



Electrophysiological signatures of masked transposition priming in a same-different task: Evidence with strings of letters vs. pseudoletters

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ABSTRACT

Research on masked transposed-letter priming (i.e., judge-JUDGE triggers a faster response than jupte-JUDGE) has become a key phenomenon to reveal how the brain encodes letter position. Recent behavioural evidence suggests that the mechanism responsible for position coding in a masked priming procedure works with familiar “object” identities (e.g., letters, digits, symbols) but not with unfamiliar object identities (e.g., pseudoletters). Here we used event-related potentials (ERPs) to explore the time course of masked transposition priming of letters vs. pseudoletters in a cue-target same-different matching task. Target stimuli were preceded by a masked prime that could be: (i) identical to the target; (ii) identical to the target except for the transposition of two internal letters/pseudoletters; or (iii) identical to the target except for the substitution of two internal letters/pseudoletters. Only cue-target ‘same’ trials were analyzed. The priming manipulation affected the “same” trials of the letter strings between 250 ms and 450 ms: identity and transposition conditions produced less negative amplitudes than the substitution condition. Because of the onset latency of this priming effect, we suggest that masked primes affected mainly the cognitive processes related to the categorization of the trials (match versus mismatch), rather than to the initial stages of orthographic processing.

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1. Introduction

In the past years, a research question that has received considerable attention in the field of visual-word recognition is how the brain encodes letter position within a word. A robust finding, which has been obtained across languages and tasks, is that transposed-letter pairs such as judge and judge are highly confusable (for review, see [8,23]). Unsurprisingly, cognitive modellers in the past years have incorporated flexible input coding schemes that can accommodate transposition effects (spatial coding model [4], SERIOL model [28], open-bigram model [12], overlap model [11], LCD model [5], noisy Bayesian Reader model [18]). A relevant issue for these models is whether or not transposition effects are specific to letter (or alphanumeric) processing.

In a series of behavioural experiments, García-Orza et al. [10] examined whether masked transposition priming is specific to letter processing. They employed a masked priming same-different matching task in which participants were required to press a

button if cue and target were the same and to press another button if cue and target were different (see [15,16] for reviews of this task). A briefly presented transposed-letter masked prime was presented immediately before the target stimulus. García-Orza et al. ([10] Experiments 1–4) found a masked transposition priming effect for “same” trials with familiar alphanumeric stimuli: pronounceable pseudowords, non-pronounceable nonwords (i.e., strings of consonants), digit strings, and symbol strings. To assess if masked transposition priming occurs with non-familiar alphanumeric-like objects, García-Orza et al. [10] conducted a fifth experiment with strings of pseudoletters (e.g., the conditions $\text{Qc}^{\text{r}}\text{r}^{\text{c}}\text{c}^{\text{q}} = \text{Qc}^{\text{r}}\text{r}^{\text{c}}\text{c}^{\text{q}}$ versus $\text{Qc}^{\text{r}}\text{r}^{\text{c}}\text{c}^{\text{q}} = \text{Qc}^{\text{r}}\text{r}^{\text{c}}\text{c}^{\text{q}}$). They found no masked transposition priming effect with this type of strings (see also [19], for a similar behavioural finding with strings of Arabic letters for readers with no knowledge of Arabic language). García-Orza et al. [p. 1614] concluded that “the fast-acting mechanism responsible for object position coding works with familiar object identities but not with unfamiliar object identities”. A potential problem in the interpretation proposed by García-Orza et al. [10] is that behavioural effects in the masked priming same-different task might not necessarily reflect the initial processing of transposition primes but rather a later matching process (i.e., the cue-target comparison), as assumed in the Bayesian Reader model [17]. Note that in the masked priming account of the same-different

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task, “evidence from both the prime and the target continuously update the probability of the hypotheses required to perform the task” [p. 4].

In a recent study, Duñabeitia and colleagues [6] re-examined the results of García-Orza et al. [10] using the event related potentials (ERPs) technique with a same-different task. Unlike García-Orza and collaborators [10], they did not use primes, and focused on “different” trials. They presented strings of consonants, symbols and numbers in two conditions: character transposition and character substitution. ERP waves showed two main differences: between 100 ms and 325 ms after target presentation, mean amplitudes to the substitution condition were more negative than those of the transposition condition but only for the letter strings, whereas at the 350–500 ms time window, the substitution condition was more positive than the transposition condition, but in this case the effect was similar for the three types of stimuli. Duñabeitia et al. [6] concluded that the early ERP effects supported a letter-specific encoding mechanism. However, there are several important differences between the García-Orza et al. [10] and the Duñabeitia et al. [6] studies that make a direct comparison difficult. Bear in mind that García-Orza et al. [10] employed the masked priming technique to prevent the presence of strategic and attentional effects that may modulate ERP responses even at early latencies with unmasked, visible stimuli.

Here we employed the same design as in the experiments of García-Orza et al. [10] and collected electrophysiological measures for strings of letters vs. pseudoletters. We examined whether the transposition priming effect with the same-different task for letter strings takes place at the time of the initial orthographic codification, as suggested by García-Orza et al. [10], and therefore modulates early ERP components, or on the contrary, whether transposition primes influence task-related processes, thus affecting ERPs at later latencies. In addition, we examined whether the ERP waves reveal a transposition effect for strings of pseudoletters—assuming that ERP waves may be more sensitive to small effects than response times (e.g., [2]). As in the García-Orza et al. study [10], we employed three priming conditions (identity, transposition, substitution), and different experimental blocks were employed for strings of letters and pseudoletters. It is important to note here that transposition effects with the masked priming same-different task are similar in magnitude for consonant strings, pseudowords, and words [10,11]. Thus, the evidence obtained with consonant strings is relevant for word encoding models.

2. Method

2.1. Participants

Twenty-four students from the University of La Laguna (mean age = 26.9 years; SD = 3.6; 14 women) took part in the experiment. Data from one participant was excluded from the ERP analyses because of excessive EEG artefacts. All participants were native

Spanish speakers, had normal or corrected-to-normal eyesight, no neurological history and were right-handed.

Stimuli. Two sets of stimuli were used in the experiment as targets: 300 strings of four uppercase letters in Courier New font and 300 strings of four pseudoletters. We employed 16 of the 21 consonants from the Roman alphabet. The pseudoletters were the same as those used by García-Orza et al. [10,14] and were created by rearranging individual features of each letter in the Roman script (Courier New) to form a pseudoletter counterpart (e.g., each pseudoletter was created from one letter). Letters and pseudoletters were presented in two separate blocks. Each letter or pseudoletter target string was preceded by a prime that determined three experimental conditions: (i) identity condition (100 trials): prime and target were the same; (ii) transposition of two inner letters/pseudoletters (100 trials); and (iii) substitution condition (100 trials): prime and target were the same except for the substitution of two internal letters/pseudoletters. On half of the trials the cue and the target were the same, while on the other half they were different. For the ‘different’ trials, we manipulated the cue–prime relationship rather than the prime–target relationship (see [16,20,22]). If we manipulated the prime–target relationship in ‘different’ trials, the cue would always be different from the prime. Under these conditions, participants might use the relation between cue and prime to prepare a ‘same’ response. This predictive strategy cannot be used in the present design (see [16,22]). Fig. 1 shows examples of the letters and pseudoletters in all the experimental conditions. For each block, three lists of stimuli were constructed in a Latin square form to counterbalance the prime–target pairs, so that each target was presented only once to each participant—and three times across participants (one in each condition).

Procedure. The presentation of the stimuli and the recording of the responses were carried out using Presentation software. All stimuli were presented on a high-resolution CRT monitor that was positioned at eye level 80 cm in front of the participant. The sequence of events in each trial is described as follows (see Fig. 1). Firstly, a fixation point appeared in the centre of the screen and remained for 1000 ms. After this, the cue was presented for 1000 ms and a blank screen for 200 ms. Then, a mask (e.g.####) was presented for 500 ms, followed by the prime for 50 ms, which was immediately followed by the presentation of the target. The target stimulus remained on the screen until the participant’s response or until 1500 ms had elapsed. Each experimental block started with a short practice session. Participants were asked to decide if cue and target were the same stimulus or not by pressing the “Yes” or “No” buttons with their left/right (or right/left for the other half of participants) index fingers. They were instructed to make this decision as quickly and accurately as possible. They were not informed of the presence of prime stimuli. To minimize physical overlap between primes and targets, different font sizes were used for these strings: 24 and 34-pt, respectively (see [10]). All letters were presented in uppercase Courier New (i.e., a non-proportional

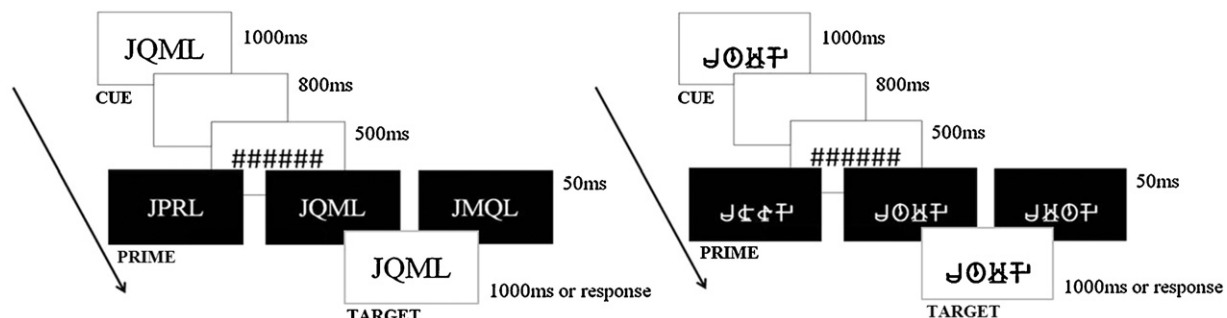


Fig. 1. Stimulus presentation procedure and experimental conditions.

font: all letters occupy the same amount of space) and the pseudoletters were presented in a pseudoletter font based on Courier New. The experiment lasted approximately 105 min, including a 10-min break between the two experimental blocks. Half of the participants received the letter block first followed by the pseudoletter block and the other half received the reverse block order. Participants were asked to avoid eye movements and blinks during the interval when the fixation asterisk was not present.

EEG Recording and ERP Analyses. The electroencephalogram (EEG) was recorded with 27 Ag/AgCl electrodes embedded in an elastic cap (Easycap, <http://www.easycap.de>) referenced to the left mastoid. Two pairs of electrodes above and below the left eye and on the outer canthi of each eye registered vertical and horizontal eye movements (EOG). The signal was amplified (BrainAmp amplifiers) and digitized at a sampling rate of 250 Hz, with a 0.01–100 Hz band pass filter. Impedance values were kept equal to or less than 5 k Ω at all electrode sites except for the four eye channels, which were kept below 10 k Ω . EEG was stored and ERPs were later analyzed using Brain-Vision Analyzer 2.0 software (<http://www.brainproducts.com>). The data were offline re-referenced to the average of the left and right mastoids, and passed through low cut-off (0.1 Hz, slope: 24 dB/oct) and high cut-off (30 Hz, slope: 24 dB/oct) filters. Artefacts were removed semi-automatically, with rejection values adjusted for each participant. This resulted in the exclusion of approximately 13% of the trials, which were evenly distributed across experimental conditions (minimum number of trials/condition=41). The data were segmented relative to reference marker positions, 100 ms before and 500 ms after onset of the targets. Baseline correction was performed using the average EEG activity in the 100 ms preceding target onset.

For statistical analyses, nine regions of interest (ROIs) were calculated from the average of three recording sites: left-anterior (F7, F3, FC5), medial-anterior (FP1, FP2, Fz), right-anterior (F4, F8, FC6), left-central (T7, C3, CP5), medial-central (FC1, FC2, Cz), right-central (T8, C4, CP6), left-posterior (P7, P3, O1), medial-posterior (CP1, CP2, Pz) and right-posterior (P8, P4, O2). Based on visual inspection of main differences in the grand averages, mean amplitudes were obtained for each condition, participant and ROI from 250 to 450 ms time window relative to the onset of the target stimuli. An additional 100–200 ms time window was also analysed to test potential earlier differences. Amplitude values of the lateral hemisphere regions were subjected ANOVAs for repeated measures with the factor PRIMING (transposition, substitution, identity) and two topographic factors: ANTERIORITY (anterior, central, posterior) and HEMISPHERE (left, right). Additionally, medial regions were entered to a separate ANOVA including the factors PRIMING (transposition, substitution, identity) and ANTERIORITY (medial-anterior, medial-central, medial-posterior). When the sphericity assumption was violated, we report the Greenhouse–Geisser epsilon values to correct for the degrees of freedom.

3. Results

3.1. ERP data

Visual inspection of the ERPs revealed that the waves to pseudoletter and letter strings (collapsed across the priming conditions) started to differ around 100 ms after target onset presentation at most recording sites. ERP waves were more positive for letters than for pseudoletters at frontal electrodes and more negative at occipital sites (see Fig. 2). Moreover, at occipital sites, the N1

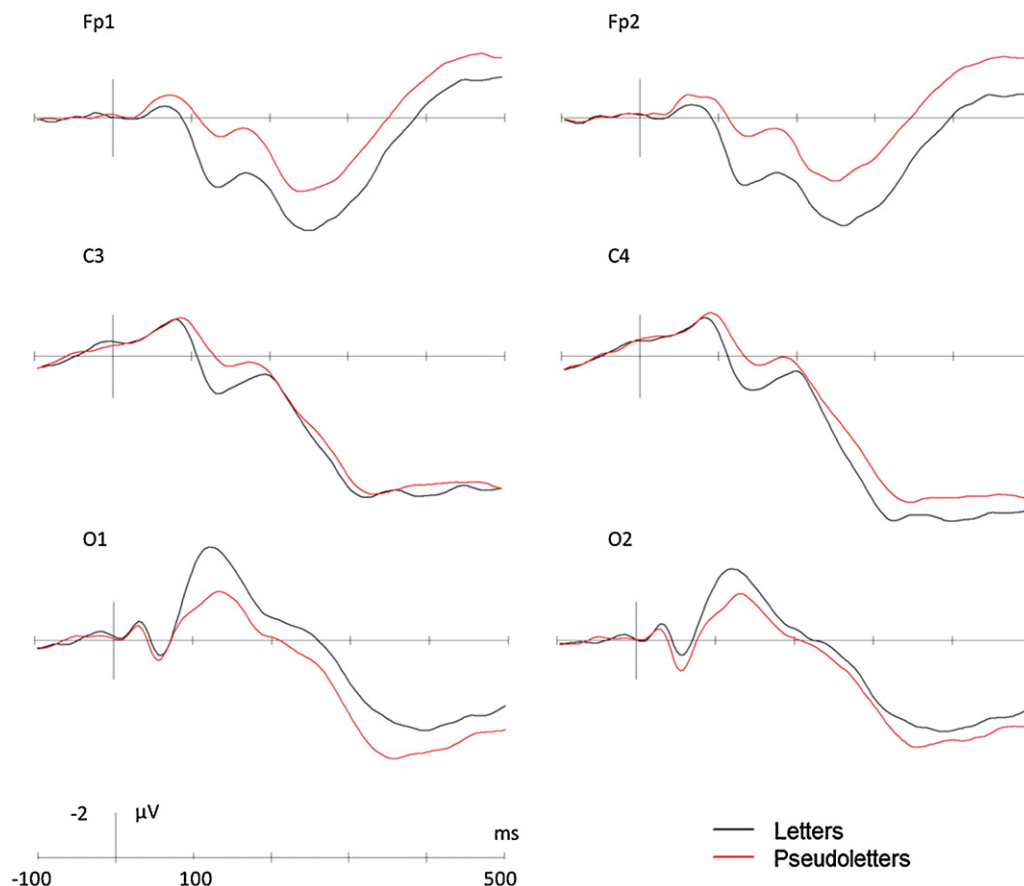


Fig. 2. ERPs to letters and pseudoletters strings at prefrontal, central and occipital electrodes.

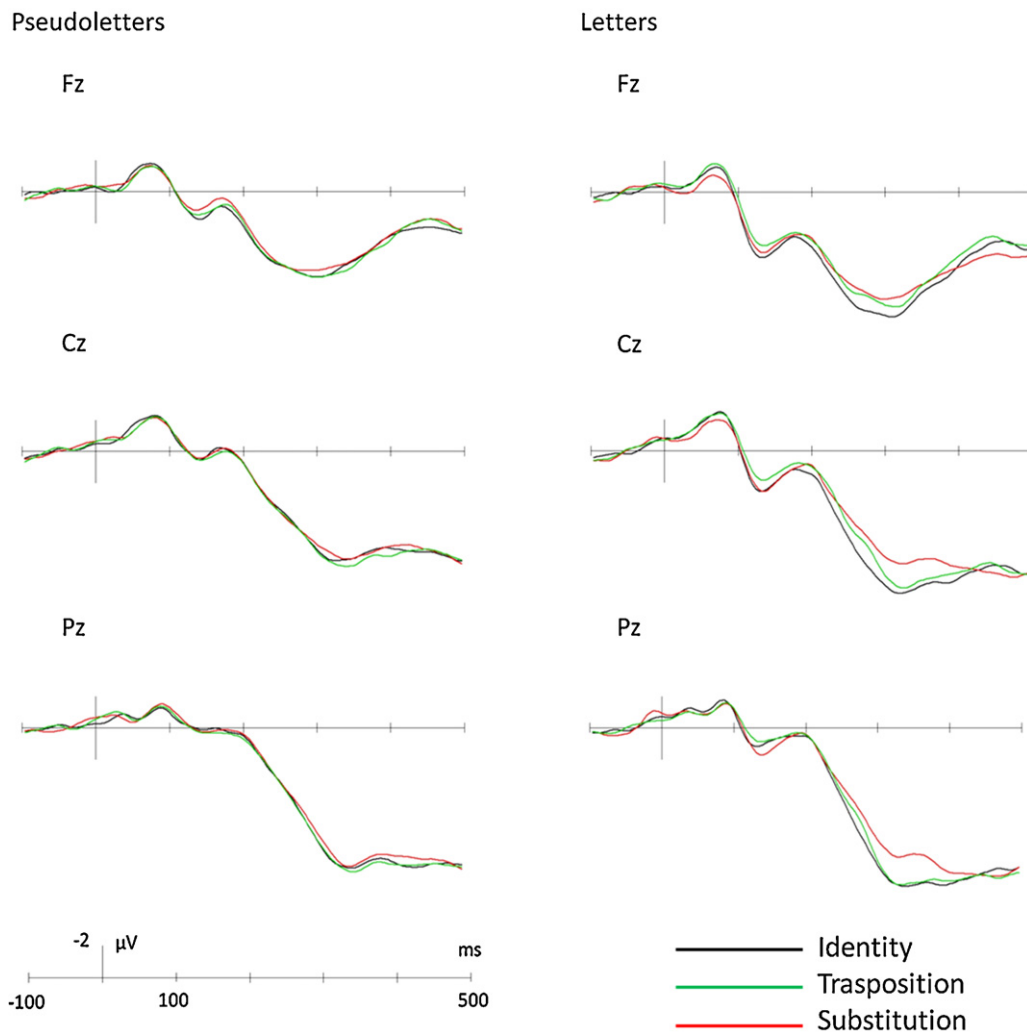


Fig. 3. ERPs to pseudoletter strings (left) and letter strings (right) for each priming condition at the three midline electrodes.

component to letter strings showed the classic leftward asymmetry attributed to orthographic processing [25], this asymmetry was not visible for pseudoletter strings. Given that the two different types of strings (letters, pseudoletters) were presented in separate experimental blocks and showed quite different ERP responses, we analyzed them separately. Fig. 3 represents separate grand averages for letter (right) and pseudoletter (left) strings, showing each priming condition at the midline electrode sites. ERP waves associated to pseudoletter strings did not show any effect of the priming manipulation in any of the two analyzed time windows (100–200 and 250–450 ms). Neither the omnibus ANOVA (PRIMING \times ANTERIORITY \times HEMISPHERE) on the lateral hemisphere ROIs, nor the ANOVA (PRIMING \times ANTERIORITY) on the midline ROIs revealed any significant effects (all $F_s < 1$).

ERP waves associated to letter strings (Fig. 3; right) showed a priming effect between 250 and 450 ms. In particular, the substitution condition produced more positive amplitudes than the identity and transposition conditions. This effect reached its maximum at parietal electrode sites, with no specific lateralization. The ANOVA on the mean amplitudes between 250 and 450 ms after target onset (PRIMING \times ANTERIORITY \times HEMISPHERE) revealed a main effect of PRIMING ($F_{2,44} = 4.6$, $P < .05$; $MSE = 3.7$) and an interaction between PRIMING and ANTERIORITY ($F_{4,88} = 4.1$; $P < .05$; $MSE = .9$). Pair-wise comparisons on this interaction revealed that there was a significant transposition-letter effect (i.e., a difference between the substitution and transposition conditions) only at the

left and right posterior ROIs. For this group of electrodes, only substitution primes had a different activation compared to the activity on transposition and identity primes (all $P_s < .05$). The ANOVA on the midline ROIs (PRIMING \times ANTERIORITY) showed an interaction of PRIMING with ANTERIORITY ($F_{4,88} = 5.5$; $P < .05$; $MSE = 1.4$). Pair-wise comparisons for the interaction showed a transposition priming effect only at the medial-posterior ROI: substitution primes produced different activity compared to transposition and identity primes (all $P_s < .05$).

3.2. Behavioural data

We conducted parallel analyses to those performed on the electrophysiological measures. Incorrect responses (3% of trials) and response times less than 250 or greater than 1250 ms (1% of trials) were excluded from the latency analysis. ANOVAs were conducted on the RTs and error rates, with PRIMING (identity, transposition, substitution) as factor. As usual with the same-different technique, we only examined “same” trials (see [16]). The mean latencies for correct responses in “same” trials (in ms) and error rates (in parenthesis) were as follow: Identity-letter condition: 594(2.4), Transposition-letter condition: 603(2.7), Substitution-letter condition: 633(3.8), Identity-pseudoletter condition: 657(2.4), Transposition-pseudoletter condition: 689(9.2), and Substitution-letter condition: 695(8.1).

Pseudoletter strings: The ANOVA on the RTs showed a significant effect of PRIMING ($F_{2,46} = 4.4, P < .05, MSE = 534.3$). Pair-wise comparisons revealed that targets preceded by an identity prime was responded to faster than targets preceded by a substitution prime ($P < .05$), while the other comparisons did not approach significance. The ANOVA on the error data revealed a significant effect of PRIMING ($F_{2,46} = 4.8, P < .05, MSE = 4$): the identity condition produced less errors than the substitution condition ($P < .05$). Letter strings. The ANOVA on the latency data revealed a main effect of PRIMING ($F_{2,46} = 21.1, P < .05, MSE = 458.8$): RTs to target stimuli were faster preceded by a transposition/identity prime (602 and 594 ms) than when they were preceded by a substitution prime (633 ms) (both P s $< .05$). The ANOVA on the error data showed a main effect of PRIMING ($F_{2,46} = 4.8, P < .05, MSE = 2.4$). Pair-wise comparisons revealed that participants made more errors in the substitution condition than in the identity/transposition conditions (both P s $< .05$).

In sum, the behavioural data successfully replicated the García-Orza et al. [10] study (i.e., a transposition priming effect for letter strings but not for pseudoletter strings). The critical transposition priming (i.e., the difference between the substitution and transposition conditions) only occurred with the letter stimuli in both RT data and ERP waves. The RTs from pseudoletter stimuli showed significant differences between the identity and substitution conditions—unlike the ERP data.

4. Discussion

In the present experiment we collected electrophysiological measures, in addition to the participants' behavioural responses, to determine the time-course of the observed priming effects with masked priming same-different task. Specifically, the study was aimed at comparing the masked transposition priming effects for strings of letters vs. pseudoletters. The behavioural data revealed a masked transposition effect for letter strings, but not for pseudoletter strings, thus replicating the study of García-Orza et al. [10].

The priming manipulation affected the ERP waves only for letter strings: between 250 and 450 ms after target presentation, the substitution condition produced more negative amplitudes than the identity and the transposition condition. The transposition effects reported by Duñabeitia et al. [6] between 200 and 325 ms were interpreted as a modulation of the N2 component. The N2 amplitude has been related to novelty or perceptual mismatch [7] and it is larger when a perceived stimulus deviates from another previously stored in memory [27]. It is important to note however that the mismatching N2 usually shows a frontal-central distribution, in contrast to the central-posterior distribution of our priming effect. Alternatively, our results can be interpreted as a modulation of the P3b, a component with positive polarity and centro-parietal distribution that has been taken as an index of task-related decision-making processes. Previous studies using the same-different task with single letters have reported a reduction of the P3 amplitude for matching compared to mismatching trials [21,26]. Generally speaking, more difficult discriminations and larger memory loads tend to produce smaller P3 amplitudes [13,24]. In our task, memory traces from cues could be reactivated by adequate primes (identity and transposition conditions), thus reducing the memory load and/or facilitating the target categorization. In any case, and independently of the precise component associated to our priming effect and its specific cognitive nature, the latency of the effect strongly suggests that it is reflecting task-related operations. There were no signs of a transposition masked priming effect for pseudoletter strings in the ERP waves, and the

RTs from pseudoletter stimuli showed only significant differences between the identity and substitution conditions. While the P3 component could index response selection, response times could rely more on execution processes, therefore these two measures can be decoupled, especially under speed instructions [3]. Taken together, the present data suggest that when there is lack of abstract representations in the processing of unfamiliar stimuli (i.e., pseudoletters), evidence coming from small variations in the identity (substitution primes) or position (transposition primes) of briefly presented primes could not be used in the matching process. This reinforces the view that abstract representations, or at least, perceptually simple, familiar representations are necessary for masked transposition priming to occur in the same-different task (see [9,10,17]). One straightforward prediction in this respect is that if participants are (repeatedly) trained with a set of pseudoletters, then the pattern of data for this set of stimuli would be similar to that with strings of letters (see [19] for behavioural evidence with learners of the Arabic alphabet).

As indicated in the Introduction, one of the goals of the present experiment was to determine whether masked priming effects with the same-different task occur at the very early stages of orthographic processing or whether they takes place when the cue-target comparison is made in order to solve the task. García-Orza et al. [10] suggested that transposition priming could emerge from a very fast mechanism of position coding during orthographic processing. In the Duñabeitia et al. study [6] with an unprimed same-different task, differences between transposition and substitution were found with letter strings as early as 100 ms after stimuli presentation and were linked to early orthographic processing, which usually take place in the first 200 ms after stimulus presentation [1]. However, in the present study, masked primes modulated ERPs after the first 250 ms, and therefore this effect cannot be taken as evidence of a modulation of the early orthographic processing, but rather that masked primes affect mainly the processes associated with the solving of the task (as predicted by the Bayesian Reader model [17]). One possible explanation for this apparent divergence is that the explicit manipulation used in Duñabeitia et al. [6] could be the result of a top-down modulation of early processes, whereas the masked prime manipulation of our study prevented such attentional effects from occurring. Further research is necessary to explore these apparent divergences.

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