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Are transposition effects specific to letters?

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Are transposition effects specific to letters?

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Recent research has consistently shown that pseudowords created by transposing two letters are perceptually similar to their corresponding base words (e.g., *jugde–judge*). In the framework of the overlap model (Gomez, Ratcliff, & Perea, 2008), this effect is due to a noisy process in the localization of the "objects" (e.g., letters, kana syllables). In the present study, we examine whether this effect is specific to letter strings or whether it also occurs with other "objects" (namely, digits, symbols, and pseudoletters). To that end, we conducted a series of five masked priming experiments using the same–different task. Results showed robust effects of transposition for all objects, except for pseudoletters. This is consistent with the view that locations of familiar objects (i.e., letters, numbers, and symbols) can be best understood as distributions along a dimension rather than as precise points.

Keywords: Letter position coding; Transposition; Masked priming; Same–different task.

One topic that has attracted considerable attention in the past years has been how the brain encodes letter position within a word. Part of the interest in this issue has been motivated by the finding of the so-called transposed-letter effect: A transposed-letter stimulus (e.g., *jugde*) is perceptually more similar to its base word (*judge*) than an orthographic control (i.e., a replaced-letter item such as *junpe*; e.g., O'Connor & Forster, 1981; Perea, Rosa, & Gómez, 2005; see also Perea & Pérez, 2009, for evidence with kana syllables). Likewise, a growing number of experiments have shown that a target word is recognized faster when it is preceded by a briefly presented transposed-letter nonword prime (*jugde–JUDGE*) than when it is preceded by an orthographic control (*jupte–JUDGE*; Perea & Lupker, 2003a, 2003b, 2004; see also Guerrera & Forster, 2007; Perea, Duñabeitia, & Carreiras, 2008b, for a recent review).

The transposed-letter effect cannot be accommodated by models of visual-word recognition that employ coding schemes in which letter identities are associated with a specific position within a word (interactive activation model, McClelland & Rumelhart, 1981; dual-route cascaded model,

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DRC, Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; multiple read-out model, MROM, Grainger & Jacobs, 1996; connectionist dual process model, CDP+ , Perry, Ziegler, & Zorzi, 2007; Bayesian reader model, Norris, 2006): In these models, *jugde* and *jupte* are assumed to have the same degree of perceptual similarity with *judge*. Nonetheless, several models of word identification with a more flexible letter position coding mechanism have been proposed in the last few years (e.g., self-organizing lexical acquisition and recognition model, SOLAR, Davis, 1999; sequential encoding regulated by inputs to oscillations within letter units model, SERIOL, Whitney, 2001; open-bigram model, Grainger & van Heuven, 2003; overlap model, Gomez, Ratcliff, & Perea, 2008; local combination detectors model, LCD Dehaene, Cohen, Sigman, & Vinckier, 2005). These new coding-scheme models share the view that letter position coding occurs very early during the time course of word processing, but they implement different mechanisms to explain why transposed-letter effects occur.

The main question in the present study is to examine whether the locus of transposition effects is specific to letter processing or whether it is due to a more general domain-independent processing—probably common to other common "objects" (e.g., digits, symbols). We focus on the overlap model versus the SERIOL and LCD models because these are the models that make specific claims on the domain specificity of transposition effects. Although the open-bigram model shares many assumptions with the SERIOL and LCD models, it does not explicitly assume that a given brain area is involved in letter position coding. Finally, the SOLAR model remains silent on this issue.

On the one hand, the overlap model (Gomez et al., 2008) assumes that "locations of objects (in our case, letters) are best understood as distributions along a dimension (in our case, position in the string), rather than as precise points" (p. 578), and this is shared with more general models of attention (e.g., the contour detector model, CODE; see Logan, 1996). More specifically, the model considers that the representation of a letter is normally distributed across ordinal positions in the letter string. For instance, in a five-letter word like *judge*, the letter *d* is associated with Position 3 but also, to a lesser degree, with Positions 2 and 4, and even with Positions 1 and 5. In this model, the similarity of two stimuli depends on the overlap between letters and their relative position in both strings. But the relevant point here is that the same mechanisms that are involved in coding letter position within a string of letters (e.g., *d* in *judge*) would also be employed in coding digit position within a number string (e.g., 3 in 24385), or even in coding symbols with a string of symbols (e.g., $ in &%$!). The reason is that, in all these cases, the position assignment process is based on a general assumption of position uncertainty among a series of objects.

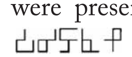
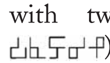
On the other hand, the SERIOL model assumes that the degree of similarity of two words (or, more generally, two letter strings) is based mainly on the number of "open bigrams" (ordered pairs of letters; e.g., *ju*, *jd*, etc.) shared by the two stimuli (Whitney, 2001). For instance, the transposed-letter pseudoword *jugde* would activate more common open bigrams with the word *judge* than would the replacement-letter pseudoword *junpe*, and hence *jugde* is more perceptually similar to its base word than *junpe* is. Importantly, the SERIOL assumes that there is a specialized area in the brain where these open bigrams are computed. As Whitney and Cornelissen (2005) indicated:

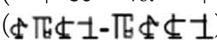
> The retinotopic representation is converted into an abstract, location-invariant encoding of letter order via the creation of a serial representation. This serial encoding activates lexical representations via bigram nodes, which encode relationships between letters. (p. 276)

Whitney and Cornelissen (2005, Figure 9) proposed that there would be a specific area of the brain—in the putative visual word form area—that could be responsible for bigram activation. The LCD model (Dehaene et al., 2005) makes a similar assumption in this respect. Consistent with this view, Vinckier et al. (2007) reported a higher degree of activation in the visual word form area for letter strings containing high-frequency bigrams and high-frequency quadrigrams than for letter strings containing low-frequency letters. (Unfortunately, there was a confound with pronounceability in that study.) As the proposed "bigram area" is a brain area specific to letter processing and not to digits or symbols (see Baker, Liu, Wald, Kwong, Benner, & Kanwisher, 2007, for functional magnetic resonance imaging, fMRI, evidence of higher level of action of letter strings than of digits and symbols within the "visual word form area"), it remains unclear whether transposition effects would also occur to the same level with strings composed of other types of stimuli—namely, digits or symbols. Bear in mind that the presence of a common brain area to encode "object" position would make unnecessary to postulate an "open bigram" area.

In sum, a relevant difference between the recently proposed coding models is that, for SERIOL and LCD models, transposition effects are thought to be specific to letter strings, while for the overlap model, the mechanisms responsible for transposition effects are also involved in the position coding of other strings of objects (e.g., numbers, symbols). Thus, the present research is aimed to test the different predictions of SERIOL/LCD and overlap models regarding the presence of transposition effects to stimuli other than letter strings.

But what about transposition effects for digit strings and symbol strings? On a priori grounds, it could be hypothesized that position coding in numbers might differ from that in words because the characteristics of Arabic numbers make positions from left to right more relevant (that is, the digit *7* is more relevant in *7362* than in *3627*). Ratinckx, Brysbaert, and Fias (2005) provided some indirect evidence exploring the naming of two-digit Arabic numbers. Using a masked priming paradigm, they found slower naming times when the target was preceded by a transposed number (e.g., 82–28) than by an unrelated one (e.g., 28–76). That is, Ratinckx et al. found a negative transposed priming effect. However, they failed to find any signs of a transposed priming effect in a number decision task ("is the presented stimuli a number or a number–letter combination?"; Experiment 4) and in an orientation task ("is the two-digit number presented in italics or not?"; Experiment 5). Ratinckx et al. concluded that the (negative) transposed priming effect found in the naming task were due to language production processes because the priming effects were absent when the task only demanded recognition processes. In any case, the use of very short strings (two-digit numbers) does not allow strong conclusions to be made on how position coding is attained with digit strings. In addition, Friedmann and Gvion (2001, Experiment 5) explored digit position encoding abilities of two positional letter dyslexics. In this infrequent reading disorder, which is due to an impairment in letter position encoding in the presence of an unimpaired letter identity process, patients make letter migrations within words in reading—that is, they could read casual as causal. When the reading of 3–6-digit-long Arabic numbers was tested, the patients showed some migration errors although significantly less than in word reading. In a same–different task in which the patients were presented with 3–6-digit number pairs that could be identical or differ in digit order, they showed normal performance. Finally one of the patients (B.S.) was asked to name a digit according to its position in the digit string; all his errors (11%) involved naming of a digit from a different position but never a substitution. Although Friedmann and Gvion (2001) assumed that the position coding mechanisms may be specific to letters, their data showed that patients in unspeeded tasks committed migrations within words and within Arabic numbers.

Finally, evidence regarding symbols (or pseudoletters) is very scarce. In recent studies, Pammer et al. (Pammer, Lavis, Cooper, Hansen, & Cornelissen, 2005; Pammer, Lavis, Hansen, & Cornelissen, 2004) employed a two-alternative choice task, in which participants were presented with a briefly presented (100 ms) symbol string (e.g., ), and then they were presented with two alternatives (e.g.,  vs. ). However, Pammer et al. (2005; Pammer et al., 2004) did not employ an orthographic control condition (i.e., a "replaced" symbol condition), and hence it is not possible to assess the magnitude of the transposed-letter effects in their experiment; furthermore, unlike the masked priming technique, this task does not necessarily tap very early stages in the process of visual-word recognition.

Given that the processing of letters, digits, and symbols must differ at some stage (e.g., serial position effects differ for letters, digits, and symbols; see Tydgat & Grainger, 2009), and given that transposition effects are thought to occur very early, it is important to focus on extremely early stages of processing. To that end, we have used a masked priming procedure in the context of a same–different task (see Kinoshita & Norris, 2009, for a review)—a task that, unlike lexical decision, can be used for digit/symbol strings (see Perea, Duñabeitia, Pollatsek, & Carreiras, 2009). In the present paper, we present five experiments where the transposed-letter priming effect was explored with different stimuli in each experiment: pronounceable pseudowords (repi–ERPI vs. nopi–ERPI), nonwords (JSTN–SJTN), numbers (5276–2576), symbols (>+"& vs. +>"&), and pseudoletters (). In the context of a masked priming paradigm, participants in the same–different task are required to press the "same" button if the probe and target are the "same" and to press the "different" button if the probe and target are "different". Kinoshita and Norris (2009) adapted the task for masked priming by putting a masked prime before the target (see also Perea & Acha, 2009; Kinoshita, Castles, & Davis, 2009; Perea et al., 2009, for extensive use of this task); they showed that when the probe and target were the same (e.g., probe, *faith*; target, *FAITH*), a related masked prime (e.g., *fiath*) produced an advantage in response time relative to a control prime (*fouth*). Furthermore, Kinoshita and Norris demonstrated that this effect was due to the activation of abstract (letter) representations. It is important to note that all priming effects in this task occur with "same" responses: The reason is that for "different" responses both the related and unrelated primes provide information that is different from the probe (Kinoshita & Norris, 2009; Norris & Kinoshita, 2008; see also Perea & Acha, 2009, for further evidence).

In the present experiments, the prime stimuli were generated from the transposition and replacement of two contiguous items in the target in three different positions: initial (e.g., REPI–ERPI), internal (e.g., EPRI–ERPI), or final (e.g., ERIP–ERPI). Additionally, an unrelated and an identity prime were included in the experiments as extra baselines (Perea & Lupker, 2004; see also Kinoshita et al., 2009). The reason is that the usual "replaced-letter" conditions may conflate the effect of change in letter position with a change in letter identity; to examine the effect of letter position independently of letter identity, the identity condition is a particularly useful baseline for the transposed-letter primes (Kinoshita et al., 2009). In addition, the unrelated condition will also be employed as a baseline for the replacement primes. To avoid physical continuity between primes and targets, primes were presented in 26-point font, and targets were presented in 32-point font. The reason is that the type of stimuli used here precluded us from using a different case (see Perea, Duñabeitia, & Carreiras, 2008a; see also Perea et al., 2009), as also happens in masked priming experiments in Hebrew, Arabic, or kana (i.e., languages that do not have an upper-case/lower-case distinction; e.g., see Frost, Kugler, & Forster, 2005; Perea & Pérez, 2009).

To assess the potential role of phonology in early processes of letter position coding, in Experiments 1–2 we employed letter strings: pronounceable pseudowords in Experiment 1 and nonpronounceable nonwords (i.e., consonant strings) in Experiment 2. In Experiment 3, we examine transposition priming effects for digit strings, whereas in Experiment 4, we did so for symbol strings. To anticipate the results, we found a transposition priming effect in Experiments 1–4. Thus, "familiar" objects do produce a similar transposition priming effect. To assess whether this effect can also occur with nonfamiliar objects, in Experiment 5 we examined transposition priming effects for pseudoletter strings.

EXPERIMENT 1: PRONOUNCEABLE PSEUDOWORDS

In a recent masked priming same–different experiment, Perea and Acha (2009, Experiment 3) found a robust effect of transposed-letter priming using pronounceable pseudowords. Interestingly, no differences were found between transposed and identity primes. Similarly, Kinoshita and Norris (2009, Experiment 4) found robust effects of transposed-letter priming using pronounceable pseudowords, and no differences were found between transposed and identity primes. Thus, a robust transposition priming effect is expected in the present experiment.

Method

Participants

A total of 32 students from the University of Málaga took part in the experiment in exchange for course credit. All were native speakers of Spanish, had normal or corrected-to-normal vision, and were naive regarding the purpose of the study.

Materials

A set of 320 pronounceable pseudowords of four letters (e.g., ERPI, ISNA) were used as targets in this experiment. These pseudowords were presented in upper case and were preceded by primes that were: (a) the same except for the transposition of the two initial letters (T-initial, e.g., repi–ERPI); (b) the same except for the substitution of the two initial letters (S-initial, dapi–ERPI); (c) the same except for a transposition of the two internal letters (T-internal, epri–ERPI); (d) the same except for the substitution of the two internal letters (S-internal, edbi–ERPI); (e) the same except for the transposition of the two final letters (T-final, erip–ERPI); (f) the same except for the substitution of the two final letters (S-final, erda–ERPI); (g) the same as the target (identity condition, erpi–ERPI); and (h) a pseudoword unrelated to the target (unrelated condition, ocma–ERPI). Primes were always pronounceable pseudowords. On half of the trials, the probe and the target were the same, and on the other half of trials the probe and the targets were different (e.g., for the probe ISNA, the prime could be ralo, and the target would be ARLO). Eight lists of materials were constructed so that each target appeared once in each list, but each time in a different priming condition. Different groups of participants were used for each list.

Procedure

Participants were tested either individually or in groups of up to 5 people. The stimuli were presented using PCs running the Experimental Run Time System (ERTS) software for MS-DOS (Beringer, 1999) on a CRT monitor with a 16.6-ms refresh rate. Reaction times were measured from target onset until the participant's response. On each trial, a probe was presented above a forward mask consisting of six hash marks (######) for 1,000 ms. Next, the probe disappeared, and the forward mask was replaced by a prime presented for 50 ms, which was replaced by a target. The target stimulus remained on the screen until the response. Participants were told that they would see strings of letters and that they were to press the button marked "SÍ" [YES] (with their right index finger) if they thought the probe and target were the same stimulus, and they were to press the button marked "NO" (with their left index finger) if they thought the probe and target were a different stimulus. Participants were instructed to make this decision as quickly and as accurately as possible. Participants were not informed of the presence of prime stimuli. Primes and targets were always presented in upper case with different Arial font size: 26 and 32 points, respectively. The experiment lasted approximately 20 min. Each participant received a different, randomized order of trials.

Results and discussion

Incorrect responses (2.5% of the trials) and response times smaller than 250 or greater than 1,500 ms (less than 0.3% of the trials) were excluded from the latency analysis. The mean response times and error percentages from the participant analysis are presented in Table 1. As usual with the same–different task (Norris & Kinoshita, 2008), we analysed separately "same" and "different" responses. Analyses of variance (ANOVAs) were conducted on the response times (RTs) and error rates, with position (initial, intermediate,

Table 1. *Mean response times, standard error response times, and percentage of errors for pronounceable pseudowords*

		Type of prime			
Responses	*Position*	*Transposed*	*Substitution*	*Identity*	*Unrelated*
"Same"				475 *95.5* (2.0)	525 *78.7* (7.6)
	Initial	485 *89.6* (1.4)	502 *87.0* (2.8)		
	Middle	477 *87.9* (2.0)	495 *85.2* (2.9)		
	Final	479 *90.0* (2.0)	493 *83.8* (1.8)		
"Different"				529 *104.8* (1.4)	527 *87.9* (1.5)
	Initial	518 *94.0* (0.7)	526 *100.0* (1.4)		
	Middle	527 *91.3* (1.5)	529 *101.6* (1.8)		
	Final	523 *96.8* (1.4)	529 *109.1* (1.4)		

Note: Mean response times in ms; standard error response times in italics; percentage of errors in parentheses.

and final) and type of prime (transposition vs. substitution) as factors. List was also included in the ANOVAs to extract the variance due to error associated with the lists (Pollatsek & Well, 1995). In addition, we conducted planned comparisons of the identity condition versus the transposed-letter conditions and planned comparisons of the unrelated condition versus the substitution-letter conditions. For the planned comparisons, α values were corrected using the Bonferroni adjustment (i.e., $\alpha = .05/3$). F values are reported for the analysis by participants (F_1) and items (F_2).

"Same" responses

The ANOVA on the RTs showed a significant effect of type of prime, $F_1(1, 24) = 8.514$, $p < .009$; $F_2(1, 152) = 26.15$, $p < .001$: Targets preceded by a transposed prime were responded to faster than targets preceded by a substitution prime. Neither the effect of position, $F_1(2, 48) = 1.954$, $p = .15$; $F_2(2, 304) = 1.49$, $p = .23$, nor the interaction between position and type of prime (both Fs < 1) was significant.

Planned comparisons between the identity prime versus the transposed primes (for each position) showed no significant differences (all ps $>$ .05): Transposed primes behaved like identity primes. Planned comparisons between the unrelated prime and the substitution primes (for each position) always showed faster response times for the substitution conditions (all ps $< .01$).

The ANOVA on the error data did not show any significant effects. Planned comparisons showed again no differences between the identity primes and the transposed prime in each position (all Fs < 1), whereas error rates for targets preceded by an unrelated prime were higher than those for the targets preceded by a substitution prime (in each position), all ps $< .01$.

"Different" responses

Neither the ANOVAs nor the planned comparisons on the RTs (or the error data) showed any significant effects.

The results of Experiment 1 were straightforward. First, we observed a significant effect of transposition priming for "same" responses: Transposed primes were more perceptually similar to their targets than were substitution primes. This replicates earlier research with the masked priming same–different task (e.g., Kinoshita & Norris, 2009; Perea & Acha, 2009). Second, planned comparisons between the identity prime and the transposed primes showed no significant differences (see Perea & Acha, 2009, for a similar finding). This implies that at the earliest stages of word processing, letter identity and letter position are not integral perceptual dimensions, and that letter position takes a long time to encode (i.e., transposed-letter primes and identity primes behaved in a similar way). Third, results also showed faster response times when targets were preceded by a substitution prime than when they were preceded by an unrelated prime (as in Experiment 3 of Perea & Acha, 2009), which means that the substitution primes are perceptually more similar to the target stimulus than is an unrelated prime. Fourth, we failed to find an interaction between type of prime and position of the transposition/substitution. The presence of a vanishing transposed-letter effect has usually been the case with initial/final letters in the lexical decision task (e.g., Perea & Lupker, 2003a) and was probably due to a ceiling effect in the transposed-letter priming conditions (Perea & Acha, 2009). Finally, as expected, there were no significant effects in "different" responses (see Perea & Acha, 2009).

In summary, Experiment 1 showed that pronounceable pseudowords elicited a robust effect of transposition priming in the same–different matching task. The question now is whether a similar pattern of effects occurs with nonpronounceable nonwords (i.e., strings of consonants; e.g., SJTN). If transposition effects occur at a very early processing level—before phonological influences take place, as proposed by Perea and Carreiras (2006, 2008; see also Acha & Perea, in press; Perea & Pérez, 2009), then the pattern of effects with consonant strings should mimic that of pronounceable pseudowords. Alternatively, if phonology plays a role in the transposed-priming effect, as suggested by Frankish and Turner (2007), a different pattern of results would be expected.

EXPERIMENT 2: NONPRONOUNCEABLE NONWORDS (CONSONANT STRINGS)

Method

Participants

A total of 32 students from the University of Málaga took part in the experiment in exchange for course credit. All were native speakers of Spanish, had normal or corrected-to-normal vision, and were naive regarding the purpose of the study. None of the participants had taken part in Experiment 1.

Materials

The manipulation was the same as that in Experiment 1, except that instead of using pronounceable pseudowords, we employed consonant strings. For instance, the target SJTN could be preceded by one of the following primes: JSTN (T-initial), FLTN (S-initial), STJN (T-internal), SFLN (S-internal), SJNT (T-final), SJFL (S-final), SJTN (identity prime), or FLCQ (unrelated prime).

Procedure

The procedure was the same as that in Experiment 1.

Results and discussion

Incorrect responses (4.6% of the trials) and response times smaller than 250 or greater than 1,500 ms (less than 0.7% of the trials) were excluded from the latency analysis. The mean response times and error percentages from the participant analysis are presented in Table 2. The design was the same as that in Experiment 1.

"Same" responses

The ANOVA on the RTs showed a significant effect of type of prime, $F_1(1, 24) = 21.34$, $p < .001$; $F_2(1, 152) = 14.58$, $p < .001$: Targets preceded by a transposed prime were responded to 16 ms faster than targets preceded by a substitution prime. The effect of position was not significant, both Fs < 1.1. The Position × Type of Prime interaction was not significant (both Fs < 1).

Planned comparisons between identity primes and transposed primes in each position showed no significant differences (all Fs < 1), transposed primes behave like identity primes. Planned comparisons between the unrelated prime and the substitution primes (for each position) always showed faster responses for the substitution primes (all ps $< .016$).

The ANOVA on the error data only showed a significant effect of type of prime, $F_1(1, 24) = 9.12$, $p < .01$; $F_2(1, 152) = 10.99$, $p < .002$. The effect of position was not significant (both ps $> .25$), and the interaction between the two factors was not significant either (both Fs < 1). Planned comparisons between identity primes

Table 2. *Mean response times, standard error response times, and percentage of errors for consonant strings*

Responses	Position	Type of prime: Transposed	Substitution	Identity	Unrelated
"Same"				511 *114.3* (3.5)	541 *105.7* (10)
	Initial	511 *108.1* (3.5)	525 *102.5* (5.9)		
	Middle	511 *112.8* (5.3)	528 *99.6* (6.8)		
	Final	505 *100.5* (4.2)	523 *109.6* (6.8)		
"Different"				542 *100.7* (3.9)	544 *103.2* (3.9)
	Initial	535 *94.5* (3.1)	546 *99.2* (2.9)		
	Middle	538 *104.1* (2.5)	541 *98.6* (3.7)		
	Final	538 *106.1* (4.2)	543 *97.5* (3.2)		

Note: Consonant strings = nonpronounceable nonwords. Mean response times in ms; standard error response times in italics; percentage of errors in parentheses.

and transposed primes in each position showed no significant differences (all $ps > .19$). Finally, planned comparisons between the unrelated prime and the substitution primes (for each position) did not show any differences (all $ps > .05$) with the exception of the substitution prime in initial position that was significantly faster than the unrelated condition, $F_1(1, 24) = 6.71$, $p = .016$; $F_2(1, 152) = 6.39$, $p = .012$.

"Different" responses

None of the effects on the RTs (or on the error data) were statistically significant.

The results of this experiment, using consonant strings as stimuli, were similar to those with pronounceable pseudowords (Experiment 1): We found a robust effect of transposition priming in "same" responses. Here, we also failed to find an interaction between type of prime and position of the transposition/substitution, although (as in Experiment 1) this could have been caused by the high degree of perceptual similarity between the transposed-letter primes (initial, internal, and final) and the identity condition: There were no differences between the transposed conditions and the identity condition. Finally, we found no significant effects in "different" responses.

Thus, the data from Experiment 2 strongly suggest that transposition priming effects are not limited to pronounceable stimuli, but they also occur (to a similar degree) with consonant strings. Furthermore, this finding supports data from Perea and colleagues, who have repeatedly failed to find consistent effects of phonology on transposed-letter priming (Perea & Carreiras, 2006, 2008; Perea & Pérez, 2009; but see Frankish & Turner, 2007).

The question now is whether a similar pattern of priming effects occurs with a different type of stimuli—namely, Arabic numbers (i.e., digit strings). According to the SERIOL model (Whitney & Cornelissen, 2005) and the LCD model (Dehaene et al., 2005), there is a domain-specific level in our brain where letter bigrams are computed. Furthermore, this level is the main level responsible for the transposition effects. Hence, these models would predict a divergence in the pattern of transposition effects in letter strings versus digit strings. Alternatively, if position coding is computed by a more general visual attention mechanism that is not restricted to letters—as proposed by the overlap model—the pattern of findings for digit strings should be similar to that of pronounceable pseudowords (Experiment 1) and nonpronounceable pseudowords (Experiment 2).

EXPERIMENT 3: DIGIT STRINGS

Method

Participants

A total of 32 students from the University of Málaga took part in the experiment in exchange for course credit. All were native speakers of Spanish, had normal or corrected-to-normal vision, and were naive regarding the purpose of the study. None of the participants had taken part in Experiments 1–2.

Materials

The manipulation was the same as that in Experiments 1–2, except that instead of using letter strings, we employed digit strings. For instance, the target stimulus 2576 could be preceded by one of the following primes: 5276 (T-initial), 3876 (S-initial), 2756 (T-internal), 2386 (S-internal), 2567 (T-final), 2538 (S-final), 2576 (identity prime), 3891 (unrelated prime).

Procedure

The procedure was the same as that in Experiments 1–2.

Results and discussion

Incorrect responses (4.0% of the trials) and response times greater than 1,500 ms (less than 1.1% of the trials) were excluded from the latency analysis. The mean response times and error percentages from the participant analysis are presented in Table 3. The design was the same as that in Experiments 1–2.

"Same" responses

The ANOVA on the RTs showed a significant effect of type of prime, $F_1(1, 24) = 33.03$, $p < .001$; $F_2(1, 152) = 23.64$, $p < .001$: Targets preceded by transposed primes were responded to faster than targets preceded by substitution primes. The main effect of position was also significant, $F_1(2, 48) = 3.47$, $p < .04$; $F_2(2, 304) = 5.33$, $p < .006$: This effect reflected faster response times when the transposition/substitution was in an internal position than when it was in the initial position (both ps < .02). Finally, the Position × Type of Prime interaction was not significant (both ps > .20).

Planned comparisons between identity primes and transposed primes in each position showed no differences (all ps > .05). Again, transposed primes behave like identity primes. Planned comparisons between the unrelated prime and the substitution primes (for each position) showed faster response times for the substitution primes (all ps < .016).

None of the effects on the error data were significant.

"Different" responses

None of the effects on the RTs (or on the error data) were significant.

The results are clear-cut: Transposition effects are not restricted to letters, but they also occur—to

Table 3. *Mean response times, standard error response times, and percentage of errors for digit strings*

Responses	*Position*	*Type of prime:* *Transposed*	*Substitution*	*Identity*	*Unrelated*
				490 *126.7* (4.2)	543 *127.7* (8.1)
"Same"	Initial	498 *117.5* (6.2)	518 *108.1* (5.3)		
	Middle	492 *124.7* (5.1)	500 *113.0* (4.0)		
	Final	492 *124.1* (4.2)	512 *127.3* (4.0)		
"Different"				517 *98.2* (2.5)	518 *96.1* (3.4)
	Initial	525 *103.3* (2.1)	516 *89.9* (4.0)		
	Middle	522 *105.1* (2.6)	512 *102.7* (2.9)		
	Final	522 *111.9* (2.8)	521 *102.3* (2.3)		

Note: Mean response times in ms; standard error response times in italics; percentage of errors in parentheses.

a similar degree—with digits. Indeed, transposed primes were again as effective as identity primes. Using Occam's razor, this finding suggests that the processes involved in letter position coding in word processing may be common to those involved in digit position coding. This would imply that there is an early stage of visual attention responsible for this effect, which would be common for both letters and digits.

A minor divergence with the two preceding experiments is the finding of a main effect of position in "same" responses. This effect shows that targets were processed faster when preceded by primes modified in internal position than when preceded by primes modified in the initial position; however, this main effect of position did not alter the magnitude of transposition priming effects.

The question now is how general this transposition priming effect is. Will the effect also occur for a string of familiar symbols such as +>"&? This is the goal of Experiment 4.

EXPERIMENT 4: SYMBOLS

Method

Participants

A total of 32 students from the University of Málaga took part in the experiment in exchange for course credit. All were native speakers of Spanish, had normal or corrected-to-normal vision, and were naive regarding the purpose of the study. None of the participants had taken part in Experiments 1–3.

Materials

The manipulation was the same as that in Experiment 3, except that instead of using digit strings we employed symbol strings. The symbols were: $, >, +, %, ", !, -, @, &, ^. For instance, the target stimulus +>"& could be preceded by one of the following primes: >+"& (T-initial), @-"& (S-initial), +">& (T-internal), +%$& (S-internal), +>&" (T-final), +>@- (S-final), +>"& (identity prime), %$@^ (unrelated prime).

Procedure

The procedure was the same as that in Experiments 1–3.

Results and discussion

Incorrect responses (3.9% of the trials) and response times greater than 1,500 ms (less than 0.5% of the trials) were excluded from the latency analysis. The mean response times and error percentages from the participant analysis are presented in Table 4. The design was the same as that in Experiments 1–3.

"Same" responses

The ANOVA on the RTs showed a significant effect of type of prime, $F_1(1, 24) = 13.52$, $p <$

Table 4. *Mean response times, standard error response times, and percentage of errors for strings of symbols*

		Type of prime			
Responses	*Position*	*Transposed*	*Substitution*	*Identity*	*Unrelated*
"Same"				511 *93.0* (4.6)	561 *84.1* (8.7)
	Initial	520 *85.8* (5)	544 *88.8* (6.2)		
	Middle	513 *86.7* (5)	526 *90.0* (5.4)		
	Final	518 *87.5* (7.0)	525 *95.0* (7.6)		
"Different"				551 *103.1* (4.8)	546 *92.7* (3.7)
	Initial	545 *93.5* (3.2)	551 *95.4* (4.3)		
	Middle	542 *102.5* (4.6)	552 *108.5* (2.5)		
	Final	551 *98.4* (3.5)	543 *86.8* (2.6)		

Note: Mean response times in ms; standard error response times in italics; percentage of errors in parentheses.

.002; $F_2(1, 152) = 11.12$, $p < .002$: Targets preceded by a transposed prime were responded 14 ms faster than targets preceded by a substitution prime. The main effect of position was significant in the analysis by participants, $F_1(2, 48) = 3.76$, $p < .031$; $F_2(2, 304) = 2.44$, $p = .088$, but no differences arose in the post hoc analyses (all ps $> .1$). The Position × Type of Prime interaction was not significant (both ps $> .15$).

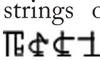
Planned comparisons between the identity prime and the transposed primes (for each position) only showed a significant difference in the analysis by participants between the identity condition and the T-final condition, $F_1(1, 24) = 6.68$, $p = .016$; $F_2(1, 152) = 3.28$, $p = .072$. Planned comparisons between the unrelated primes and substitution primes (for each position) always showed faster response times for the substitution conditions (all ps $< .007$).

The ANOVA on the error data did not showed any significant effects.

"Different" responses

Once again, none of the effects on the RTs (or on the error data) were statistically significant.

The results are again straightforward: Transposition priming effects are not restricted to letters and digits, but they also occur for strings created by combining familiar symbols. Furthermore, the basic pattern of effects with symbol strings was remarkably similar to that in Experiments 1–3. This finding reinforces the view that the processes of letter position coding are common to other familiar "objects", such as digits (Experiment 3) and familiar symbols (Experiment 4). This is consistent with the predictions of the overlap model (Gómez et al., 2008).

The question we want to examine in Experiment 5 is whether transposition effects also occur for a string of unfamiliar symbols: strings of pseudoletters such as the sequence . The overlap model is silent in this respect. If the mechanism responsible for letter/digit/symbol position coding only works with familiar objects (i.e., once their identity has been well attained), then pseudoletters should not produce early transposition effects. In contrast, if the mechanism responsible for letter/digit/symbol position coding is able to work with any kind of stimuli (independently of their familiarity), then the pattern of effects should be similar to that in Experiments 1–4.

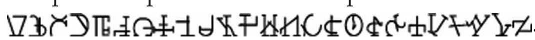
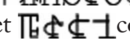
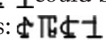
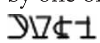
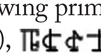
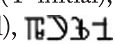
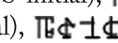
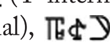
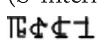
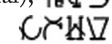
EXPERIMENT 5: PSEUDOLETTERS

Method

Participants

A total of 32 students from the University of Málaga took part in the experiment in exchange for course credit. All were native speakers of Spanish, had normal or corrected-to-normal vision, and were naive regarding the purpose of the study. None of the participants had taken part in Experiments 1–4.

Materials

The manipulation was the same as that in Experiments 1–4 except that instead of using letter/digit/symbol strings, we employed strings composed of pseudoletters. The pseudoletters were: . For instance, the target  could be preceded by one of the following primes:  (T-initial),  (S-initial),  (T-internal),  (S-internal),  (T-final),  (S-final),  (identity prime),  (unrelated prime).

Procedure

The procedure was the same as that in Experiments 1–4.

Results and discussion

Incorrect responses (6.8% of the trials) and response times greater than 1,500 ms (less than 0.4% of the trials) were excluded from the latency analysis. The mean response times and error percentages from the participant analysis are presented in Table 5. The design was the same as that in Experiments 1–4.

Table 5. *Mean response times, standard error response times, and percentage of errors for pseudoletters*

		Type of Prime			
Responses	*Position*	*Transposed*	*Substitution*	*Identity*	*Unrelated*
"Same"				595 *142.5* (1.2)	628 *146.2* (1.2)
	Initial	613 *140.8* (0.9)	608 *139.3* (1.4)		
	Middle	615 *137.5* (1.7)	602 *139.0* (1.8)		
	Final	615 *152.1* (1.4)	602 *139.0* (1.5)		
"Different"				606 *115.5* (5.1)	602 *112.2* (4.6)
	Initial	607 *107.0* (5.6)	608 *115.0* (7.1)		
	Middle	603 *112.4* (4.6)	613 *107.9* (4.6)		
	Final	611 *110.4* (6.7)	611 *115.0* (5.6)		

Note: Mean response times in ms; standard error response times in italics; percentage of errors in parentheses.

"Same" responses

Unlike Experiments 1–4, the ANOVA on the RTs showed that targets preceded by transposed primes were responded to 9 ms more slowly than targets preceded by substitution primes, although the effect only approached significance in the analysis by participants, $F_1(1, 24) = 3.18$, $p = .087$; $F_2(1, 152) = 5.95$, $p < .02$. The main effect of position was not significant (both *F*s < 1). The Position × Type of Prime interaction was not significant (both *F*s < 1).

Planned comparisons showed faster response times for targets preceded by an identity prime than for the targets preceded by a transposition prime in the analysis by items (all *p*s < .016), but not in the analysis by participants (T-initial vs. identity: $p = .12$; *T*-internal vs. identity: $p = .12$; *T*-final vs. identity: $p = .068$). Finally, planned comparisons showed faster response times for targets preceded by a substitution prime than for the targets preceded by an unrelated prime (all *p*s < .016; except for the F_1 ratio corresponding to the comparison between S-internal vs. unrelated, which was $p = .040$).

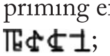
The ANOVA on the error data did not showed any significant effects. None of the planned comparisons showed a significant effect.

"Different" responses

Once again, none of the effects on the RTs (or on the error data) were significant except for a main effect of position on the RTs in the analysis by participants, $F_1(2, 48) = 4.31$, $p < .02$; $F_2(2, 304) = 2.28$, $p = .104$.

Unlike Experiments 1–4, when the string is composed of pseudoletters, the transposition priming effect vanishes. Indeed, we even found a small inhibitory effect of the transposed condition relative to the control, substitution priming condition. It is important to note that, unlike Experiments 1–4, targets preceded by an identity prime produced faster responses than the targets preceded by a transposed prime (around 20 ms). Finally, we should note that the "pseudoletters" are processed at some stage as symbols, as deduced from the advantage of the substitution priming condition over the unrelated priming condition.

GENERAL DISCUSSION

The results of the present series of masked priming same–different experiments provide important clues on whether the brain encodes differently position for strings of familiar or unfamiliar stimuli. First, we replicated the transposition priming effect for pronounceable pseudowords (Experiment 1; see also Perea & Acha, 2009; Kinoshita & Norris, 2009) and extended it to nonpronounceable nonwords (i.e., strings of consonants) (Experiment 2). Second, we demonstrated that transposition priming effects are not specific to letter strings, but they also occurred for digit strings (Experiment 3) and symbol strings (Experiment 4). That is, letter (object) position coding seems to occur well before the letter/digit/symbol distinction starts to matter. Third, we demonstrated that transposition priming effects do not occur for all strings of "objects": We found no signs of a facilitative transposition priming effect for pseudoletters (e.g., the sequence ; Experiment 5); this suggests that the fast-acting mechanism responsible for "object" position coding works with familiar "object" identities but not with unfamiliar object identities. We examine the implications of these findings in the following paragraphs.

One initial implication of the present data is that it is not necessary to argue a position coding level specific for letters (e.g., via an "open bigram" area in the brain), as defended by the SERIOL model and the LCD model. Instead, it seems more parsimonious to assume the existence of a central spatial encoding mechanism involved at "object" position coding within a string—as defended by the overlap model. Consistent with this view, McCloskey and Rapp (2000) reported on a woman with visual-localization deficit who frequently misperceived the orientation and ordering of objects, letters, and words. Indeed, from a developmental perspective, Goswami and Ziegler (2006) argued that open bigrams do not have a special role in the acquisition of visual-word recognition (i.e., in particular for sublexical processing). Although the SERIOL and the LCD models could easily accommodate the present data by rejecting—or at least downplaying—the role of the "open bigrams" at encoding letter position, this modification may violate the spirit of these models. Note that these same points also apply to the open-bigram model (Grainger & van Heuven, 2003) even though this model does not make any specific assumptions on the brain areas responsible for letter transposition effects.

The present experiment also provides some further evidence concerning "phonological" influences on transposition priming. The presence of similar transposition priming effects for pronounceable pseudowords and for unpronounceable nonwords (i.e., strings of consonants) supports the idea that the locus of transposed-letter priming effects is very early and that phonology is not involved (in a significant way) in transposed-letter priming. Furthermore, the robust transposition priming effect with symbol strings—which cannot be pronounced—also provides converging evidence in this point. Taken together, the obtained pattern of data is consistent with prior research of Perea and colleagues (e.g., Acha & Perea, in press; Perea & Carreiras, 2006, 2008; Perea & Pérez, 2009), which have repeatedly shown that phonology is not involved in transposed-letter priming effects. Of course, phonology must play a role at some point of visual-word processing, but it seems to occur once letter position coding has taken place (e.g., see Carreiras, Vergara, & Perea, 2009; Grainger, Kiyonaga, & Holcomb, 2006).

One finding that needs to be commented on is that we found a similar magnitude of transposition priming for initial, middle, and final transpositions. In previous studies, final transpositions tend to produce a smaller transposed-letter effect than do middle transpositions (e.g., Perea & Lupker, 2003a, 2003b); nonetheless, in some experiments, the response times were similar for the middle and final transpositions (e.g., Johnson, Perea, & Rayner, 2007; Perea & Lupker, 2003a; see also Gomez et al., 2008, for further evidence). In the case of initial transpositions, transposed-letter effects tend to be rather small in previous research with the masked priming lexical decision task (Perea & Lupker, 2007) and in a parafoveal priming task in which the participants' eye movements were monitored (Johnson et al., 2007). In a masked priming same–different task, Kinoshita et al. (2009) found differences between response times to five-letter word targets when preceded by an identity prime and when preceded by an initial transposition (18 ms), whereas they failed to find a significant difference between the response times to word targets preceded by an identity primes and those to targets preceded by an internal transposition (8 ms). (Unfortunately, Kinoshita et al. did not include a replacement-letter priming condition, and hence they could not explore the Position ×

Type of prime interaction, which limits their conclusions.) In our experiment, we failed to find differences between transposed and identity primes across all positions. To assess this apparent divergence, we conducted an additional experiment, using four-letter words (as in the rest of the present study), and transposed the initial versus middle letters (the transposition in the final position was not included because of the limited number of word stimuli that produced pronounceable transpositions). We again found a robust transposition priming effect, $F_1(1, 25) = 99.4$, $p < .001$, $F_2(1, 60) = 177$, $p < .0001$, and failed to find the Position × Type of Prime interaction (all ps $> .1$); more important, we found no significant differences between the target words preceded by an identity prime and a transposed-letter prime (all ps $> .1$). Thus, this pattern of data is consistent with Experiments 1–5, and we believe that the lack of interaction between position and type of prime arises from the high degree of effectiveness of the transposed primes in all positions in the masked priming same–different task (at least for four-letter stimuli): Transposition primes are (numerically) nearly as good as identity primes, and this makes it difficult to find any differential effects depending on position. In other words, the masked priming same–different task seems to tap early parallel processes that are not particularly sensitive to position effects.

What is the mechanism underlying "letter" position coding? We argue that the similar pattern of data for letter transpositions, digit transpositions, and symbol transpositions strongly suggests the presence of a general visual-localization system. This view is consistent with research by Pammer et al. (2005; Pammer et al., 2004) and McCloskey and Rapp (2000). Interestingly, for this mechanism to be fast acting and fully operative, the identity of the objects has to be attained very rapidly. This explains why pseudoletters—which do not have specific "letter/object" identities—do not show a transposition priming effect.[1] One obvious prediction from this view, which is currently being tested, is that unfamiliar objects, such as kana syllables for nonspeakers of Japanese, should not produce a transposition priming effect for beginner learners of Japanese, while these same objects should produce a transposition priming effect once they are repeatedly experienced by intermediate learners of Japanese.

In summary, the present study demonstrated that the transposition priming effect does not only occur for letter strings, but it also occurs to a similar degree for digit strings and symbol strings. We showed this by using a task that taps very early processes—namely, a masked priming same–different task. These findings are consistent with the overlap model of letter position coding, as well as with any coding scheme in which there is a domain-general system involved at "object" position coding. Importantly, transposition priming did not occur for strings of pseudoletters, which strongly suggests that letter identity must be well attained before "object" position coding takes place. More research is needed to assess how letter identity is obtained when beginner/intermediate readers learn a new orthography.

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[1] An anonymous reviewer suggested that the transposition priming effect with pseudoletters might emerge if the probe is presented for a longer period of time. That is, a one-sec presentation of the probe might be ample time to encode familiar stimuli, but insufficient to encode pseudoletters. However, the issue at stake in the present experiments is the processing of the masked prime: Even with a longer duration of the probe, the processing of the "object position" in a masked prime composed of pseudoletters would be slow—when compared to primes composed of letters/digits/symbols.

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