., & Grainger, J. (1998). MROM-P: An interactive activation, multiple read-out model of orthographic and phonological processes in visual word recognition. In J. Grainger & A. Jacobs (Eds.), *Localist connectionist approaches to human cognition* (pp. 147–188). Mahwah, NJ: Erlbaum.
- Kennedy, A., & Pynte, J. (2005). Parafoveal-on-foveal effects in normal reading. *Vision Research*, 45, 153–168.
- Mathôt, S., Schreij, D., & Theeuwes, J. (2012). OpenSesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods*, 44, 314–324. doi:<https://doi.org/10.3758/s13428-011-0168-7>
- McClelland, J. L., & Mozer, M. C. (1986). Perceptual interactions in two-word displays: Familiarity and similarity effects. *Journal of Experimental Psychology: Human Perception and Performance*, 12, 18–35. doi:<https://doi.org/10.1037/0096-1523.12.1.18>
- McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: I. An account of basic findings. *Psychological Review*, 88, 375–407. doi:<https://doi.org/10.1037/0033-295X.88.5.375>

- Norris, D., & Kinoshita, S. (2012). Orthographic processing is universal: It's what you do with it that's different. *Behavioral and Brain Sciences*, 35, 296–297.
- Perea, M., & Lupker, S. (2004). Can CANISO activate CASINO? Transposed-letter similarity effects with nonadjacent letter positions. *Journal of Memory and Language*, 51, 231–246. doi:<https://doi.org/10.1016/j.jml.2004.05.005>
- Peressotti, F., & Grainger, J. (1995). Letter position coding in random consonant arrays. *Perception & Psychophysics*, 57, 875–890.
- Peressotti, F., & Grainger, J. (1999). The role of letter identity and letter position in orthographic priming. *Perception & Psychophysics*, 61, 691–706.
- Rumelhart, D. E., & McClelland, J. L. (1982). An interactive activation model of context effects in letter perception: II. The contextual enhancement effect and some tests and extensions of the model. *Psychological Review*, 89, 60–94. doi:<https://doi.org/10.1037/0033-295X.89.1.60>
- Schoonbaert, S., & Grainger, J. (2004). Letter position coding in printed word perception: Effects of repeated and transposed letters. *Language and Cognitive Processes*, 19, 333–367. doi:<https://doi.org/10.1080/01690960344000198>
- Segui, J., & Grainger, J. (1990). Priming word recognition with orthographic neighbors: Effects of relative prime–target frequency. *Journal of Experimental Psychology: Human Perception and Performance*, 16, 65–76. doi:<https://doi.org/10.1037/0096-1523.16.1.65>
- Snell, J., Vitu, F., & Grainger, J. (2017). Integration of parafoveal orthographic information during foveal word reading: Beyond the sublexical level? *Quarterly Journal of Experimental Psychology*, 70, 1984–1994.
- Van Assche, E., & Grainger, J. (2006). A study of relative-position priming with superset primes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 32, 399–415. doi:<https://doi.org/10.1037/0278-7393.32.2.399>
- Van Heuven, W. J. B., Mandera, P., Keuleers, E., & Brysbaert, M. (2014). SUBTLEX-UK: A new and improved word frequency database for British English. *Quarterly Journal of Experimental Psychology*, 67, 1176–1190. doi:<https://doi.org/10.1080/17470218.2013.850521>
- Whitney, C. (2001). How the brain encodes the order of letters in a printed word: The SERIOL model and selective literature review. *Psychonomic Bulletin & Review*, 8, 221–243. doi:<https://doi.org/10.3758/BF03196158>