

**Differential sensitivity of letters, numbers and symbols to
character transpositions**

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Differential sensitivity of letters, numbers and symbols to character transpositions

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Abstract

The present 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 compared to 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, while 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 milliseconds, and that operates in addition to more general-purpose position coding mechanisms.

Differential sensitivity of letters, numbers and symbols to character transpositions

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. Since 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 since the answer could help us better understand the mechanisms underlying visual word recognition, as compared to recognition of visually presented numbers and symbols.

The mechanisms underlying letter processing have been investigated in depth in the psycholinguistic literature (see Carreiras & Grainger, 2004; Grainger, Rey, & Dufau, 2008). 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 Carreiras, Duñabeitia, & Molinaro, 2009; Duñabeitia & Carreiras, in press; 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 *hOrSe*; 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

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3 unaffected by replacing some letters by letter-like symbols or digits (e.g., taking *MAT3R14L5* or
4 *MATER!ALS* as *MATERIALS*; see Carreiras, Duñabeitia, & Perea, 2007; Perea, Duñabeitia, &
5 Carreiras, 2008a; Duñabeitia, Perea, & Carreiras, 2009a; Kinoshita & Lagoutaris, 2010; Molinaro,
6 Duñabeitia, Marín-Gutiérrez, & Carreiras, 2010), or by removing some of the letters (for an illusory-
7 letter phenomenon, see Davis & Bowers, 2006; Harris & Morris, 2001; Jordan, Thomas, & Scott-
8 Brown, 1999).

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16 Most relevant for the present study is the host of recent experiments demonstrating that small
17 changes in letter order only mildly disrupt fluent word recognition. Most of the evidence that has led
18 to this conclusion comes from studies testing how strings including transposed-letters (TL, hereafter)
19 are processed (see Perea, Duñabeitia, & Carreiras, 2008b; Grainger, 2008, for review). Preceding
20 research has consistently shown that nonsense letter strings created by transposing internal letters of a
21 real word (e.g., *CHOLocate* from *CHOCOLATE*) are more often perceived as a real word, as
22 compared to strings formed by letter replacements (e.g., *CHOTONATE*; see Perea & Carreiras, 2006;
23 Perea & Estévez, 2008; Perea & Fraga, 2006). Furthermore, TL masked primes facilitate the
24 recognition of the corresponding base word as compared to primes with replaced-letters (e.g.,
25 *chocolate-CHOCOLATE* vs. *chotonate-CHOCOLATE*; see Perea & Lupker, 2003, 2004; see also
26 Duñabeitia, Perea, & Carreiras, 2007; Grainger, Kiyonaga, & Holcomb, 2006; Kinoshita & Norris,
27 2009; Perea et al., 2008b; Schoonbaert & Grainger, 2004), at least when the TL primes are not real
28 words (see Duñabeitia, Perea, & Carreiras, 2009b). This evidence has led most authors to conclude
29 that any model of orthographic coding that relies on slot-coding schemes by which each letter is
30 assigned a single invariant position within the string (e.g., McClelland & Rumelhart, 1981) is
31 essentially wrong (see Davis & Bowers, 2006, for review), hence favoring other position coding
32 mechanisms that allow certain tolerance to location variation and account for letter migration errors
33 such as the TL effect (e.g., Davis, 2010; Gómez, Ratcliff, & Perea, 2008; Grainger et al., 2006;
34 Whitney, 2001).

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56 The present study aims at investigating the impact of character transpositions on processing
57 letter strings as compared to digit and symbol strings, in order to shed light on a) the specific
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3 adaptation of the human visual recognition system for letter processing, and b) the similarities and
4 differences in character position coding mechanisms for letters, symbols and digits. According to the
5 neural “recycling hypothesis”, the visual word recognition system is a convolution of perceptual
6 systems initially devoted to visual object recognition, which have been adapted for letter string
7 processing (see Dehaene, Cohen, Sigman, & Vinckier, 2005; Dehaene et al., 2010; McCandliss,
8 Cohen, & Dehaene, 2003). Thus, functional specialization for reading is said to arise from the
9 recycling of areas of the cortex which in principle evolved for other purposes, in line with the premise
10 that it is hardly plausible that relatively recent milestones in the human evolutionary process like
11 reading and writing have led to the creation of domain-specific neural networks (see Duñabeitia et al.,
12 2011). It is therefore possible that when recognizing printed words we apply a letter position coding
13 mechanism that is the default mechanism used by the visual system to code for combinations of any
14 kind of visual object.
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28 In line with this possibility, García-Orza, Perea and Muñoz (2010) have recently presented
29 evidence showing that significant TL priming effects can be found for different types of stimulus
30 strings. García-Orza et al. used the masked priming version of the same-different matching task,
31 which has been shown by Kinoshita and Norris (2009) to be sensitive to TL priming effects, but is not
32 influenced by lexical factors (see also Duñabeitia, Kinoshita, Carreiras, & Norris, 2011; Norris &
33 Kinoshita, 2008). In the masked priming version of the same-different matching task, a reference
34 stimulus is first presented for about 1000ms, immediately followed by a masked prime (for about
35 50ms), which is in turn replaced by the target. Participants have to decide whether the target is the
36 same as or different from the reference, and “*same*” responses typically benefit from the previous
37 presentation of a related masked prime (e.g., a TL prime). García-Orza et al. showed that TL masked
38 primes facilitated “*same*” responses to targets as compared to primes with character replacements, for
39 letter, digit and symbol strings. In more detail, the authors reported TL priming effects for
40 pronounceable and unpronounceable nonword strings (e.g., *JSTN-JTSN* vs. *JRLN-JTSN*), as well as
41 for digit strings (e.g., *5276-5726* vs. *5316-5726*), and symbol strings (e.g., *>+”&->”+&* vs. *>%?&-
42 >”+&*), whereas they failed to obtain significant TL priming effects for pseudoletter strings.
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3 The importance of these results for models of orthographic processing is patent, considering
4 that some of them make specific claims regarding the nature of the position coding processes and the
5 type of printed stimuli these processes may apply to (see García-Orza et al., 2010, for details). While
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8 some accounts of letter position coding are exclusively focused on letter processing and are silent
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10 with respect to general position coding mechanisms for various types of visual object (i.e., purely
11 orthographic models of position coding; e.g., Davis, 2010; Grainger & van Heuven, 2003; Grainger,
12 Granier et al., 2006; Whitney, 2001), other accounts do not a priori differentiate between letters and
13 other printed elements such as digits or symbols, since they explicitly assume that the mechanisms
14 underlying letter position coding are shared by general object position coding. The Overlap model
15 (Gómez et al. 2008) is a clear reflection of the latter view. According to this model, object position
16 coding follows an uncertainty principle in the form of a noisy or fuzzy slot-based position assignment.
17 Thus, a given object (e.g., a letter in a string) is assigned a given position but with a certain degree of
18 uncertainty, with locations closest to the actual object location having the highest probability levels
19 (i.e., the lowest uncertainty rates) and the furthest locations having the lowest probability levels (i.e.,
20 the highest uncertainty rates; see also Norris, Kinoshita, & Van Casteren, 2010, for a Bayesian model
21 using perceptual uncertainty).

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36 On the other hand, there are models that explicitly state that position coding is different in
37 essence for letters than for other types of visual objects. The open-bigram coding schemes proposed
38 by Grainger, Whitney, and colleagues (Grainger & van Heuven, 2003; Grainger et al., 2006; Whitney,
39 2001; see also Whitney & Berndt, 1999; Whitney & Cornelissen, 2008) are one example of this
40 approach. This point was most forcefully made in recent theoretical work arguing that it is likely that
41 more than one type of position coding mechanism is involved in visual word recognition (Grainger &
42 Dufau, 2011; Grainger & Holcomb, 2009; Grainger & Ziegler, 2011). The general idea is that during
43 the very first stages of reading acquisition, some type of default position coding scheme is likely
44 involved in establishing a routine for phonological recoding (i.e., mapping letters and letter clusters
45 onto sounds). However, via repeated exposure to printed words, a specialized system for orthographic
46 processing is set up, that, on the one hand, is geared to provide fast access to semantic information via
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3 a coarse-grained orthographic code, and on the other hand, is geared to improve the process of
4 phonological recoding via the use of a parallel, fine-grained orthographic code (Grainger & Ziegler,
5 2011). It should be noted that both the coarse-grained and fine-grained orthographic codes, described
6 in the work of Grainger and colleagues, involve word-centered, location-invariant coordinate systems,
7 such that letter position is coded with respect to where the letter is in the word and not where it is
8 relative to eye fixation. The complete model of orthographic processing involves a prior stage of
9 retinotopic mapping of visual features onto location-specific letter identities.
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18 In this dual-route approach to orthographic processing, the coarse-grained code computes
19 approximate letter order, and exploits the most informative contiguous and non-contiguous letter
20 combinations in order to constrain word identity. The fine-grained code computes more precise letter
21 position information in order to extract frequently co-occurring contiguous letter combinations (e.g.,
22 complex graphemes, affixes) and to provide an accurate translation of prelexical orthography onto
23 prelexical phonology. Most important, for the present purposes, is the idea that the coarse-grained
24 orthographic code will only be acquired for strings of elements that can form familiar wholes, as is the
25 case for strings of letters. This is clearly not the case for symbol strings, and is likely not to be the
26 case for digit strings given the rarity of familiar numbers such as well-known dates. Moreover, the
27 flexible nature of the coarse-grained orthographic code in this theory implies that it is the major
28 mechanism underlying letter transposition effects. However, transposition effects can also be
29 generated at two other processing stages in the overall framework proposed by Grainger and Ziegler
30 (2011): 1) during the mapping of visual features onto location-specific letter detectors, given a certain
31 amount of noise in this mapping process (i.e., the mechanism driving TL effects in the overlap
32 model); and 2) during fine-grained orthographic processing, assuming again a certain amount of noise
33 in this position-coding mechanism. However, these mechanisms were initially proposed as part of the
34 reading system, with no specific mention to other types of printed stimuli (i.e., symbols or digits).
35 Hence, it remains to be seen whether digit or symbol strings might also be processed by similar
36 mechanisms, or whether such mechanisms are specifically used to process letter strings. While
37 symbol strings might not be processed in the same manner, digit strings could be initially subjected to
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3 the same type of analysis as letter strings are, considering recent evidence showing that the processing
4 of digit strings highly resembles that of letter strings, while both differ from the processing of symbol
5 strings (e.g., Tydgat & Grainger, 2009). Finally, general-purpose object position coding mechanisms
6 might also be sensitive to the close spatial proximity of different objects that need to be processed
7 simultaneously, therefore generating transposition effects that are not specific to strings of letters or
8 digits.
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16 Given the above theoretical considerations, the present study provides a further test of effects
17 of letter transpositions on letters, digits, and symbols. We make three significant changes with respect
18 to the prior work of García-Orza et al. (2010). First, we use the classic same-different matching task
19 (Ratcliff, 1981) as opposed to the masked prime version of this task (Kinoshita & Norris, 2009), with
20 the aim to increase effect sizes and the possibility of observing differences between stimulus types.
21 Second, we use an arguably stronger within-participant manipulation of stimulus type, rather than the
22 between-participant manipulation used in the García-Orza et al. study, in order to increase the
23 opportunity of observing differences across stimulus types. Third, we combine behavioral measures of
24 TL effects with ERP recordings, thus providing the possibility of observing differences across
25 stimulus categories that might not be visible in the final button-press. Participants were presented with
26 pairs of 4-character strings made of digits, symbols or letters, and were simply asked to decide
27 whether the two strings were identical or different (the classic same-different matching task, also
28 known as the perceptual matching task; see Proctor, 1981; Ratcliff, 1981). The first and the second
29 members of the pair could be exact repetitions (i.e., *same* trials; e.g., *RFCV-RFCV*, *1754-1754*, $\&\$!=-$
30 $\&\$!=-$), or different strings created by transposing the two internal characters (i.e., *different*
31 *transposed-character* trials; e.g., *RFCV-RCFV*, *1754-1574*, $\&\$!=-\&!\$=$) or by replacing those two
32 characters (i.e., *different replaced-character* trials; e.g., *RFCV-RSTV*, *1754-1684*, $\&\$!=-\&\%€=$).
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34 While participants performed the perceptual matching task, their behavioral responses (reaction times
35 and error rates) as well as their electrophysiological activity (event-related brain potentials, ERPs)
36 were recorded. The ERP results will be critical for isolating distinct patterns of transposition effects
37 across the three types of stimuli at different points in time. This is crucial given that we expect
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3 different patterns to emerge depending on when letter-specific (and possibly mechanisms specific to
4 letters and digits) come into play. ERPs provide a unique opportunity to uncover early short-lived
5 differences across character types due to the fine-grained temporal resolution of this technique.
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7 Besides, differences in electrophysiological measures of brain activity during transposed and
8 replaced-character string processing will shed light on the time-course of the underlying processes.
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14 The key prediction for the present study is that, if visual word recognition involves a type of
15 letter position coding that is not used with other types of character strings, then we should see a
16 different pattern of TL effects for letter strings compared with both digit and symbol strings.
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18 Furthermore, given that letters and digits might share some position-sensitive processing that only
19 applies to stimuli that are typically processed as strings (i.e., words and numbers), then at some point
20 in processing we would expect to see a similar pattern of transposition effects for these two types of
21 character, in the absence of an effect for symbols. Finally, the emergence of transposition effects with
22 symbol stimuli will provide an indication of the relative time-course of letter/digit-specific coding
23 mechanisms and more general-purpose object position coding mechanisms.
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37 **Method**

38 Participants:

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40 24 undergraduate and graduate students (10 women) with a mean age of 22.78 (± 3.88) years from the
41 University of La Laguna initially took part in the experiment in exchange for course credit, even
42 though for technical problems only data from 23 participants (10 women) with a mean age of 22.95
43 (± 3.88) years were recorded. They were all native Spanish speakers, with no history of neurological
44 or psychiatric impairment, and with normal or corrected-to-normal vision. All participants were right-
45 handed, as assessed with an abridged Spanish version of the Edinburgh Handedness Inventory
46 (Oldfield, 1971). They all signed informed consent forms before the experiment and were
47 appropriately informed regarding the basic procedure of the experiment, according to the ethical
48 commitments established by the Ethics Committee that approved the experiment.
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Materials:

540 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, ?&€<-?&€<, 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, ?&€<-?&€<, 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, ?&€<-?&€<, 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 a total 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, symbols) presentation order was randomized across participants, and within each block item presentation order was randomly varied across participants.

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5 Procedure:
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7 Participants were individually tested in a well-lit soundproof Faraday room. The presentation of the
8 stimuli and recording of the responses was carried out using Presentation software. All stimuli were
9 presented on a high-resolution CRT monitor that was positioned at a distance of 70 cm. Participants
10 were informed that they were going to be presented with two strings of characters, one after the other,
11 exclusively composed of digits, symbols or letters. They were instructed to press as fast and
12 accurately as possible one out of two buttons on a gamepad when the two strings were identical and
13 the other when they were different. The buttons corresponding to the “*same*” and to the “*different*”
14 responses were counterbalanced across the participants. All stimuli were presented in white Courier
15 New font on a black background. Each character occupied a 4.5mm (width) x 6mm (height) rectangle
16 on the screen. Each trial started with the presentation of a fixation cross (“+”) in the center of the
17 screen for 500ms. Immediately after this, the reference stimulus was presented for 300ms, and was
18 horizontally centered and positioned 3mm above the exact center of the screen. Next, the target string
19 appeared for 300ms, and was horizontally centered and positioned 3mm below the center of the
20 screen. The manipulation of the location of references and targets on the vertical axis was carried out
21 in order to avoid physical overlap between the two strings. After the target disappeared, there was an
22 inter-trial interval that randomly varied between 900, 1000 and 1100ms. The trial concluded with the
23 presentation of an asterisk (“*”) for 500ms, in order to allow participants to blink (see Figure 1 for a
24 schematic representation of a trial). Participants were asked to respond as fast as possible once the
25 target had appeared on the screen, and response latencies were collected from target onset onwards,
26 until the next trial began. The experiment was divided in three separate blocks, one for each stimulus
27 category (digits, symbols and letters). We opted for the creation of different blocks in order to
28 maximize the chances of uncovering differences between character transpositions and replacements
29 within each type of stimulus category. In this respect, it should be mentioned that García-Orza et al.
30 (2010) also explored each type of string separately, although contrarily to the present study, they
31 tested different participants in each condition. Each participant received a total of 12 practice trials at
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3 the beginning of each block, formed of stimuli that were similar to those used in the experimental
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5 trials of the corresponding block.
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12 Behavioral analysis method:

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15 Statistical analyses were performed only on the “*different*” response trials, since there was no
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17 experimental manipulation on the “*same*” response trials. Incorrect responses and reaction times
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19 below or above 2.5 standard deviations from the mean were excluded from the latency analysis. Mean
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21 latencies for correct responses and error rates are presented in Table 1. ANOVAs over participants
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23 and items on the response latencies and on the error rates were conducted based on a 3 (Type of
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25 Character: digits, symbols, letters) x 2 (Type of Relationship: transposition, replacement) x 2 (List: 1,
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27 2). The factor List was included in the ANOVAs as a dummy variable to extract the variance of the
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29 error associated with the lists (Pollatsek & Well, 1995).
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35 EEG recordings and analysis method:

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38 Scalp voltages were collected from 58 Ag/AgCl electrodes which were mounted in an elastic cap
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40 (ElectroCap International, Eaton, USA, 10-10 system). The right mastoid was used as reference. Eye
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42 movements and blinks were monitored with four further electrodes providing bipolar recordings of
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44 the horizontal and vertical electro-oculogram (EOG). Inter-electrode impedances were kept below
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46 5K Ω . EEG was filtered with an analogue bandpass filter of 0.01-50Hz and a digital 25Hz low-pass
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48 filter was applied before analysis. The signals were sampled continuously throughout the experiment
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50 with a sampling rate of 250Hz, and digitally re-referenced to linked mastoids. Epochs of the EEG
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52 corresponding to 700ms after target string presentation in the “*different*” trials were averaged and
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54 analyzed. Baseline correction was performed using the average EEG activity in the 100ms preceding
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56 the onset of the target stimuli as a reference signal value. All those epochs free of ocular and muscular
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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. 9 representative electrodes were selected for the repeated-measures ANOVA analyses, creating the factors Electrode (3 levels: frontal, central, parietal) and Laterality (3 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 row of electrodes was formed by P5 (left), Pz (midline) and P6 (right). Together with these factors, Type of Character (3 levels: letters, symbols, digits) and Type of Relationship (2 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: 100-200ms post-target onset, 200-325ms post-target onset and 350-500ms post-target onset (see Figure 2).

Results

Behavioral measures:

The latency analyses revealed a significant main effect of Type of Character, [$F(2,42)=7.26, p<.01; F(2,176)=29.20, p<.001$] and a main effect of Type of Relationship, [$F(1,21)=31.16, p<.001; F(1,88)=147.64, p<.001$] with targets related to the references by means of transposition of their internal characters being responded to 45ms slower than targets related to the references by

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3 replacement of the same characters (i.e., a character transposition similarity effect). Importantly, the
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5 interaction between the two factors was also significant, reflecting the fact that the magnitude of the
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7 transposition cost varied as a function of stimulus type [$F(2,42)=8.85$, $p<.01$; $F(2,176)=11.16$,
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9 $p<.001$]. Subsequent pairwise comparisons showed that there were significant transposition costs
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11 (replacement minus transposition) for the three types of stimuli: digits (35ms) [$F(1,21)=13.95$,
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13 $p<.01$; $F(1,88)=58.91$, $p<.001$], symbols (27ms) [$F(1,21)=8.80$, $p<.01$; $F(1,88)=12.71$, $p<.01$], and
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15 letters (72ms) [$F(1,21)=35.95$, $p<.001$; $F(1,88)=91.33$, $p<.001$]. In order to further explore the
16
17 evident difference in the magnitude of the transposition cost effects obtained for the different types of
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19 strings, the net transposition costs were calculated (RTs in the replacement conditions minus RTs in
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21 the transposition conditions) and contrasted. Pairwise comparisons showed that the transposition cost
22
23 was larger (37ms larger) for letter strings than for digit strings [$F(1,21)=10.07$, $p<.01$;
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25 $F(1,88)=11.86$, $p<.01$], and also larger (45ms larger) for letter strings than symbol strings
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27 [$F(1,21)=11.35$, $p<.01$; $F(1,88)=17.35$, $p<.001$]. The 8ms difference between the transposition costs
28
29 associated with the digit and the symbol strings was not significant (both $ps>.17$).
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32 The error rate analyses showed a significant main effect of Type of Character [$F(2,42)=9.54$, $p<.001$;
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34 $F(2,176)=48.89$, $p<.001$]. There was also a main effect of Type of Relationship, with targets related
35
36 to the references by transposition being responded to less accurately (12.43% more errors) than
37
38 targets related by replacement (i.e., a character transposition similarity effect) [$F(1,21)=31.39$,
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40 $p<.001$; $F(1,88)=282.84$, $p<.001$]. As with the latency analysis, the interaction between the two
41
42 factors was significant, suggesting that the magnitude of the transposition cost differed across
43
44 stimulus types [$F(2,42)=7.30$, $p<.01$; $F(2,176)=13.62$, $p<.001$]. Pairwise comparisons showed that
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46 the transposition costs in the error rates were significant for the three types of strings: digit strings
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48 (7.72% more errors) [$F(1,21)=10.70$, $p<.01$; $F(1,88)=48.68$, $p<.001$], symbol strings (11.39% more
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50 errors) [$F(1,21)=23.01$, $p<.001$; $F(1,88)=56.68$, $p<.001$], and letter strings (18.16% more errors)
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52 [$F(1,21)=29.13$, $p<.001$; $F(1,88)=141.86$, $p<.001$]. Critically, the transposition cost was larger for
53
54 the letter strings as compared to both the digit strings (10.43% more errors) [$F(1,21)=20.94$, $p<.001$;
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56 $F(1,88)=27.22$, $p<.001$], and to the symbol strings (6.78% more errors) [$F(1,21)=4.84$, $p<.05$;
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3 F2(1,88)=8.97, $p < .01$]. The difference in the transposition cost between digit and symbol strings
4 (3.66% more errors for symbol string transposition cost) was only significant in the item analysis
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6 [F1(1,21)=1.64, $p > .20$; F2(1,88)=4.30, $p < .05$].
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10 - Insert Table 1 around here -
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13 Electrophysiological measures:
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16 - Insert Figure 2 around here -
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20 100-200ms post-target:
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24 The main effect of Type of Relationship was significant [F(1,22)=4.96, $p < .05$], reflecting the fact that
25 in this time-window, targets deviating from the references due to character replacements elicited
26 larger negativities than targets deviating from the references due to character transpositions. The Type
27 of Character effect was not significant [$p > .89$]. Interestingly, the interaction between these two factors
28 did approach significance [F(2,44)=2.97, $p = .06$]. As can be seen in Figure 2, there was a large
29 transposition effect for letters, no visible effect for symbols, and an intermediate effect for digits.
30
31 None of the interactions of these factors with the topographical factors Electrode and Laterality
32 reached significance [all $F_s < 1.5$ and $p_s > .18$]. Follow-up pairwise comparisons showed that the Type
33 of Relationship effect was significant for letter strings [F(1,22)=12.63, $p < .01$], negligible for symbol
34 strings [F < 1, $p > .94$], and not significant for digit strings [F(1,22)=2.07, $p = .16$].
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47 200-325ms post-target:
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51 The main effect of Type of Character was not significant [F < 1, $p > .63$]. The effect of Type of
52 Relationship was significant [F(1,22)=5.46, $p < .05$], reflecting the fact that targets containing
53 transposed-characters elicited more negative-going waveforms than targets containing replaced-
54 characters. Critically, the interaction between these two factors was significant [F(2,44)=4.73, $p < .05$].
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3 The three-way and four-way interactions between these factors and the topographical factors did not
4 reach significance [$F_s < 1$ and $p_s > .60$].
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8 Simple tests were then conducted in order to understand the origin of the interaction between Type of
9 Character and Type of Relationship. These analyses revealed that the effect of Type of Relationship
10 was neither significant for digit strings [$F < 1$, $p > .53$] nor symbols strings [$F < 1$, $p > .95$], but was
11 significant for letter strings [$F(1,22) = 11.87$, $p < .01$] (see Figure 2). Letter strings that differed from the
12 reference stimulus by letter replacements elicited more negative-going waveforms in this epoch than
13 strings that differed by letter transpositions (see Figure 2). The interaction between this Type of
14 Relationship effect for letter strings and the Laterality factor approached significance [$F(2,44) = 2.57$,
15 $p = .09$], reflecting the fact that the Type of Relationship effect was significant at all sites, but slightly
16 greater over right compared with left electrode columns [right: $F(1,22) = 16.01$, $p < .01$; midline:
17 $F(1,22) = 9.18$, $p < .01$; left: $F(1,22) = 8.37$, $p < .01$].
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31 350-500ms post-target:
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36 The main effect of Type of Relationship was significant [$F(1,22) = 7.00$, $p < .05$], showing that targets
37 that differed from the reference stimulus by replaced-characters elicited more positive-going
38 waveforms than targets that differed by transposed-characters. The Type of Character effect was not
39 significant [$F(2,44) = 2.43$, $p = .11$]. Importantly, the interaction between these two factors did not
40 approach significance [$F < 1$, $p > .85$], and there were no significant interactions with the topographical
41 factors except for an interaction between Type of Relationship and Electrode [$F(2,44) = 3.87$, $p = .05$].
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48 Follow-up simple tests showed that replaced-character targets elicited significantly more positive-
49 going waveforms than transposed-character targets at parietal and central sites, but not at frontal sites
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3 [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
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5 Figure 2).¹
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10 Discussion

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13 Are position coding mechanisms different for letters as compared to other sequences of
14 common visual characters such as digits or symbols? The results of the present study suggest that this
15 is indeed the case, and that changing the ordering of the letters within an unpronounceable string of
16 consonants leads to behavioral and electrophysiological effects that are different from the effects
17 observed for changes carried out within digit and symbol strings. At the behavioral level, we found
18 that when a reference string and the subsequent target string differed by means of internal character
19 transpositions, “*different*” responses in the same-different matching task were slowed as compared to
20 strings that differed by character replacements (i.e., a reaction time transposition cost). Importantly,
21 this transposition cost was reliably larger for manipulations involving letter transpositions as
22 compared to digit and symbol transpositions. In a similar vein, participants made more errors on
23 strings containing character transpositions than on strings containing character replacements (i.e., an
24 accuracy transposition cost). In line with the results observed in the reaction times, this transposition
25 cost in accuracy was greater for letter transpositions compared with both digit and symbol
26 transpositions. At the electrophysiological level, parallel effects to the behavioral ones were obtained
27 in a negative-going component between 200 and 325 ms, with letter strings including replacements
28 peaking more negatively than letter strings including transpositions. Importantly, this effect was
29 present only for letter strings, and no differences were found in this time-window for transpositions
30 versus replacements involving either digits or symbols. A similar sensitivity to character
31 transpositions was also seen in an earlier epoch, between 100 and 200 ms post-target onset, where
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56 ¹ We performed the same analysis on data that included trials on which an error was made (92.6% of the data after artifact
57 rejection). Results clearly replicated the pattern observed with the trimmed set of data that included exclusively the segments
58 associated with correct responses. Nonetheless, for sake of simplicity, we only report the analysis performed on the correct
59 segments.
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3 once again letter stimuli showed a robust effect and symbol stimuli no effect². Finally, all three types
4 of stimulus showed a transposition effect in a time-window between 350 and 500 ms, with more
5 negative-going waveforms in the transposed-character condition compared with the replaced character
6 condition.
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11 In the visual word processing literature the ubiquitous transposed-letter similarity effect (see
12 Perea, Duñabeitia, & Carreiras, 2009b, for review) has been typically taken as an index of the
13 relatively flexible manner by which readers process the order of the letters in a visually presented
14 string (e.g., Gómez et al., 2008). When presented with a nonword created by transposing two adjacent
15 or non-adjacent letters from a real word (e.g., *CHOLUOCATE*), the resulting nonword is often
16 incorrectly perceived and readers tend to lexicalize that string by reordering the letters to form a
17 known word (e.g., *CHOCOLATE*; see Perea & Carreiras, 2006; Perea & Estévez, 2008; Perea &
18 Fraga, 2006). This effect has been interpreted as a reflection of the tolerance of these mechanisms to
19 variations or deviations from the standard (e.g., Davis, 2010; Norris, et al., 2010; Whitney, 2001; see
20 Grainger, 2008, for review). However, recent research has questioned whether this apparent flexibility
21 in the coding of positional information is an exclusive property of the visual word recognition system
22 (e.g., Whitney, 2001), or instead, whether it is a characteristic that applies to the processing of other
23 non-alphabetic visual materials (e.g., Gómez et al., 2008). García-Orza et al. (2010) have recently
24 presented evidence from the masked priming version of the same-different judgment task, showing
25 that the character transposition effect can be effectively found for pronounceable and non-
26 pronounceable letter strings, as well as for digit and symbol strings. The authors concluded that their
27 results demonstrate that positional uncertainty is a general property of the human visual system that
28 plays a similar role in the recognition of any sequence of familiar objects. This was therefore taken as
29 evidence in support of models of orthographic coding that are not based on letter-specific processing
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54 ² It should be mentioned that in the N1 epoch there was also some evidence for an effect with digit strings. Nonetheless, as
55 stated in the Results section, the effect was not significant ($p=.16$). The apparent difference that can be appreciated in Figure 2
56 corresponds to a marginally significant interaction with Laterality [$F(2,44)=2.80, p=.07$]. While the Type of Relationship
57 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
58 significant in the midline [$F(1,22)=3.29, p=.08$]. However, considering that these differences do not unambiguously show an
59 effect for digit strings, we will not elaborate on it in depth. Moreover, since no effect was found for digit strings in the N2
60 epoch, we cannot safely conclude anything from the trend found in the N1 component.

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3 mechanisms, but rather appeal to general mechanisms that are involved in processing positional
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5 information about various types of visual object (Gómez et al., 2008).
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8 The present results are at odds with the results of García-Orza et al. (2010), insofar as the
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10 present data provide strong evidence in favor of letter-specific position encoding mechanisms. While
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12 an omnipresent character transposition cost was found for all character strings, this cost was
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14 significantly greater for letter strings than for symbol and digit strings as seen in the behavioral data
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16 (both in the error rates and in the reaction times), and more importantly, in the electrophysiological
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18 responses in the 200-325 ms time-window. We argue that the significantly greater transposition
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20 effects seen for letter strings compared with digit and symbol strings in the present study, and not seen
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22 in the García-Orza et al. study, is due to increased sensitivity obtained by using an explicit same-
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24 different matching task (rather than the masked-prime version used by García-Orza et al.) as well as
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26 the within-participants manipulation of stimulus type that was used in our study. Similar to what
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28 García-Orza et al. found at the behavioral level, we also found a transposition effect in ERP
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30 recordings that was the same for all character strings in the 350-500 ms time-windows. Most critical
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32 is the fact that transposition effects were seen exclusively for letter strings in an intermediate time-
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34 window (200-325 ms), and in the 100-200 ms time-window. Thus, the present results represent a step
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36 forward in our understanding of how positional information is encoded during the processing of
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38 strings of elements, and suggest that in this respect letter strings are processed differently from strings
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40 of other types of familiar characters such as digits and symbols.
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43 How can one interpret the greater transposed-character similarity effect observed for letters as
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45 compared to digits and symbols in reaction times and error rates? Put differently, why is positional
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47 uncertainty greater when processing letter strings than symbol or number strings? One straightforward
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49 explanation is that strings of letters trigger a qualitatively distinct type of processing compared with
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51 strings of other familiar elements such as digits and symbols. This hypothesis was explicitly
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53 developed in the recent theoretical work of Grainger and colleagues (Grainger & Dufau, 2011;
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55 Grainger & Ziegler, 2011), where a clear distinction was drawn between two very different types of
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57 word-centered letter position coding mechanism: one designed to map letters onto whole-word
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3 orthographic representations as efficiently as possible given constraints on letter visibility, and the
4 other designed to provide more precise positional information in order to accurately map letters onto
5 phonology. It is the first type of position coding mechanism that would be specific to strings of letters,
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7 whereas the second would correspond to a more general type of position coding mechanism
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9 applicable to various types of visual object. The first type of position coding mechanism requires less
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11 precision than the second and would therefore be the source of the increased effects of letter
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13 transpositions seen with letter strings compared with both digit and symbol strings.
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18 The ERP results of the present study are particularly informative with respect to this
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20 hypothesized distinction between different types of position coding mechanisms in the Grainger and
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22 Ziegler (2011) model. As pointed out in the Introduction, although there is clearly one type of
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24 position-coding that is specific to letter stimuli, it is also possible that letter and digit stimuli might
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26 share the other two position-coding mechanisms that are described in the overall framework. There
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28 was some evidence in favor of this possibility in the earliest (100-200 ms) time-window, where letter
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30 strings showed a robust transposition effect, symbol strings showed no effect, and there was some
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32 evidence for an effect with digit strings. Even if the evidence in favor of an effect for digit strings was
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34 not conclusive (i.e., marginal only in the midline), we would tentatively suggest that this pattern
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36 might correspond to positional errors arising during the parallel encoding of location-specific letter
37
38 and digit identities. Indeed, prior behavioral research has shown that the serial position curves for
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40 character-in-string identification are very similar for letters and digits, which both differ from the
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42 pattern seen with symbol stimuli (e.g., Tydgat & Grainger, 2009). The earliest difference in the
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44 negative-going component between 100 and 200 ms could be interpreted as a visual N1 component,
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46 which has been proven to be sensitive to basic perceptual discrimination processes between two
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48 consecutive stimuli.
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51 The N1 typically reflects discrimination processes within the focus of attention (e.g., Vogel &
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53 Luck, 2000). In line with this, the greater negativity associated with targets including character
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55 replacements could indicate that due to the perceptual difference between references and targets of
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57 this category (as compared to targets including character transpositions), the processing of this type of
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3 stimulus requires enhanced attentional demands (see Martínez et al., 2006, for a similar conclusion).
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5 Indeed, considering the tight relationship between attention and perception (e.g., Mangun & Hillyard,
6
7 1991), we believe that the N1 effect found in the present study reflects the greater attentional
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9 resources needed to process the visual information contained in replaced-character strings, which
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11 perceptually deviate from the reference more than transposed-character strings. Note that the N1
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13 transposition effect was significant for letters, marginally significant for digit strings at midline
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15 electrode sites, and not significant for symbol strings. We interpret this pattern as reflecting the
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17 perceptual processes associated with the initial parallel mapping of visual features onto location-
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19 specific letter identities (a process that might be shared with digit strings), proposed by Grainger and
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21 Ziegler (2011; see also Grainger & van Heuven, 2003).
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24 The timing of the early N1-like transposition effect coincides with another ERP effect, with a
25
26 different spatial distribution, that has been found in masked priming studies of letter and word
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28 processing. Petit, Midgley, Holcomb and Grainger (2006) identified a component that was sensitive to
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30 physical differences between primes and targets, which was referred to as the N/P150. The N/P150
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32 was significantly larger for dissimilar prime-target pairs than for similar pairs (see also Cornelissen et
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34 al., 2003, for MEG data). This N/P150 component has been repeatedly shown to reflect larger
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36 amplitudes for mismatching patterns than for matching stimuli (e.g., Carreiras, Duñabeitia, &
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38 Molinaro, 2009; Duñabeitia, Molinaro, & Carreiras, 2011; see Grainger & Holcomb, 2009b, for
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40 review). Not only exact repetitions elicit N/P150 effects, but also targets that are different from the
41
42 references but that are perceptually very similar to them (e.g., strings like ABCDEF and 4BCD3F),
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44 result in N/P150 differences as compared to more distinct stimuli (e.g., 7BCD9F; see Molinaro,
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46 Duñabeitia, & Carreiras, 2010). This suggests that the N/P150 component reflects an early perceptual
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48 process in which the mapping of visual features onto higher-level representations has been initiated.
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50 For strings consisting of letters, this would correspond to the initial phase of mapping visual features
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52 onto location-specific letter identities in parallel.
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55 The transposition effect seen exclusively for letters strings between 200 and 325 ms after
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57 target presentation would appear to be driven by changes in amplitude of the N2 ERP component. The
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3 N2 is typically elicited by a template that deviates from another that has been mentally stored
4 previously (see Potts & Tucker, 2001). According to preceding studies, greater standard-target
5 variations result in an increase of the N2 amplitudes. In the present case, the greater N2 elicited by
6 strings containing letter replacements can be understood as showing that these strings represent a
7 larger mismatch or deviation from the reference (the standard for comparison) than strings containing
8 letter transpositions. In other words, according to Hoffman (1990), the N2 reflects a deviation from a
9 prevailing stimulus, and according to the present results, we are safe to conclude that letter
10 transpositions were perceived to deviate less from the corresponding references, as compared with
11 symbol and digit transpositions, since no N2 transposition effect was found for the two latter types of
12 stimuli.
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24 N2 effects have been typically linked either to the inhibition of the prevalent response (see
25 Nieuwenhuis, Yeung, & Cohen, 2004), or to the detection of a response conflict (see Van Veen &
26 Carter, 2002) or conflicting action tendencies (Azizian, Freitas, Parvaz, & Squires, 2006). In light of
27 the present data, we suggest that the N2 transposition effect seen for letter strings is a consequence of
28 a reduced conflict in the transposition condition compared with the replacement condition.
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34 Importantly, when transpositions involved other types of characters (digits or symbols), there was no
35 N2 transposition effect, presumably because participants perceived the transposed-symbol and
36 transposed-digit strings as similar to the referents as the replaced-digit and replaced-symbol strings. In
37 this respect, it might be worth noting that when compared with the waveforms corresponding to the
38 “*same*” responses, all transposed-character and replaced-character targets showed a negative-going
39 deflection in this time-window (i.e., an N2 effect). However, in the case of letter strings, transposed-
40 letter targets elicited a brain electrophysiological response that was much closer to the brain activity
41 associated with the “*same*” trials than the electrophysiological response elicited by replaced-letter
42 targets, thus confirming that letter strings containing letter transpositions were processed as being
43 highly similar to the references and represented a smaller deviation from the prevailing referent
44 stimulus (see Figure 3). As argued above, this transposition effect seen uniquely with letter strings,
45 and not with digit or symbol strings, is thought to reflect a letter-specific coarse-grained coding
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3 scheme that would generate a greater perceived similarity between the transposed-letter strings and
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5 their references.
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8 *- Insert Figure 3 around here -*
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11 With regard to the general transposition effect found for letter, digit and symbol strings in the
12 350-500 ms time-window of the ERP recordings, it should be mentioned that at the temporal, spatial
13 and component-shape levels, this effect would appear to be on the P3 component (see Nieuwenhuis,
14 de Geus, & Aston-Jones, in press, for review). The P3 (more correctly defined as P3b in this type of
15 experiment) is a broadly distributed long-lasting positively peaking potential that starts after 300-400
16 ms post-stimulus (Patel & Azzam, 2005, for review). Indeed, the P3b typically has a parietal
17 maximum, coherent with the findings reported in the present study (see also Comerchero & Polich,
18 1999). This component is generally taken as an index of the match or mismatch of the given target
19 stimulus as compared to a consciously maintained working memory trace (Näätänen, 1990), which in
20 the present case would be linked to the reference stimulus. Therefore, one could interpret the P3
21 transposition effect found in the present study as reflecting the overall greater mismatch between
22 target and reference in the replaced character condition than in the transposed character condition.
23 Indeed, in experiments requiring reference-target comparisons, P3 amplitudes have been shown to be
24 sensitive to the similarity of the target with regard to the standard (the reference), in a way that the
25 amplitude of the P3 is inversely proportional to the similarity between the two items (see Comerchero
26 & Polich, 1999). Furthermore, according to Näätänen (1990), transposed-character strings would
27 constitute a match to the memory trace established by the referent, whereas replaced-character strings
28 would notably deviate from that trace, thus leading to the observed P3 effect. In other words, target
29 strings containing transposed characters are more similar to the references than target strings
30 containing character replacements, thus leading to decreased P3 amplitudes. It should be noted that
31 the N2/P3 complex is sometimes difficult to disentangle, since both components are sensitive to
32 variations between a memory residual (namely, the reference) and a mismatching template (the target;
33 see Luck & Hillyard, 1994). Nonetheless, while the present results confirm that replaced-character
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3 strings are perceived to be more different from the references than transposed-character strings, the
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5 N2 was sensitive to the type of character manipulated, whereas the P3 component was not.
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8 Altogether, the pattern observed in the present ERP experiment is straightforward. In a first
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10 epoch (100-200 ms), the visual system evaluates strings containing transposed-characters as being
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12 more perceptually similar to the references than strings containing replaced-characters. This early
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14 transposition effect was found to be greatest for letter strings, absent for symbol strings, and with
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16 some evidence that there might be an effect for digit strings. Then, in a subsequent time-window
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18 (200-325 ms), targets that are not identical to the references elicit a negative-going deflection, N2.
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20 Critically, in the case of letter strings, targets including letter transpositions elicit reduced negativities
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22 as compared to targets including letter replacements, showing that at this stage, the letter-in-string
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24 position processing subsystem fails at fully distinguishing between two letter strings that differ in the
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26 position of two of the letter identities that form them. Finally, in a later epoch (350-500 ms), a general
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28 transposed-character similarity effect emerged, showing a larger positive-going deflection for
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30 replaced-character strings than for transposed-character strings that was independent of the type of
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32 character under test.
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35 It should be noted that the reaction times for targets containing letter transpositions were on
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37 average much larger than the reaction times in all the other conditions, emphasizing the fact that
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39 participants needed more time to reject letter string pairs related by transposition as being the same.
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41 Coherently, the electrophysiological data showed that in the N2 component, strings containing
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43 transposed-letters, as compared to strings including letter replacements, generated responses that were
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45 less deviant from the “*same*” responses. Altogether, this pattern highlights the high degree of
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47 similarity between strings containing transpositions and their references, but emphasizes a reading-
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49 specific mechanism (or set of mechanisms) that acts during a very concrete time-window (between
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51 200 and 350 ms, approximately) that leads to transposed-letter strings being perceived as more similar
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53 to the references than replaced-letter strings.
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3 One obvious question that arises is whether or not the greater similarity between transposed-
4 letter strings and their references compared to the similarity of transposed-digit or transposed-symbol
5 strings to their references, corresponds to a quantitative or a qualitative processing difference. We
6 cannot unequivocally rule out either of these options, but specifically according to the present
7 electrophysiological findings, we believe that a qualitative conception is more suited to account for
8 the present pattern of results. While a general transposition cost was clearly evident in the behavioral
9 data (see also García-Orza et al., 2010) as well as in the last epoch of interest in the present ERP
10 analysis, our middle time-window showed a difference exclusively for letter strings, revealing a letter-
11 specific modulation of the N2 component. Although the difference shown in the reaction time and
12 accuracy data is based on magnitude differences (larger reaction times and higher error rates for
13 transposed-letter strings than for replaced-letter strings), and thus could be interpreted as a
14 quantitative difference, the electrophysiological pattern was clear-cut, showing that the N2 component
15 was only sensitive to transposition effects with letter strings, thus favoring an interpretation in terms
16 of qualitative differences in processing³.
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32 Further evidence in favor of reading-specific mechanisms for early orthographic processing
33 can be found in brain imaging studies. The last decade has witnessed an increasing number of studies
34 demonstrating functional specialization of specific brain areas (e.g., the so-called Visual Word Form
35 Area, VWFA) for letter string processing as compared to the processing of other visual materials
36 (e.g., Baker et al., 2007; Reinke, Fernandez, Schwindt, O'Craven, & Grady, 2008; Szwed et al., 2011;
37 see Cohen & Dehaene, 2004, for review). However, the existence of a preferential tuning of a given
38 brain area for alphabetic materials is not exempt from debate (e.g., James, James, Jobard, Wong, &
39 Gauthier, 2005; see also Moore & Price, 1999, and Price, Winterburn, Giraud, Moore, & Noppeney,
40 2003). A relative specialization of the human brain for reading might have resulted in a different
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51 ³ We acknowledge that contrary to what could be expected, the letter-specific N2 difference was slightly larger at right than
52 at left-brain sites (although significant at all locations). Nonetheless, two main points should be mentioned in this regard.
53 First, the interaction only approached significance ($p=.07$). And second, and more importantly, ERPs have a rich temporal
54 sensitivity, but a relatively poor spatial resolution, and we cannot safely conclude anything regarding the minimal spatial
55 variation of the effect. We are currently working further in this direction, trying to track the specific activation patterns for
56 each type of string and their corresponding neural signatures in a functional MRI study with a similar procedure and the
57 same set of materials. We strongly believe that those results will shed light on the topographical distribution of the observed
58 effects.
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3 degree of sensitivity to position migrations when these take place in letter strings as compared to
4 symbol or digit strings. We have suggested that a form of coarse-grained orthographic coding might
5 be basis of this difference. One specific implementation of coarse-grained coding of letters strings, is
6 the notion of open-bigram representations that code for the presence of ordered, but not necessarily
7 contiguous, pairs of letters (Grainger & Whitney, 2004; Grainger & van Heuven, 2003; Whitney,
8 2001). Then, a plausible assumption is that, as stated by Dehaene et al. (2005, p. 337), “bigram
9 neurons, however, can respond selectively, yet with some tolerance for location of the component
10 letters”. Certainly, these bigram neurons would not take part in the processing of other visually
11 presented materials (e.g., digits or symbols), since by definition bigrams exclusively refer to pairs of
12 letters.
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24 One could rightly question whether or not the present results really reflect a different
25 character position coding mechanism operating for letters, as compared to digit or symbol strings, or
26 whether these effects could be the consequence of other factors operating on top of a common
27 position coding mechanism. One such factor could be related to differential crowding effects for
28 letters, digits, and symbols (Grainger, Tydgate, & Isselé, 2010; Tydgate & Grainger, 2009). However,
29 there are two reasons to doubt that the different crowding effects that have been shown for letters and
30 symbols (Grainger et al., 2010) could be the basis of the pattern of transposition effects seen in the
31 present study. First, the reduced crowding for letters reported by Grainger et al. (2010) was taken as
32 evidence in favor of a smaller receptive field size of retinotopic letter detectors compared with other
33 types of visual object. Therefore, if the mechanisms driving crowding and transposition effects were
34 the same, one would have expected a smaller (not larger) transposition effect for letter than for digit
35 or symbol strings, since the reduced receptive field size for letters would imply a better positional
36 coding of these items. Second, the results reported by Tydgate and Grainger (2009) show equivalent
37 serial position function for letters and digits, which both differed from symbol stimuli. This therefore
38 suggests that crowding effects should be the same for letters and digits. Even though there was some
39 evidence for similar transposition effects for digits and letters in the N1 component, overall the
40 present data show a clearly different pattern of transposition effects for letter strings than for digit
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3 strings. Hence, we believe that we can safely conclude that the present results are not a reflection of
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5 differential crowding as a function of stimulus type. We may of course be overlooking other possible
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7 confounding factors, but we leave that possibility to be explored in future research.
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10 The present results do not parallel those reported by García-Orza et al. (2010), who failed to
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12 find any differences in the transposed-character similarity effect for digit, letter and symbol strings in
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14 a masked priming version of the same-different judgment task. However, several methodological
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16 constraints that prevent a straightforward comparison between the two studies should be taken into
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18 account. It should be considered that the same-different judgment task and the masked priming
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20 version of this task might tap into different processing stages, since the former is an explicit task
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22 where participants consciously respond to the similarity manipulation across target and reference
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24 stimuli which are clearly visible, while in the latter the target and reference stimuli are the same and
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26 the similarity manipulation is performed via an intervening subliminal prime stimulus (i.e.,
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28 transpositions are carried out on the masked primes; see Duñabeitia, Kinoshita, et al., 2011; Kinoshita
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30 & Norris, 2009; Norris & Kinoshita, 2008). In this regard, it should be noted that conscious and
31
32 unconscious processing have been shown to activate distinct neural networks, mainly due to top-down
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34 processing differences, and that consciously presented stimuli give rise to reverberation of neural
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36 activity, facilitating propagation and maintenance of information (see Dehaene, Changeux, Naccache,
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38 Sackur, & Sergent, 2006). Hence, one possible reason for the discrepancy between the García-Orza et
39
40 al. study and the present study might be the conscious vs. unconscious nature of the experimental
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42 manipulation, which clearly has an impact on the neural resources at play during same/different
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44 judgments (see also Kouider & Dehaene, 2007, for review). We believe that the mechanisms
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46 responsible for character position coding should not be radically different for implicit vs. explicit
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48 manipulations, or for conscious vs. unconscious stimulus presentation (for transposed-letter effects in
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50 explicit tasks involving conscious manipulations, see Rayner, White, Johnson, & Liversedge, 2006;
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52 White, Johnson, Liversedge, & Rayner, 2008; see also Duñabeitia et al., 2009a, for an experiment
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54 testing consciously presented variations of letter shapes on reading performance). However, the level
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56 at which the differences between transposed and replaced-character strings and their references are
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3 evaluated does clearly depend on the conscious nature of the judgment. Hence, we hypothesize that
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5 the reason for the discrepant results between García-Orza et al.'s study and the present one may rely
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7 on the sensitivity of the task, paradigm and technique at use. While the masked priming version of the
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9 same-different task is an ideal task for those studies aimed at exploring pre-lexical orthographic
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11 representations at an automatic level (e.g., Kinoshita & Norris, 2008), the original explicit and
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13 conscious same-different paradigm, together with ERP recordings, allows for the in-depth study of
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15 basic perceptual as well as pre-orthographic and memory-related cognitive processes, unraveling a
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17 complex pattern of deflections probably associated with different neural functional mechanisms.
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20 We would want to stress the usefulness of the perceptual matching task in combination with
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22 ERP recordings. The perceptual matching task (or same-different judgment task) had been extensively
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24 used in cognitive psychology (see Ratcliff 1981, 1985), but in the last decade has fallen into disuse.
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26 Here we have shown that this task is sensitive to small variations carried out on short strings, yielding
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28 strong behavioral effects both in the latency and accuracy data. Furthermore, when used together with
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30 electrophysiological recordings, this methodology has been shown to index basic differences between
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32 processing strategies, being linked to two well-known ERP components: N1, N2 and P3. Hence, we
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34 plead for the generalization of this specific combination of task and technique for future research
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36 aimed at exploring the coding of letter position and identity.
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For Review Only

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TABLES

Table 1: Mean reaction times (in ms) and percentages of errors (within parentheses) for the “different” trials obtained in the Experiment.

<i>Type of Character</i>	<i>Type of Relationship</i>		
	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%)

Note: Mean reaction times and percentages of errors for the “same” trials were 530 ms (3.72%), 545 ms (9.76%) and 556 ms (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.

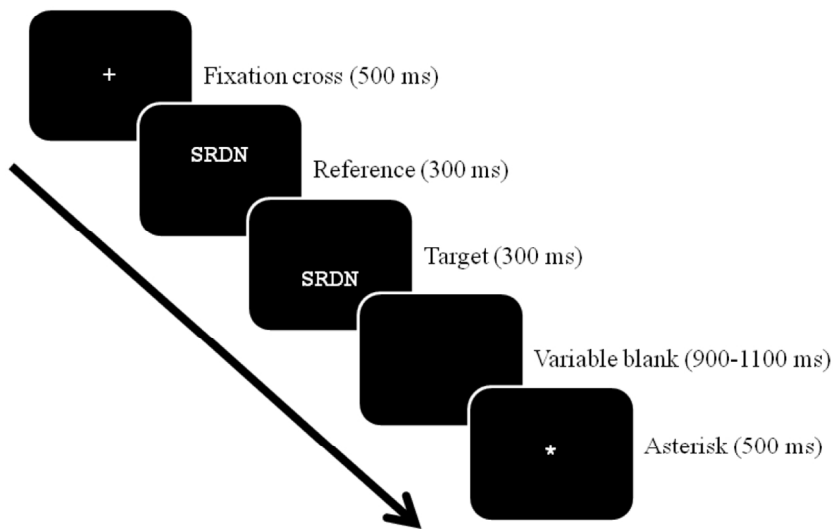
FIGURE CAPTIONS

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

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11 *Figure 2:* Grand average ERPs corresponding to the SYMBOL, DIGIT, and LETTER strings,
12 together with the averaged waveforms, in the midline electrodes (Fz, Cz, Pz) for the transposed-
13 character (solid green lines) and replaced-character conditions (dotted red lines). The lower panel
14 represents the N1, the N2 and the P3 components in their corresponding time-windows in
15 topographical maps (created by subtracting the observed voltage for replaced-character strings minus
16 transposed-character strings).
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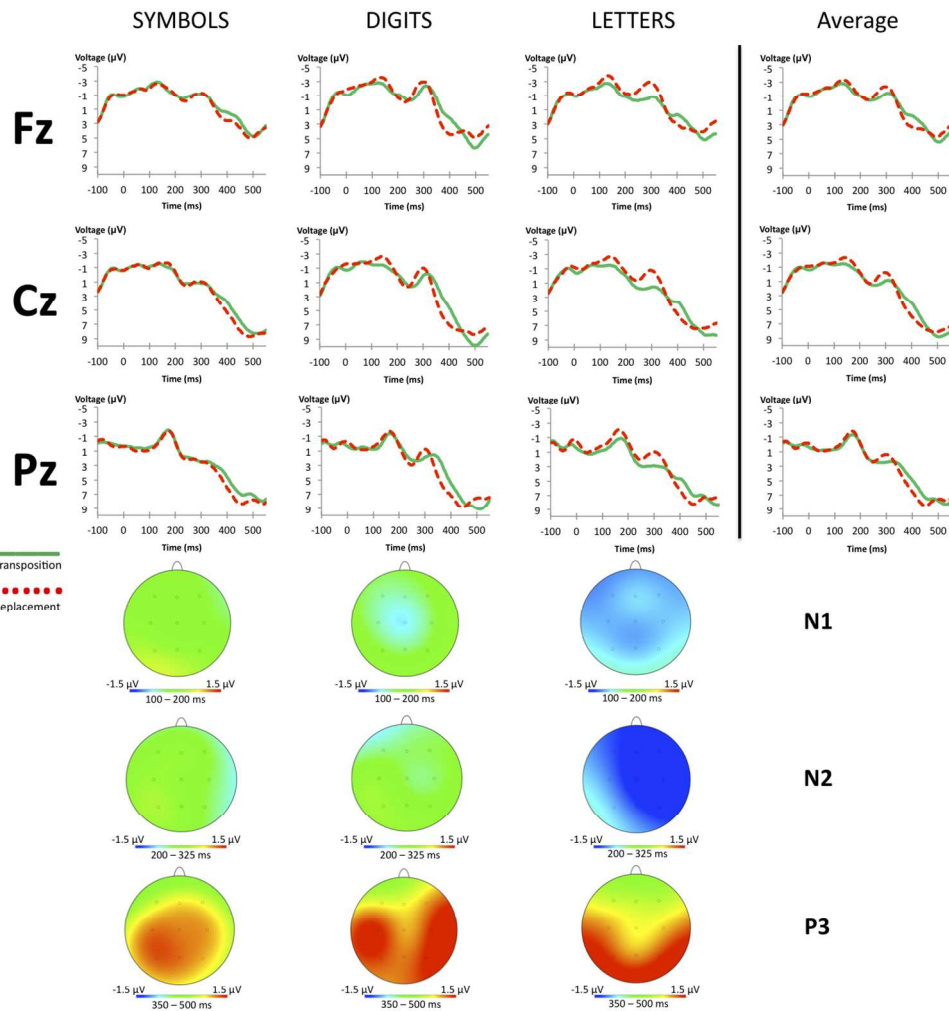
24 *Figure 3:* Blowups of the N2 component for SYMBOL, DIGIT and LETTER strings in the midline
25 electrodes (Fz, Cz, Pz) for the transposed-character (solid green lines), replaced-character (dotted red
26 lines), and “same” conditions (dotted blue lines).
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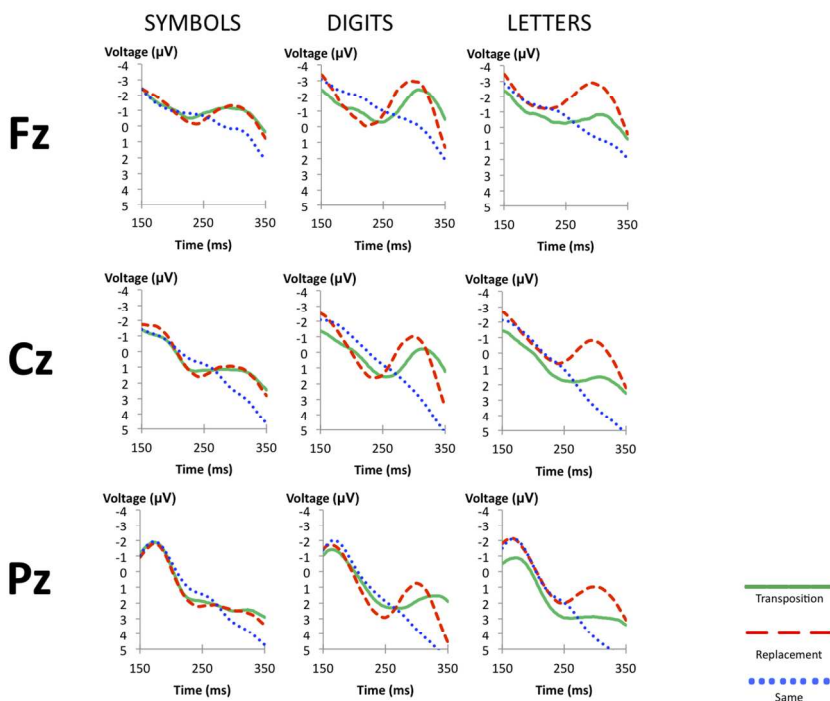


Schematic representation of an experimental trial.
254x190mm (150 x 150 DPI)

View Only



Grand average 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). The lower panel represents 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).
254x260mm (150 x 150 DPI)



Blowups 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).
254x190mm (150 x 150 DPI)

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