

# Differential Sensitivity of Letters, Numbers, and Symbols to Character Transpositions

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## Abstract

■ This study was designed to explore whether the human visual system has different degrees of tolerance to character position changes for letter strings, digit strings, and symbol strings. An explicit perceptual matching task was used (same-different judgment), and participants' electrophysiological activity was recorded. Materials included trials in which the referent stimulus and the target stimulus were identical or differed either by two character replacements or by transposing two characters. Behavioral results showed clear differences in the magnitude of the transposed-character effect for letters as com-

pared with digit and symbol strings. Electrophysiological data confirmed this observation, showing an N2 character transposition effect that was only present for letter strings. An earlier N1 transposition effect was also found for letters but was absent for symbols and digits, whereas a later P3 effect was found for all types of string. These results provide evidence for a position coding mechanism that is specific to letter strings, that was most prominent in an epoch between 200 and 325 msec, and that operates in addition to more general-purpose position coding mechanisms. ■

## INTRODUCTION

Efficient reading is based on the correct recognition and processing of individual printed words, which constitute the primary building blocks of visual language processing. On a daily basis, a reader has to process a huge number of letter strings presented in sentence context and/or in isolation. Nevertheless, a considerable portion of the printed material is often made of stimuli other than letters, such as symbols and digits. Because the literate brain is constantly exposed to letter strings and other types of heterogeneous strings, the question is whether they are processed through the same mechanism or through stimulus-specific processing mechanisms. This is not a trivial question, because the answer could help us better understand the mechanisms underlying visual word recognition, as compared with recognition of visually presented numbers and symbols.

The mechanisms underlying letter processing have been investigated in depth in the psycholinguistic literature (see Grainger, Rey, & Dufau, 2008; Carreiras & Grainger, 2004). Most researchers would agree that efficient visual word processing requires at least two key steps in the earliest stages of letter-in-string processing: letter identity coding (determining what the constituent letters are) and letter

position coding (determining the order of those letters; see Duñabeitia & Carreiras, 2011; Carreiras, Duñabeitia, & Molinaro, 2009; Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006; see Grainger, 2008, for a summary). It is broadly accepted that the visual word recognition system has to distinguish between strings that are highly similar in terms of visual overlap (*cat* and *rat*) and in terms of orthographic overlap (*dog* and *god*), but at the same time, it has to be able to recognize allographs of the same word as different instances of one entity (*horse*, *HORSE*, *HoRsE*, and *bOrSe*; see Chauncey, Holcomb, & Grainger, 2008; Petit, Midgley, Holcomb, & Grainger, 2006). Interestingly, recent research has shown that the word recognition system is extremely tolerant to various transformations of the stimulus (see Duñabeitia, Molinaro, & Carreiras, 2011, for an extreme manipulation involving mirror letters and mirror words). For example, word recognition is largely unaffected by replacing some letters by letter-like symbols or digits (e.g., taking *M4T3R14L5* or *MΔT€R!ΔL\$* as *MATERIALS*; see Kinoshita & Lagoutaris, 2010; Molinaro, Duñabeitia, Marín-Gutiérrez, & Carreiras, 2010; Duñabeitia, Perea, & Carreiras, 2009a; Perea, Duñabeitia, & Carreiras, 2008; Carreiras, Duñabeitia, & Perea, 2007) or by removing some of the letters (for an illusory-letter phenomenon, see Davis & Bowers, 2006; Harris & Morris, 2001; Jordan, Thomas, & Scott-Brown, 1999).

Most relevant for this study is the host of recent experiments demonstrating that small changes in letter order only mildly disrupt fluent word recognition. Most of the evidence that has led to this conclusion comes from

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studies testing how strings, including transposed-letters (TL), are processed (see Grainger, 2008; Perea et al., 2008, for reviews). Preceding research has consistently shown that nonsense letter strings created by transposing internal letters of a real word (e.g., *CHOLOCATE* from *CHOCOLATE*) are more often perceived as a real word, as compared with strings formed by letter replacements (e.g., *CHOTONATE*; see Perea & Estévez, 2008; Perea & Carreiras, 2006; Perea & Fraga, 2006). Furthermore, TL masked primes facilitate the recognition of the corresponding base word as compared with primes with replaced-letters (e.g., *cholocate*–*CHOCOLATE* vs. *chotonate*–*CHOCOLATE*; see Perea & Lupker, 2003, 2004; see also Kinoshita & Norris, 2009; Perea et al., 2008; Duñabeitia, Perea, & Carreiras, 2007; Grainger, Kiyonaga, & Holcomb, 2006; Schoonbaert & Grainger, 2004), at least when the TL primes are not real words (see Duñabeitia, Perea, & Carreiras, 2009b). This evidence has led most authors to conclude that any model of orthographic coding that relies on slot-coding schemes by which each letter is assigned a single invariant position within the string (e.g., McClelland & Rumelhart, 1981) is essentially wrong (see Davis & Bowers, 2006, for a review), hence favoring other position coding mechanisms that allow certain tolerance to location variation and account for letter migration errors such as the TL effect (e.g., Davis, 2010; Gómez, Ratcliff, & Perea, 2008; Grainger, Granier, et al., 2006; Whitney, 2001).

This study aims at investigating the impact of character transpositions on processing letter strings as compared with digit and symbol strings to shed light on (a) the specific adaptation of the human visual recognition system for letter processing and (b) the similarities and differences in character position coding mechanisms for letters, symbols, and digits. According to the neural “recycling hypothesis,” the visual word recognition system is a convolution of perceptual systems initially devoted to visual object recognition, which have been adapted for letter string processing (see Dehaene et al., 2010; Dehaene, Cohen, Sigman, & Vinckier, 2005; McCandliss, Cohen, & Dehaene, 2003). Thus, functional specialization for reading is said to arise from the recycling of areas of the cortex, which in principle evolved for other purposes, in line with the premise that it is hardly plausible that relatively recent milestones in the human evolutionary process like reading and writing have led to the creation of domain-specific neural networks (see Duñabeitia, Molinaro, et al., 2011). It is therefore possible that when recognizing printed words we apply a letter position coding mechanism that is the default mechanism used by the visual system to code for combinations of any kind of visual object.

In line with this possibility, García-Orza, Perea, and Muñoz (2010) have recently presented evidence showing that significant TL priming effects can be found for different types of stimulus strings. García-Orza et al. used the masked priming version of the same–different matching task, which has been shown by Kinoshita and Norris (2009) to be sensitive to TL priming effects but is not in-

fluenced by lexical factors (see also Duñabeitia, Kinoshita, Carreiras, & Norris, 2011; Norris & Kinoshita, 2008). In the masked priming version of the same–different matching task, a reference stimulus is first presented for about 1000 msec, immediately followed by a masked prime (for about 50 msec), which is in turn replaced by the target. Participants have to decide whether the target is the same as or different from the reference and “same” responses typically benefit from the previous presentation of a related masked prime (e.g., a TL prime). García-Orza et al. showed that TL masked primes facilitated “same” responses to targets as compared with primes with character replacements for letter, digit, and symbol strings. In more detail, the authors reported TL priming effects for pronounceable and unpronounceable nonword strings (e.g., *JSTN*–*JTSN* vs. *JRLN*–*JTSN*) as well as for digit strings (e.g., *5276*–*5726* vs. *5316*–*5726*) and symbol strings (e.g., *>+&*–*>* vs. *%?&*–*>*“+&”), whereas they failed to obtain significant TL priming effects for pseudoletter strings.

The importance of these results for models of orthographic processing is patent, considering that some of them make specific claims regarding the nature of the position coding processes and the type of printed stimuli these processes may apply to (see García-Orza et al., 2010, for details). Whereas some accounts of letter position coding are exclusively focused on letter processing and are silent with respect to general position coding mechanisms for various types of visual object (i.e., purely orthographic models of position coding; e.g., Davis, 2010; Grainger, Granier, et al., 2006; Grainger & Van Heuven, 2003; Whitney, 2001), other accounts do not a priori differentiate between letters and other printed elements such as digits or symbols, because they explicitly assume that the mechanisms underlying letter position coding are shared by general object position coding. The overlap model (Gómez et al., 2008) is a clear reflection of the latter view. According to this model, object position coding follows an uncertainty principle in the form of a noisy or fuzzy slot-based position assignment. Thus, a given object (e.g., a letter in a string) is assigned a given position but with a certain degree of uncertainty, with locations closest to the actual object location having the highest probability levels (i.e., the lowest uncertainty rates) and the furthest locations having the lowest probability levels (i.e., the highest uncertainty rates; see also Norris, Kinoshita, & van Casteren, 2010, for a Bayesian model using perceptual uncertainty).

On the other hand, there are models that explicitly state that position coding is different in essence for letters than for other types of visual objects. The open-bigram coding schemes proposed by Grainger, Whitney, and colleagues (Grainger, Granier, et al., 2006; Grainger & Van Heuven, 2003; Whitney, 2001; see also Whitney & Cornelissen, 2008; Whitney & Berndt, 1999) are one example of this approach. This point was most forcefully made in recent theoretical work arguing that it is likely that more than one type of position coding mechanism is involved in visual word recognition (Grainger & Dufau, submitted; Grainger &

Ziegler, 2011; Grainger & Holcomb, 2009a). The general idea is that during the very first stages of reading acquisition, some type of default position coding scheme is likely involved in establishing a routine for phonological recoding (i.e., mapping letters and letter clusters onto sounds). However, via repeated exposure to printed words, a specialized system for orthographic processing is set up, that, on the one hand, is geared to provide fast access to semantic information via a coarse-grained orthographic code and, on the other hand, is geared to improve the process of phonological recoding via the use of a parallel, fine-grained orthographic code (Grainger & Ziegler, 2011). It should be noted that both the coarse-grained and fine-grained orthographic codes, described in the work of Grainger and colleagues, involve word-centered, location-invariant coordinate systems, such that letter position is coded with respect to where the letter is in the word and not where it is relative to eye fixation. The complete model of orthographic processing involves a prior stage of retinotopic mapping of visual features onto location-specific letter identities.

In this dual-route approach to orthographic processing, the coarse-grained code computes approximate letter order and exploits the most informative contiguous and noncontiguous letter combinations to constrain word identity. The fine-grained code computes more precise letter position information to extract frequently co-occurring contiguous letter combinations (e.g., complex graphemes and affixes) and to provide an accurate translation of prelexical orthography onto prelexical phonology. Most important, for the present purposes, is the idea that the coarse-grained orthographic code will only be acquired for strings of elements that can form familiar wholes, as is the case for strings of letters. This is clearly not the case for symbol strings and is likely not to be the case for digit strings given the rarity of familiar numbers such as well-known dates. Moreover, the flexible nature of the coarse-grained orthographic code in this theory implies that it is the major mechanism underlying letter transposition effects. However, transposition effects can also be generated at two other processing stages in the overall framework proposed by Grainger and Ziegler (2011): (1) during the mapping of visual features onto location-specific letter detectors, given a certain amount of noise in this mapping process (i.e., the mechanism driving TL effects in the overlap model) and (2) during fine-grained orthographic processing, assuming again a certain amount of noise in this position-coding mechanism. However, these mechanisms were initially proposed as part of the reading system, with no specific mention to other types of printed stimuli (i.e., symbols or digits). Hence, it remains to be seen whether digit or symbol strings might also be processed by similar mechanisms or whether such mechanisms are specifically used to process letter strings. Whereas symbol strings might not be processed in the same manner, digit strings could be initially subjected to the same type of analysis as letter strings are, considering recent evidence showing

that the processing of digit strings highly resembles that of letter strings, while both differ from the processing of symbol strings (e.g., Tydgate & Grainger, 2009). Finally, general-purpose object position coding mechanisms might also be sensitive to the close spatial proximity of different objects that need to be processed simultaneously, therefore generating transposition effects that are not specific to strings of letters or digits.

Given the above theoretical considerations, this study provides a further test of effects of letter transpositions on letters, digits, and symbols. We make three significant changes with respect to the prior work of García-Orza et al. (2010). First, we use the classic same-different matching task (Ratcliff, 1981) as opposed to the masked prime version of this task (Kinoshita & Norris, 2009), with the aim to increase effect sizes and the possibility of observing differences between stimulus types. Second, we use an arguably stronger within-participant manipulation of stimulus type, rather than the between-participant manipulation used in the García-Orza et al. study, to increase the opportunity of observing differences across stimulus types. Third, we combine behavioral measures of TL effects with ERP recordings, thus providing the possibility of observing differences across stimulus categories that might not be visible in the final button-press. Participants were presented with pairs of four-character strings made of digits, symbols or letters, and were simply asked to decide whether the two strings were identical or different (the classic same-different matching task, also known as the perceptual matching task; see Proctor, 1981; Ratcliff, 1981). The first and the second members of the pair could be exact repetitions (i.e., *same* trials, e.g., *RFCV-RFCV*, *1754-1754*,  $\mathcal{E}\$! = -\mathcal{E}\$! =$ ) or different strings created by transposing the two internal characters (i.e., different transposed-character trials, e.g., *RFCV-RCFV*, *1754-1574*,  $\mathcal{E}\$! = -\mathcal{E}\$! =$ ) or by replacing those two characters (i.e., different replaced-character trials, e.g., *RFCV-RSTV*, *1754-1684*,  $\mathcal{E}\$! = -\mathcal{E}\%€ =$ ). While participants performed the perceptual matching task, their behavioral responses (RTs and error rates) as well as their electrophysiological activity (ERPs) were recorded. The ERP results will be critical for isolating distinct patterns of transposition effects across the three types of stimuli at different points in time. This is crucial given that we expect different patterns to emerge depending on when letter-specific (and possibly mechanisms specific to letters and digits) come into play. ERPs provide a unique opportunity to uncover early short-lived differences across character types because of the fine-grained temporal resolution of this technique. Also, differences in electrophysiological measures of brain activity during transposed- and replaced-character string processing will shed light on the time course of the underlying processes.

The key prediction for this study is that, if visual word recognition involves a type of letter position coding that is not used with other types of character strings, then we should see a different pattern of TL effects for letter

strings compared with both digit and symbol strings. Furthermore, given that letters and digits might share some position-sensitive processing that only applies to stimuli that are typically processed as strings (i.e., words and numbers), then at some point in processing, we would expect to see a similar pattern of transposition effects for these two types of character, in the absence of an effect for symbols. Finally, the emergence of transposition effects with symbol stimuli will provide an indication of the relative time course of letter/digit-specific coding mechanisms and more general-purpose object position coding mechanisms.

## METHODS

### Participants

Twenty-four undergraduate and graduate students (10 women) with a mean age of 22.78 years ( $SD = 3.88$  years) from the University of La Laguna initially took part in the experiment in exchange for course credit, although for technical problems only data from 23 participants (10 women) with a mean age of 22.95 years ( $SD = 3.88$ ) were recorded. They were all native Spanish speakers, with no history of neurological or psychiatric impairment and with normal or corrected-to-normal vision. All participants were right-handed, as assessed with an abridged Spanish version of the Edinburgh Handedness Inventory (Oldfield, 1971). They all signed informed consent forms before the experiment and were appropriately informed regarding the basic procedure of the experiment, according to the ethical commitments established by the ethics committee that approved the experiment.

### Materials

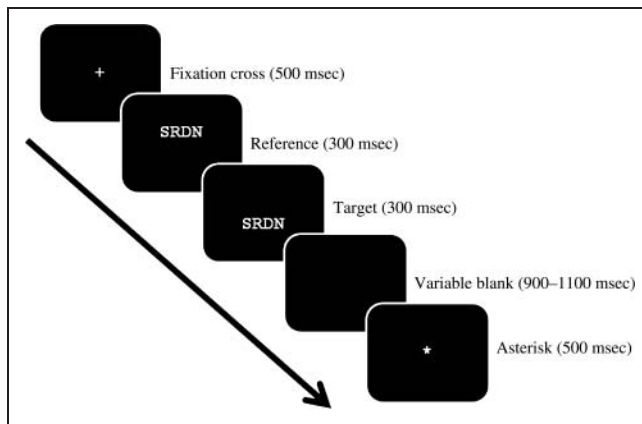
Five hundred forty reference–target pairs were used as stimuli. Each of the pairs was composed of two 4-character-long strings of digits, meaningful symbols, or uppercase consonants. The same target stimulus appeared twice in the experiment, once requiring a “same” response (270 trials) and once a “different” response (270 trials). In the 270 trials requiring a “same” response, the target was the exact repetition of the reference (i.e., identity condition; e.g.,  $7286-7286$ ,  $?G\text{€} < - ?G\text{€} <$ ,  $NDTF-NDTF$ ). In the 270 trials, requiring a “different” response, the target was either (i) the same as the reference but with the two internal characters transposed (i.e., different transposed-character condition; e.g.,  $7286-7826$ ,  $?G\text{€} < - ?\text{€}G <$ ,  $NDTF-NTDF$ ) or (ii) the same as the reference but with the two internal characters replaced by others (i.e., different replaced-character condition; e.g.,  $7286-7356$ ,  $?G\text{€} < - ?\$ \% <$ ,  $NDTF-NSBF$ ). The experiment was divided in three blocks, each of them corresponding to a specific type of character (letters, digits, or symbols). In this way, out of 540 reference–target pairs, 180 were made of consonants, 180 were made of digits, and 180 were made of symbols (and in each case,

90 pairs involved identical reference–target stimuli, 45 pairs differed by a transposition, and 45 pairs differed by replacement). For the letter strings, the uppercase version of the consonants G, N, D, K, F, T, S, B, and L were used. For the digit strings, the numbers 1, 2, 3, 4, 5, 6, 7, 8, and 9 were used. For the symbol strings, the characters %, ?, &, &, +, (, <, \$, and € were used. Apart from the appearance of each target string twice (once requiring “same” and once requiring “different” responses), no other item repetition occurred within the whole experiment. Two lists were constructed so that, within a list, each target word appeared only once in association with a “different” response (critical trials), and across both lists, each target appeared in both the transposition and the replacement conditions. Assignment of lists was counterbalanced across participants so that half of the participants were randomly assigned to one list and the other half, to the other list. Block (letters, digits, and symbols) presentation order was randomized across participants, and within each block item, presentation order was randomly varied across participants.

### Procedure

Participants were individually tested in a well-lit sound-proof Faraday room. The presentation of the stimuli and recording of the responses was carried out using Presentation software. All stimuli were presented on a high-resolution CRT monitor that was positioned at a distance of 70 cm. Participants were informed that they were going to be presented with two strings of characters, one after the other, exclusively composed of digits, symbols, or letters. They were instructed to press as fast and accurately as possible one out of two buttons on a gamepad when the two strings were identical and the other when they were different. The buttons corresponding to the “same” and to the “different” responses were counterbalanced across the participants. All stimuli were presented in white Courier New font on a black background. Each character occupied a 4.5 mm (width)  $\times$  6 mm (height) rectangle on the screen. Each trial started with the presentation of a fixation cross (“+”) in the center of the screen for 500 msec. Immediately after this, the reference stimulus was presented for 300 msec and was horizontally centered and positioned 3 mm above the exact center of the screen. Next, the target string appeared for 300 msec and was horizontally centered and positioned 3 mm below the center of the screen. The manipulation of the location of references and targets on the vertical axis was carried out to avoid physical overlap between the two strings. After the target disappeared, there was an intertrial interval that randomly varied between 900, 1000, and 1100 msec. The trial concluded with the presentation of an asterisk (“\*”) for 500 msec to allow participants to blink (see Figure 1 for a schematic representation of a trial). Participants were asked to respond as fast as possible once the target had appeared on the screen, and response latencies were collected from target onset onward, until the next trial began.





**Figure 1.** Schematic representation of an experimental trial.

The experiment was divided in three separate blocks, one for each stimulus category (digits, symbols, and letters). We opted for the creation of different blocks to maximize the chances of uncovering differences between character transpositions and replacements within each type of stimulus category. In this respect, it should be mentioned that García-Orza et al. (2010) also explored each type of string separately, although contrarily to this study, they tested different participants in each condition. Each participant received 12 practice trials at the beginning of each block, formed of stimuli that were similar to those used in the experimental trials of the corresponding block.

### Behavioral Analysis Method

Statistical analyses were performed only on the “different” response trials, because there was no experimental manipulation on the “same” response trials. Incorrect responses and RTs below or above 2.5 standard deviations from the mean were excluded from the latency analysis. Mean latencies for correct responses and error rates are presented in Table 1. ANOVAs over participants and items on the response latencies and on the error rates were conducted based on a 3 (Type of Character: digits, symbols, letters)  $\times$  2 (Type of Relationship: transposition, replacement)  $\times$  2

(List: 1, 2). The factor list was included in the ANOVAs as a dummy variable to extract the variance of the error associated with the lists (Pollatsek & Well, 1995).

### EEG Recordings and Analysis Method

Scalp voltages were collected from 58 Ag/AgCl electrodes, which were mounted in an elastic cap (ElectroCap International, Eaton, OH, 10–10 system). The right mastoid was used as reference. Eye movements and blinks were monitored with further four electrodes providing bipolar recordings of the horizontal and vertical EOG. Inter-electrode impedances were kept below 5 K $\Omega$ . EEG was filtered with an analogue bandpass filter of 0.01–50 Hz and a digital 25 Hz low-pass filter was applied before analysis. The signals were sampled continuously throughout the experiment with a sampling rate of 250 Hz and digitally rereferenced to linked mastoids. Epochs of the EEG corresponding to 700 msec after target string presentation in the “different” trials were averaged and analyzed. Baseline correction was performed using the average EEG activity in the 100 msec preceding the onset of the target stimuli as a reference signal value. All those epochs free of ocular and muscular artifacts after an artifact rejection process and ocular correction of the trials were averaged (91.9% of the data in the digit string block, 93.5% of the data in the symbol string block, and 92.3% of the data in the letter string block). Additionally, we removed all the epochs associated with incorrect responses in the “different” trials (i.e., trials in which the target was incorrectly identified as being identical to the reference stimuli) and then averaged and analyzed only these artifact-free segments. This data filtering process resulted in the inclusion of 87.8% of the data in the digit string block, 78.9% of the data in the symbol string block, and 80.3% of the data in the letter string block in the analysis. Nine representative electrodes were selected for the repeated measures ANOVA analyses, creating the factors Electrode (three levels: frontal, central, parietal) and Laterality (three levels: right hemisphere, midline, left hemisphere). The selected frontal electrodes were F5 (left), Fz (midline), and F6 (right). The central electrodes were C5 (left), Cz (midline), and C6 (right). The parietal

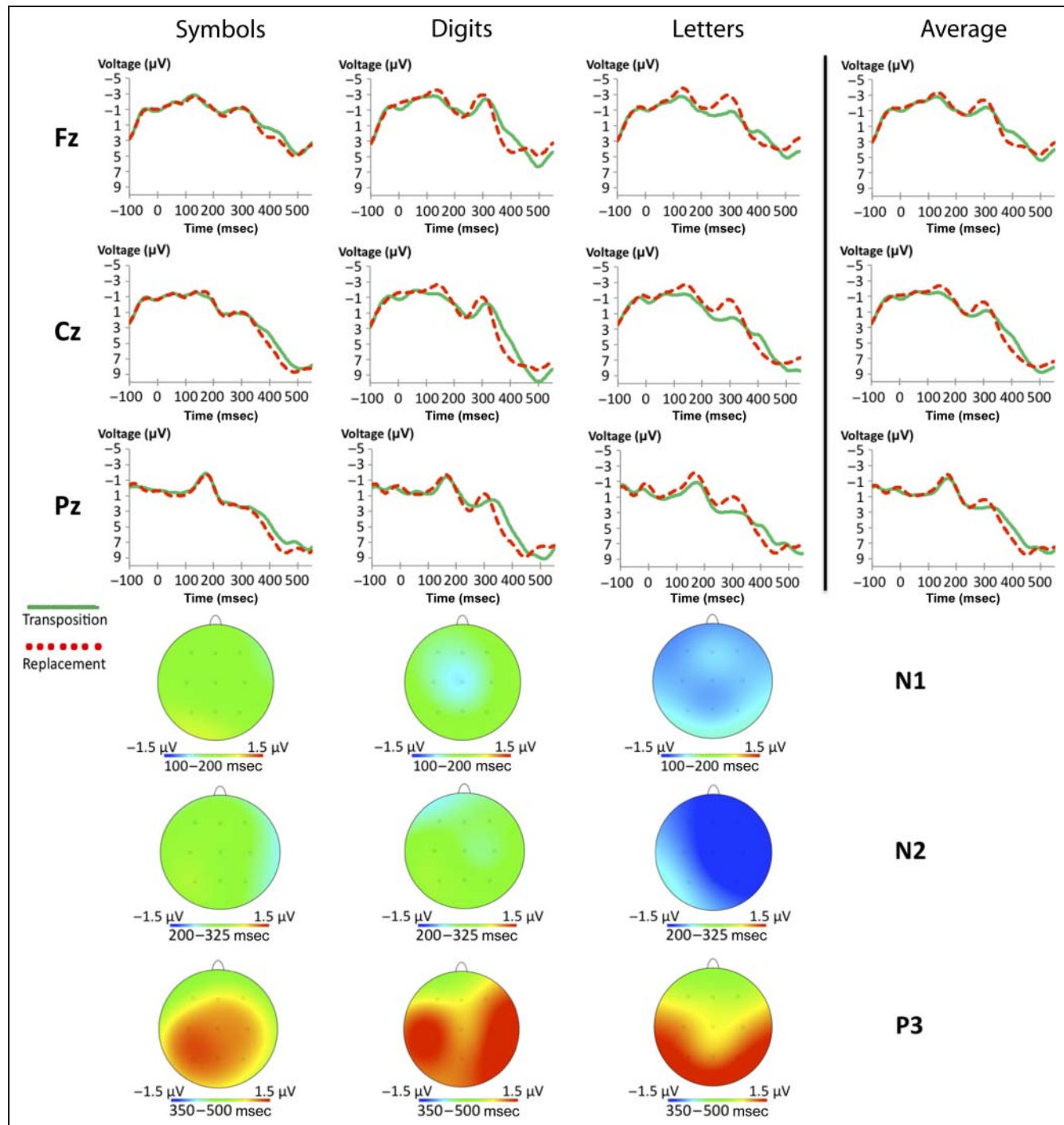
**Table 1.** Mean Reaction Times (in msec) and Percentages of Errors (within Parentheses) for the “Different” Trials Obtained in the Experiment

Type of Character	Type of Relationship		
	Transposition	Replacement	Transposition Effect
Digits	613 (11.01%)	578 (3.29%)	–35 (–7.72%)
Symbols	632 (21.55%)	605 (10.16%)	–27 (–11.39%)
Letters	672 (24.15%)	600 (5.99%)	–72 (–18.16%)

Mean RTs and percentages of errors for the “same” trials were 530 msec (3.72%), 545 msec (9.76%), and 556 msec (7.68%) for the digit, symbol, and letter strings, respectively. “Transposition effect” is the outcome of the subtraction of the values in the transposition condition from those in the replacement condition.

row of electrodes was formed by P5 (left), Pz (midline), and P6 (right). Together with these factors, Type of Character (three levels: letters, symbols, digits) and Type of Relationship (two levels: transposition, replacement) used for the behavioral analyses were taken as main factors in the ANOVA, corresponding to the variables of interest. Where appropriate, critical  $p$  values were adjusted using

the Greenhouse–Geisser correction for violation of the assumption of sphericity. Following visual inspection and cross-validating these observations with the preceding literature, three critical ERP time windows were selected for analysis: 100–200 msec posttarget onset, 200–325 msec posttarget onset, and 350–500 msec posttarget onset (see Figure 2).



**Figure 2.** Grand-averaged ERPs corresponding to the symbol, digit, and letter strings, together with the averaged waveforms, in the midline electrodes (Fz, Cz, Pz) for the transposed-character (solid green lines) and replaced-character conditions (dotted red lines). Bottom: The N1, the N2 and the P3 components in their corresponding time windows in topographical maps (created by subtracting the observed voltage for replaced-character strings minus transposed-character strings).

## RESULTS

### Behavioral Measures

The latency analyses revealed a significant main effect of Type of Character [ $F_1(2, 42) = 7.26, p < .01; F_2(2, 176) = 29.20, p < .001$ ], and a main effect of Type of Relationship [ $F_1(1, 21) = 31.16, p < .001; F_2(1, 88) = 147.64, p < .001$ ], with targets related to the references by means of transposition of their internal characters being responded to 45 msec slower than targets related to the references by replacement of the same characters (i.e., a character transposition similarity effect). Importantly, the interaction between the two factors was also significant, reflecting the fact that the magnitude of the transposition cost varied as a function of stimulus type [ $F_1(2, 42) = 8.85, p < .01; F_2(2, 176) = 11.16, p < .001$ ]. Subsequent pairwise comparisons showed that there were significant transposition costs (replacement minus transposition) for the three types of stimuli: digits (35 msec) [ $F_1(1, 21) = 13.95, p < .01; F_2(1, 88) = 58.91, p < .001$ ], symbols (27 msec) [ $F_1(1, 21) = 8.80, p < .01; F_2(1, 88) = 12.71, p < .01$ ], and letters (72 msec) [ $F_1(1, 21) = 35.95, p < .001; F_2(1, 88) = 91.33, p < .001$ ]. To further explore the evident difference in the magnitude of the transposition cost effects obtained for the different types of strings, the net transposition costs were calculated (RTs in the replacement conditions minus RTs in the transposition conditions) and contrasted. Pairwise comparisons showed that the transposition cost was larger (37 msec larger) for letter strings than for digit strings [ $F_1(1, 21) = 10.07, p < .01; F_2(1, 88) = 11.86, p < .01$ ] and also larger (45 msec larger) for letter strings than symbol strings [ $F_1(1, 21) = 11.35, p < .01; F_2(1, 88) = 17.35, p < .001$ ]. The 8-msec difference between the transposition costs associated with the digit and the symbol strings was not significant (both  $ps > .17$ ).

The error rate analyses showed a significant main effect of Type of Character [ $F_1(2, 42) = 9.54, p < .001; F_2(2, 176) = 48.89, p < .001$ ]. There was also a main effect of type of relationship, with targets related to the references by transposition being responded to less accurately (12.43% more errors) than targets related by replacement (i.e., a character transposition similarity effect) [ $F_1(1, 21) = 31.39, p < .001; F_2(1, 88) = 282.84, p < .001$ ]. As with the latency analysis, the interaction between the two factors was significant, suggesting that the magnitude of the transposition cost differed across stimulus types [ $F_1(2, 42) = 7.30, p < .01; F_2(2, 176) = 13.62, p < .001$ ]. Pairwise comparisons showed that the transposition costs in the error rates were significant for the three types of strings: digit strings (7.72% more errors) [ $F_1(1, 21) = 10.70, p < .01; F_2(1, 88) = 48.68, p < .001$ ], symbol strings (11.39% more errors) [ $F_1(1, 21) = 23.01, p < .001; F_2(1, 88) = 56.68, p < .001$ ], and letter strings (18.16% more errors) [ $F_1(1, 21) = 29.13, p < .001; F_2(1, 88) = 141.86, p < .001$ ]. Critically, the transposition cost was larger for the letter strings as compared with both the digit strings (10.43% more errors) [ $F_1(1, 21) = 20.94, p < .001; F_2(1, 88) = 27.22, p < .001$ ] and to the symbol

strings (6.78% more errors) [ $F_1(1, 21) = 4.84, p < .05; F_2(1, 88) = 8.97, p < .01$ ]. The difference in the transposition cost between digit and symbol strings (3.66% more errors for symbol string transposition cost) was only significant in the item analysis [ $F_1(1, 21) = 1.64, p > .20; F_2(1, 88) = 4.30, p < .05$ ].

### Electrophysiological Measures

#### 100–200 msec Posttarget

The main effect of Type of Relationship was significant [ $F(1, 22) = 4.96, p < .05$ ], reflecting the fact that in this time-window, targets deviating from the references because of character replacements elicited larger negativities than targets deviating from the references because of character transpositions. The type of character effect was not significant ( $p > .89$ ). Interestingly, the interaction between these two factors did approach significance [ $F(2, 44) = 2.97, p = .06$ ]. As can be seen in Figure 2, there was a large transposition effect for letters, no visible effect for symbols, and an intermediate effect for digits. None of the interactions of these factors with the topographical factors Electrode and Laterality reached significance [all  $F_s < 1.5$  and  $ps > .18$ ]. Follow-up pairwise comparisons showed that the Type of Relationship effect was significant for letter strings [ $F(1, 22) = 12.63, p < .01$ ], negligible for symbol strings [ $F < 1, p > .94$ ], and not significant for digit strings [ $F(1, 22) = 2.07, p = .16$ ].

#### 200–325 msec Posttarget

The main effect of Type of Character was not significant [ $F < 1, p > .63$ ]. The effect of Type of Relationship was significant [ $F(1, 22) = 5.46, p < .05$ ], reflecting the fact that targets containing transposed-characters elicited more negative-going waveforms than targets containing replaced-characters. Critically, the interaction between these two factors was significant [ $F(2, 44) = 4.73, p < .05$ ]. The three-way and four-way interactions between these factors and the topographical factors did not reach significance [ $F_s < 1$  and  $ps > .60$ ].

Simple tests were then conducted to understand the origin of the interaction between type of character and type of relationship. These analyses revealed that the effect of Type of Relationship was neither significant for digit strings [ $F < 1, p > .53$ ] nor symbols strings [ $F < 1, p > .95$ ] but was significant for letter strings [ $F(1, 22) = 11.87, p < .01$ ] (see Figure 2). Letter strings that differed from the reference stimulus by letter replacements elicited more negative-going waveforms in this epoch than strings that differed by letter transpositions (see Figure 2). The interaction between this type of relationship effect for letter strings and the laterality factor approached significance [ $F(2, 44) = 2.57, p = .09$ ], reflecting the fact that the type of relationship effect was significant at all sites but slightly greater over right compared with the left electrode columns



[right:  $F(1, 22) = 16.01, p < .01$ ; midline:  $F(1, 22) = 9.18, p < .01$ ; left:  $F(1, 22) = 8.37, p < .01$ ].

### 350–500 msec Posttarget

The main effect of Type of Relationship was significant [ $F(1, 22) = 7.00, p < .05$ ], showing that targets that differed from the reference stimulus by replaced-characters elicited more positive-going waveforms than targets that differed by transposed-characters. The Type of Character effect was not significant [ $F(2, 44) = 2.43, p = .11$ ]. Importantly, the interaction between these two factors did not approach significance [ $F < 1, p > .85$ ], and there were no significant interactions with the topographical factors except for an interaction between Type of Relationship and Electrode [ $F(2, 44) = 3.87, p = .05$ ]. Follow-up simple tests showed that replaced-character targets elicited significantly more positive-going waveforms than transposed-character targets at parietal and central sites, but not at frontal sites [frontal:  $F(1, 22) = 2.32, p > .14$ ; central:  $F(1, 22) = 7.17, p < .05$ ; parietal:  $F(1, 22) = 12.51, p < .01$ ] (see Figure 2).<sup>1</sup>

## DISCUSSION

Are position coding mechanisms different for letters as compared with other sequences of common visual characters such as digits or symbols? The results of this study suggest that this is indeed the case and that changing the ordering of the letters within an unpronounceable string of consonants leads to behavioral and electrophysiological effects that are different from the effects observed for changes carried out within digit and symbol strings. At the behavioral level, we found that when a reference string and the subsequent target string differed by means of internal character transpositions, “different” responses in the same–different matching task were slowed as compared with strings that differed by character replacements (i.e., an RT transposition cost). Importantly, this transposition cost was reliably larger for manipulations involving letter transpositions as compared with digit and symbol transpositions. In a similar vein, participants made more errors on strings containing character transpositions than on strings containing character replacements (i.e., an accuracy transposition cost). In line with the results observed in the RTs, this transposition cost in accuracy was greater for letter transpositions compared with both digit and symbol transpositions. At the electrophysiological level, parallel effects to the behavioral ones were obtained in a negative-going component between 200 and 325 msec, with letter strings including replacements peaking more negatively than letter strings including transpositions. Importantly, this effect was present only for letter strings, and no differences were found in this time window for transpositions versus replacements involving either digits or symbols. A similar sensitivity to character transpositions was also seen in an earlier epoch, between 100 and 200 msec posttarget onset,

where once again letter stimuli showed a robust effect and symbol stimuli no effect.<sup>2</sup> Finally, all three types of stimulus showed a transposition effect in a time window between 350 and 500 msec, with more negative-going waveforms in the transposed-character condition compared with the replaced character condition.

In the visual word processing literature, the ubiquitous TL similarity effect (see Perea, Duñabeitia, & Carreiras, 2009, for a review) has been typically taken as an index of the relatively flexible manner by which readers process the order of the letters in a visually presented string (e.g., Gómez et al., 2008). When presented with a nonword created by transposing two adjacent or nonadjacent letters from a real word (e.g., *CHOLUCATE*), the resulting nonword is often incorrectly perceived and readers tend to lexicalize that string by reordering the letters to form a known word (e.g., *CHOCOLATE*; see Perea & Estévez, 2008; Perea & Carreiras, 2006; Perea & Fraga, 2006). This effect has been interpreted as a reflection of the tolerance of these mechanisms to variations or deviations from the standard (e.g., Davis, 2010; Norris et al., 2010; Whitney, 2001; see Grainger, 2008, for a review). However, recent research has questioned whether this apparent flexibility in the coding of positional information is an exclusive property of the visual word recognition system (e.g., Whitney, 2001) or, instead, whether it is a characteristic that applies to the processing of other nonalphabetic visual materials (e.g., Gómez et al., 2008). García-Orza et al. (2010) have recently presented evidence from the masked priming version of the same–different judgment task, showing that the character transposition effect can be effectively found for pronounceable and nonpronounceable letter strings, as well as for digit and symbol strings. The authors concluded that their results demonstrate that positional uncertainty is a general property of the human visual system that plays a similar role in the recognition of any sequence of familiar objects. This was therefore taken as evidence in support of models of orthographic coding that are not based on letter-specific processing mechanisms but rather appeal to general mechanisms that are involved in processing positional information about various types of visual object (Gómez et al., 2008).

The present results are at odds with the results of García-Orza et al. (2010), insofar as the present data provide strong evidence in favor of letter-specific position encoding mechanisms. While an omnipresent character transposition cost was found for all character strings, this cost was significantly greater for letter strings than for symbol and digit strings as seen in the behavioral data (both in the error rates and in the RTs) and, more importantly, in the electrophysiological responses in the 200–325 msec time window. We argue that the significantly greater transposition effects seen for letter strings compared with digit and symbol strings in this study and not seen in the García-Orza et al. study is because of increased sensitivity obtained by using an explicit same–different matching task (rather than the masked-prime version used by García-Orza et al.) as



well as the within-participants manipulation of stimulus type that was used in our study. Similar to what García-Orza et al. found at the behavioral level, we also found a transposition effect in ERP recordings that was the same for all character strings in the 350–500 msec time windows. Most critical is the fact that transposition effects were seen exclusively for letter strings in an intermediate time window (200–325 msec) and in the 100–200 msec time window. Thus, the present results represent a step forward in our understanding of how positional information is encoded during the processing of strings of elements and suggest that, in this respect, letter strings are processed differently from strings of other types of familiar characters such as digits and symbols.

How can one interpret the greater transposed-character similarity effect observed for letters as compared with digits and symbols in RTs and error rates? Put differently, why is positional uncertainty greater when processing letter strings than symbol or number strings? One straightforward explanation is that strings of letters trigger a qualitatively distinct type of processing compared with strings of other familiar elements such as digits and symbols. This hypothesis was explicitly developed in the recent theoretical work of Grainger and colleagues (Grainger & Dufau, submitted; Grainger & Ziegler, 2011), where a clear distinction was drawn between two very different types of word-centered letter position coding mechanism: one designed to map letters onto whole-word orthographic representations as efficiently as possible given constraints on letter visibility and the other designed to provide more precise positional information to accurately map letters onto phonology. It is the first type of position coding mechanism that would be specific to strings of letters, whereas the second would correspond to a more general type of position coding mechanism applicable to various types of visual object. The first type of position coding mechanism requires less precision than the second and would therefore be the source of the increased effects of letter transpositions seen with letter strings compared with both digit and symbol strings.

The ERP results of this study are particularly informative with respect to this hypothesized distinction between different types of position coding mechanisms in the Grainger and Ziegler (2011) model. As pointed out in the Introduction, although there is clearly one type of position-coding that is specific to letter stimuli, it is also possible that letter and digit stimuli might share the other two position-coding mechanisms that are described in the overall framework. There was some evidence in favor of this possibility in the earliest (100–200 msec) time window, where letter strings showed a robust transposition effect, symbol strings showed no effect, and there was some evidence for an effect with digit strings. Even if the evidence in favor of an effect for digit strings was not conclusive (i.e., marginal only in the midline), we would tentatively suggest that this pattern might correspond to positional errors arising dur-

ing the parallel encoding of location-specific letter and digit identities. Indeed, prior behavioral research has shown that the serial position curves for character-in-string identification are very similar for letters and digits, which both differ from the pattern seen with symbol stimuli (e.g., Tydgat & Grainger, 2009). The earliest difference in the negative-going component between 100 and 200 msec could be interpreted as a visual N1 component, which has been proven to be sensitive to basic perceptual discrimination processes between two consecutive stimuli.

The N1 typically reflects discrimination processes within the focus of attention (e.g., Vogel & Luck, 2000). In line with this, the greater negativity associated with targets including character replacements could indicate that because of the perceptual difference between references and targets of this category (as compared with targets including character transpositions), the processing of this type of stimulus requires enhanced attentional demands (see Martinez et al., 2006, for a similar conclusion). Indeed, considering the tight relationship between attention and perception (e.g., Mangun & Hillyard, 1991), we believe that the N1 effect found in this study reflects the greater attentional resources needed to process the visual information contained in replaced-character strings, which perceptually deviate from the reference more than transposed-character strings. Note that the N1 transposition effect was significant for letters, marginally significant for digit strings at midline electrode sites, and not significant for symbol strings. We interpret this pattern as reflecting the perceptual processes associated with the initial parallel mapping of visual features onto location-specific letter identities (a process that might be shared with digit strings), proposed by Grainger and Ziegler (2011; see also Grainger & Van Heuven, 2003).

The timing of the early N1-like transposition effect coincides with another ERP effect, with a different spatial distribution, that has been found in masked priming studies of letter and word processing. Petit et al. (2006) identified a component that was sensitive to physical differences between primes and targets, which was referred to as the N/P150. The N/P150 was significantly larger for dissimilar prime–target pairs than for similar pairs (see also Cornelissen, Tarkiainen, Helenius, & Salmelin, 2003, for MEG data). This N/P150 component has been repeatedly shown to reflect larger amplitudes for mismatching patterns than for matching stimuli (e.g., Duñabeitia, Molinaro, et al., 2011; Carreiras et al., 2009; see Grainger & Holcomb, 2009b, for a review). Not only exact repetitions elicit N/P150 effects, but also targets that are different from the references but that are perceptually very similar to them (e.g., strings like ABCDEF and 4BCD3F), result in N/P150 differences as compared with more distinct stimuli (e.g., 7BCD9F; see Molinaro et al., 2010). This suggests that the N/P150 component reflects an early perceptual process in which the mapping of visual features onto higher-level representations has been initiated. For strings consisting of letters, this would correspond to the initial phase of mapping

visual features onto location-specific letter identities in parallel.

The transposition effect seen exclusively for letters strings between 200 and 325 msec after target presentation would appear to be driven by changes in amplitude of the N2 ERP component. The N2 is typically elicited by a template that deviates from another that has been mentally stored previously (see Potts & Tucker, 2001). According to preceding studies, greater standard–target variations result in an increase of the N2 amplitudes. In the present case, the greater N2 elicited by strings containing letter replacements can be understood as showing that these strings represent a larger mismatch or deviation from the reference (the standard for comparison) than strings containing letter transpositions. In other words, according to Hoffman (1990), the N2 reflects a deviation from a prevailing stimulus, and according to the present results, we are safe to conclude that letter transpositions were perceived to deviate less from the corresponding references, as compared with symbol and digit transpositions, because no N2 transposition effect was found for the two latter types of stimuli.

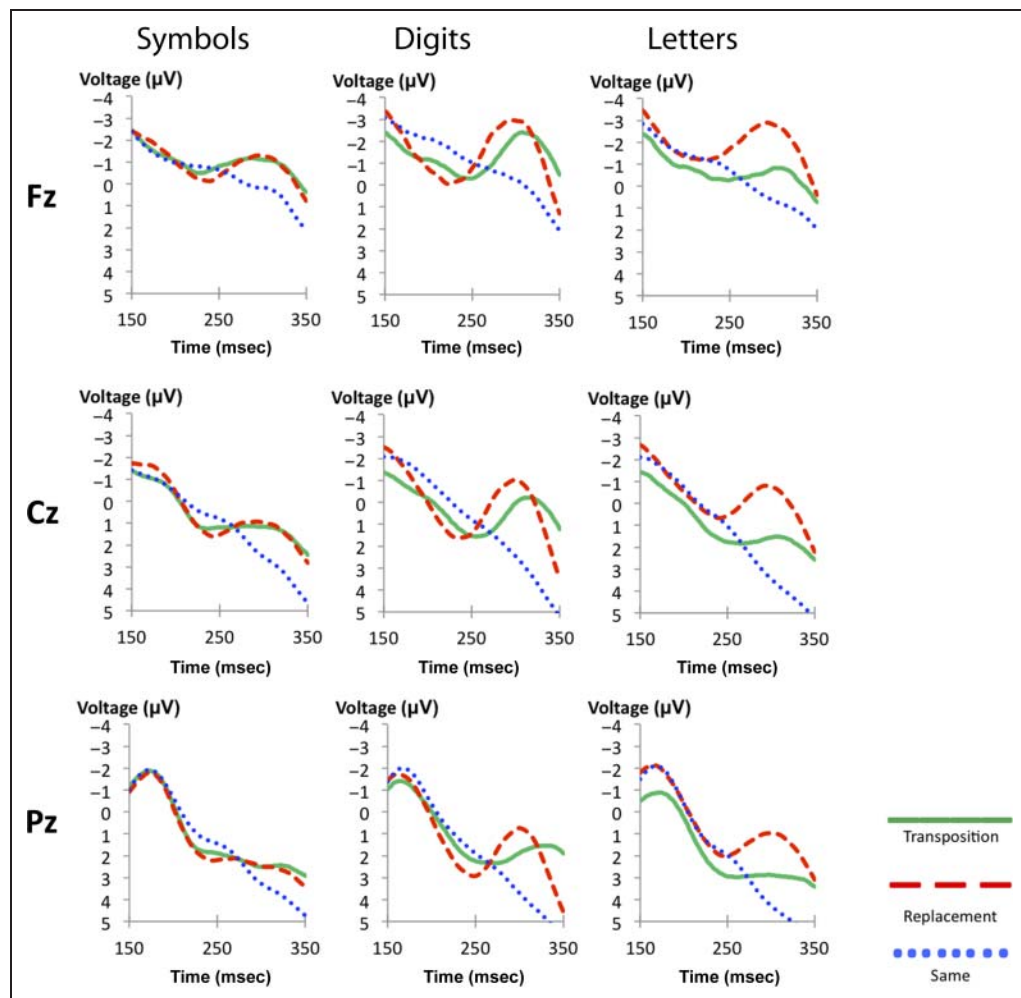
N2 effects have been typically linked either to the inhibition of the prevalent response (see Nieuwenhuis, Yeung, & Cohen, 2004) or to the detection of a response conflict (see Van Veen & Carter, 2002) or conflicting action tendencies (Azizian, Freitas, Watson, & Squires, 2006). In light of the present data, we suggest that the N2 transposition effect seen for letter strings is a consequence of a reduced conflict in the transposition condition compared with the replacement condition. Importantly, when transpositions involved other types of characters (digits or symbols), there was no N2 transposition effect, presumably because participants perceived the transposed-symbol and transposed-digit strings as similar to the referents as the replaced-digit and replaced-symbol strings. In this respect, it might be worth noting that when compared with the waveforms corresponding to the “same” responses, all transposed-character and replaced-character targets showed a negative-going deflection in this time window (i.e., an N2 effect). However, in the case of letter strings, TL targets elicited a brain electrophysiological response that was much closer to the brain activity associated with the “same” trials than the electrophysiological response elicited by replaced-letter targets, thus confirming that letter strings containing letter transpositions were processed as being highly similar to the references and represented a smaller deviation from the prevailing referent stimulus (see Figure 3). As argued above, this transposition effect seen uniquely with letter strings, and not with digit or symbol strings, is thought to reflect a letter-specific coarse-grained coding scheme that would generate a greater perceived similarity between the TL strings and their references.

With regard to the general transposition effect found for letter, digit, and symbol strings in the 350–500 msec time window of the ERP recordings, it should be men-

tioned that at the temporal, spatial and component-shape levels, this effect would appear to be on the P3 component (see Nieuwenhuis, de Geus, & Aston-Jones, 2011, for a review). The P3 (more correctly defined as P3b in this type of experiment) is a broadly distributed long-lasting positively peaking potential that starts after 300–400 msec poststimulus (Patel & Azzam, 2005, for a review). Indeed, the P3b typically has a parietal maximum, coherent with the findings reported in this study (see also Comerchero & Polich, 1999). This component is generally taken as an index of the match or mismatch of the given target stimulus as compared with a consciously maintained working memory trace (Näätänen, 1990), which in the present case would be linked to the reference stimulus. Therefore, one could interpret the P3 transposition effect found in this study as reflecting the overall greater mismatch between target and reference in the replaced character condition than in the transposed-character condition. Indeed, in experiments requiring reference–target comparisons, P3 amplitudes have been shown to be sensitive to the similarity of the target with regard to the standard (the reference), in a way that the amplitude of the P3 is inversely proportional to the similarity between the two items (see Comerchero & Polich, 1999). Furthermore, according to Näätänen (1990), transposed-character strings would constitute a match to the memory trace established by the referent, whereas replaced-character strings would notably deviate from that trace, thus leading to the observed P3 effect. In other words, target strings containing transposed characters are more similar to the references than target strings containing character replacements, thus leading to decreased P3 amplitudes. It should be noted that the N2/P3 complex is sometimes difficult to disentangle, because both components are sensitive to variations between a memory residual (namely, the reference) and a mismatching template (the target; see Luck & Hillyard, 1994). Nonetheless, whereas the present results confirm that replaced-character strings are perceived to be more different from the references than transposed-character strings, the N2 was sensitive to the type of character manipulated, whereas the P3 component was not.

Altogether, the pattern observed in the present ERP experiment is straightforward. In a first epoch (100–200 msec), the visual system evaluates strings containing transposed-characters as being more perceptually similar to the references than strings containing replaced-characters. This early transposition effect was found to be greatest for letter strings, absent for symbol strings, and with some evidence that there might be an effect for digit strings. Then, in a subsequent time window (200–325 msec), targets that are not identical to the references elicit a negative-going deflection, N2. Critically, in the case of letter strings, targets including letter transpositions elicit reduced negativities as compared with targets including letter replacements, showing that, at this stage, the letter-in-string position processing subsystem fails at fully distinguishing between two letter strings that differ in the position of two of the letter identities that form them. Finally, in a later epoch

**Figure 3.** Blow-ups of the N2 component for symbol, digit, and letter strings in the midline electrodes (Fz, Cz, Pz) for the transposed-character (solid green lines), replaced-character (dotted red lines), and “same” conditions (dotted blue lines).



(350–500 msec), a general transposed-character similarity effect emerged, showing a larger positive-going deflection for replaced-character strings than for transposed-character strings that was independent of the type of character under test.

It should be noted that the RTs for targets containing letter transpositions were, on average, much larger than the RTs in all the other conditions, emphasizing the fact that participants needed more time to reject letter string pairs related by transposition as being the same. Coherently, the electrophysiological data showed that, in the N2 component, strings containing TLs, as compared with strings including letter replacements, generated responses that were less deviant from the “same” responses. Altogether, this pattern highlights the high degree of similarity between strings containing transpositions and their references but emphasizes a reading-specific mechanism (or set of mechanisms) that acts during a very concrete time window (between 200 and 350 msec, approximately) that leads to TL strings being perceived as more similar to the references than replaced-letter strings.

One obvious question that arises is whether the greater similarity between TL strings and their references compared

with the similarity of transposed-digit or transposed-symbol strings to their references corresponds to a quantitative or a qualitative processing difference. We cannot unequivocally rule out either of these options, but specifically according to the present electrophysiological findings, we believe that a qualitative conception is more suited to account for the present pattern of results. While a general transposition cost was clearly evident in the behavioral data (see also García-Orza et al., 2010) as well as in the last epoch of interest in the present ERP analysis, our middle time window showed a difference exclusively for letter strings, revealing a letter-specific modulation of the N2 component. Although the difference shown in the RT and accuracy data is based on magnitude differences (larger RTs and higher error rates for TL strings than for replaced-letter strings) and thus could be interpreted as a quantitative difference, the electrophysiological pattern was clear-cut, showing that the N2 component was only sensitive to transposition effects with letter strings, thus favoring an interpretation in terms of qualitative differences in processing.<sup>3</sup>

Further evidence in favor of reading-specific mechanisms for early orthographic processing can be found in brain imaging studies. The last decade has witnessed an

increasing number of studies demonstrating functional specialization of specific brain areas (e.g., the so-called visual word form area) for letter string processing as compared with the processing of other visual materials (e.g., Szwed et al., 2011; Reinke, Fernandes, Schwindt, O'Craven, & Grady, 2008; Baker et al., 2007; see Cohen & Dehaene, 2004, for a review). However, the existence of a preferential tuning of a given brain area for alphabetic materials is not exempt from debate (e.g., James, James, Jobard, Wong, & Gauthier, 2005; see also Price, Winterburn, Giraud, Moore, & Noppeney, 2003; Moore & Price, 1999). A relative specialization of the human brain for reading might have resulted in a different degree of sensitivity to position migrations when these take place in letter strings as compared with symbol or digit strings. We have suggested that a form of coarse-grained orthographic coding might be basis of this difference. One specific implementation of coarse-grained coding of letters strings is the notion of open-bigram representations that code for the presence of ordered, but not necessarily contiguous, pairs of letters (Grainger & Whitney, 2004; Grainger & Van Heuven, 2003; Whitney, 2001). Then, a plausible assumption is that, as stated by Dehaene et al. (2005, p. 337), "bigram neurons, however, can respond selectively, yet with some tolerance for location of the component letters." Certainly, these bigram neurons would not take part in the processing of other visually presented materials (e.g., digits or symbols) because by definition bigrams exclusively refer to pairs of letters.

One could rightly question whether the present results really reflect a different character position coding mechanism operating for letters, as compared with digit or symbol strings, or whether these effects could be the consequence of other factors operating on top of a common position coding mechanism. One such factor could be related to differential crowding effects for letters, digits, and symbols (Grainger, Tydgate, & Isselé, 2010; Tydgate & Grainger, 2009). However, there are two reasons to doubt that the different crowding effects that have been shown for letters and symbols (Grainger et al., 2010) could be the basis of the pattern of transposition effects seen in this study. First, the reduced crowding for letters reported by Grainger et al. (2010) was taken as evidence in favor of a smaller receptive field size of retinotopic letter detectors compared with other types of visual object. Therefore, if the mechanisms driving crowding and transposition effects were the same, one would have expected a smaller (not larger) transposition effect for letter than for digit or symbol strings, because the reduced receptive field size for letters would imply a better positional coding of these items. Second, the results reported by Tydgate and Grainger (2009) show equivalent serial position function for letters and digits, which both differed from symbol stimuli. This therefore suggests that crowding effects should be the same for letters and digits. Although there was some evidence for similar transposition effects for digits and letters in

the N1 component, overall the present data show a clearly different pattern of transposition effects for letter strings than for digit strings. Hence, we believe that we can safely conclude that the present results are not a reflection of differential crowding as a function of stimulus type. We may of course be overlooking other possible confounding factors, but we leave that possibility to be explored in future research.

The present results do not parallel those reported by García-Orza et al. (2010), who failed to find any differences in the transposed-character similarity effect for digit, letter and symbol strings in a masked priming version of the same-different judgment task. However, several methodological constraints that prevent a straightforward comparison between the two studies should be taken into account. It should be considered that the same-different judgment task and the masked priming version of this task might tap into different processing stages, because the former is an explicit task where participants consciously respond to the similarity manipulation across target and reference stimuli which are clearly visible, while in the latter the target and reference stimuli are the same and the similarity manipulation is performed via an intervening subliminal prime stimulus (i.e., transpositions are carried out on the masked primes; see Duñabeitia, Kinoshita, et al., 2011; Kinoshita & Norris, 2009; Norris & Kinoshita, 2008). In this regard, it should be noted that conscious and unconscious processing have been shown to activate distinct neural networks, mainly because of top-down processing differences, and that consciously presented stimuli give rise to reverberation of neural activity, facilitating propagation and maintenance of information (see Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006). Hence, one possible reason for the discrepancy between the García-Orza et al. study, and this study might be the conscious versus unconscious nature of the experimental manipulation, which clearly has an impact on the neural resources at play during same/different judgments (see also Kouider & Dehaene, 2007, for a review). We believe that the mechanisms responsible for character position coding should not be radically different for implicit versus explicit manipulations or for conscious versus unconscious stimulus presentation (for TL effects in explicit tasks involving conscious manipulations, see White, Johnson, Liversedge, & Rayner, 2008; Rayner, White, Johnson, & Liversedge, 2006; see also Duñabeitia et al., 2009a, for an experiment testing consciously presented variations of letter shapes on reading performance). However, the level at which the differences between transposed- and replaced-character strings and their references are evaluated does clearly depend on the conscious nature of the judgment. Hence, we hypothesize that the reason for the discrepant results between García-Orza et al.'s study and the present one may rely on the sensitivity of the task, paradigm, and technique at use. While the masked priming version of the same-different task is an ideal task for those studies aimed at exploring prelexical orthographic representations



at an automatic level (e.g., Kinoshita & Norris, 2009), the original explicit and conscious same–different paradigm, together with ERP recordings, allows for the in-depth study of basic perceptual as well as preorthographic and memory-related cognitive processes, unraveling a complex pattern of deflections probably associated with different neural functional mechanisms.

We would want to stress the usefulness of the perceptual matching task in combination with ERP recordings. The perceptual matching task (or same–different judgment task) had been extensively used in cognitive psychology (see Ratcliff, 1981, 1985), but in the last decade has fallen into disuse. Here we have shown that this task is sensitive to small variations carried out on short strings, yielding strong behavioral effects both in the latency and accuracy data. Furthermore, when used together with electrophysiological recordings, this methodology has been shown to index basic differences between processing strategies, being linked to two well-known ERP components: N1, N2, and P3. Hence, we plead for the generalization of this specific combination of task and technique for future research aimed at exploring the coding of letter position and identity.

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### Notes

1. We performed the same analysis on data that included trials on which an error was made (92.6% of the data after artifact rejection). Results clearly replicated the pattern observed with the trimmed set of data that included exclusively the segments associated with correct responses. Nonetheless, for sake of simplicity, we only report the analysis performed on the correct segments.
2. It should be mentioned that in the N1 epoch there was also some evidence for an effect with digit strings. Nonetheless, as stated in the Results section, the effect was not significant ( $p = .16$ ). The apparent direction that can be appreciated in Figure 2 corresponds to a marginally significant interaction with laterality [ $F(2, 44) = 2.80, p = .07$ ]. Although the type of relationship effect was not significant in left hemisphere [ $F(1, 22) = 2.66, p = .12$ ] or right hemisphere sites [ $F < 1, p > .82$ ], it was marginally significant in the midline [ $F(1, 22) = 3.29, p = .08$ ]. However, considering that these differences do not unambiguously show an effect for digit strings, we will not elaborate on it in depth. Moreover, because no effect was found for digit strings in the N2 epoch,

we cannot safely conclude anything from the trend found in the N1 component.

3. We acknowledge that, contrary to what could be expected, the letter-specific N2 difference was slightly larger at the right than the left brain sites (although significant at all locations). Nonetheless, two main points should be mentioned in this regard. First, the interaction only approached significance ( $p = .07$ ). And second, and more importantly, ERPs have a rich temporal sensitivity, but a relatively poor spatial resolution, and we cannot safely conclude anything regarding the minimal spatial variation of the effect. We are currently working further in this direction, trying to track the specific activation patterns for each type of string and their corresponding neural signatures in a functional MRI study with a similar procedure and the same set of materials. We strongly believe that those results will shed light on the topographical distribution of the observed effects.

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