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BRIEF REPORT

Does letter rotation slow down orthographic processing in word recognition?

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Abstract
Leading neural models of visual word recognition assume that letter rotation slows down the conversion of the visual input to a stable orthographic representation (e.g., local detectors combination model; Dehaene, Cohen, Sigman, & Vinckier, 2005, *Trends in Cognitive Sciences, 9*, 335–341). If this premise is true, briefly presented rotated primes should be less effective at activating word representations than those primes with upright letters. To test this question, we conducted a masked priming lexical decision experiment with vertically presented words either rotated 90° or in marquee format (i.e., vertically but with upright letters). We examined the impact of the format on both letter identity (masked identity priming: identity vs. unrelated) and letter position (masked transposed-letter priming: transposed-letter prime vs. replacement-letter prime). Results revealed sizeable masked identity and transposed-letter priming effects that were similar in magnitude for rotated and marquee words. Therefore, the reading cost from letter rotation does not arise in the initial access to orthographic/lexical representations.

Keywords Word recognition · Masked priming · Lexical decision · Rotated letters

Typically, words in Indo-European languages are written horizontally, with each letter upright. Thus, to recognize a printed word (e.g., *judge*), readers need to encode the identity of each of the component letters (i.e., *j*/*u*/*d*/*g*/*e*) and their relative position (e.g., "*j* to the left of *u,*" "*j* to the left of *d*"; see Grainger, 2018, for a review of orthographic processing in visual word recognition). An important theoretical question is to what degree the encoding of identity and the relative position of the letters depends on the orientation of the stimuli. In the local combination detectors (LCDs) model, Dehaene, Cohen, Sigman, and Vinckier (2005) proposed a neurobiological framework to explain how readers acquire the ability to encode letter position within a word. Dehaene et al. (2005) posited the existence of local bigram neurons that are "sensitive to local combinations of letters. . . . One neuron, for instance, might respond optimally to 'N one or two letters left of A, both around 0.5 degree right of fixation'" (p. 337). In the process of learning to read, these LCDs are shaped via perceptual learning so that "only frequent, informative letters and combinations are selected to be represented by dedicated neurons" (p. 338). The transposed-letter nonword *jugde* would be perceptually more similar to *JUDGE* than *jupte* because it shares more LCDs at the "open bigram" level, thus capturing masked transposed-letter priming effects (i.e., faster responses for *jugde–JUDGE* than for the replacement-control condition *jupte–JUDGE*; Perea & Lupker, 2003, 2004; Schoonbaert & Grainger, 2004).

As pointed out by Witzel, Qiao, and Forster (2011), an obvious prediction from Dehaene et al.'s LCDs model is that masked transposed-letter priming in Indo-European languages should vanish—or greatly diminish—when stimulus orientation is unfamiliar (e.g., vertical orientation). To test this prediction, Witzel et al. (2011) conducted two masked priming lexical decision experiments. In Experiment 1, they compared masked transposed-letter priming effects (transposed-letter prime vs. replacement-letter prime) in Japanese and English for native Japanese speakers who were proficient in English. The rationale was that Japanese readers are familiar with horizontal/vertical Japanese and horizontal English, but they are not used to reading vertical English. Keep in mind that Japanese can be written horizontally—as Indo-European languages—or vertically, with upright letters (i.e., marquee format). Therefore, it is unlikely that their cognitive system is

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equipped with dedicated “open bigram” neurons to encode local combinations of detectors in vertical English (e.g., “N one or two letters above of A”). As expected, masked transposed-letter priming effects occurred in the horizontal and vertical formats of Japanese (25 vs. 19 ms, respectively) as well as in horizontal English (35 ms). But the critical finding was that masked transposed-letter priming also occurred in vertical English (15 ms). Likewise, Witzel et al. (2011) found sizeable masked identity priming effects (i.e., unrelated condition–identity condition) in all four scenarios. In Experiment 2, Witzel et al. (2011) conducted a masked transposed-letter priming experiment using marquee format with native speakers of English—this experiment alleviates the concern that Japanese readers have considerable expertise at reading vertical text. Results showed a sizeable 22-ms transposed-letter priming effect. Thus, readers can readily achieve a stable orthographic code even with an unfamiliar word orientation (i.e., marquee format).

The findings reported by Witzel et al. (2011) with vertical English pose problems for Dehaene et al.’s (2005) perceptual learning mechanisms in the LCDs model. Nonetheless, as argued by Witzel et al. (2011), one can assume that the orthographic code is not encoded as a visual arrangement of letters (i.e., “N one or two letters left of A”), but rather in ordinal terms (i.e., “N one or two positions before A”). That is, readers may quickly encode the letters that compose the letter string into an ordinal orthographic code. After all, the constituent letters in marquee words are not distorted: Letters in marquee format have the same upright orientation as in canonical horizontal text. The difference between the two formats is that word orientation is vertical in marquee and horizontal in canonical text.

The aim of the current masked priming experiment was to examine whether readers can rapidly activate the identity and the order of the letters when using a vertical format that drastically alters the visual input from the letters: a 90° rotation (see Fig. 1). For comparison purposes, we included a vertical condition with marquee words—each stimulus occupied exactly the same vertical space in the two types of format. The LCDs model assumes that “letter detectors should be disrupted by rotation (>40°)”; LCDs model; Dehaene et al., 2005, p. 340). Similarly, in the framework of the SERIOL model of word recognition, Whitney (2002) indicated that “input levels to letter units are reduced for rotated input” (p. 118). If the processes that are necessary to encode an ordinal orthographic code from a visual input consisting of rotated words is not completed fast enough, the size of masked priming effects would be substantially reduced relative to marquee text. Indeed, previous research with unprimed paradigms has consistently shown that word identification times are substantially slower for rotated words than for horizontally presented words (e.g., see Barnhart & Goldinger, 2013; Gomez & Perea, 2014; Koriat & Norman, 1984). This reading cost, which is similar for clockwise and anticlockwise rotations, increases with the rotation angle (e.g., it is substantially greater with 90° rotations than with 45° rotations). In an effort to determine the locus of the orientation effect, Gomez and Perea (2014) conducted fits with Ratcliff’s (1978) diffusion model in a lexical decision task. They found higher values in the parameter responsible for the encoding of letter strings (T_{er} parameter) for rotated than for horizontal words—this would be consistent with an early disruption at accessing abstract letter/word representations from the visual input.

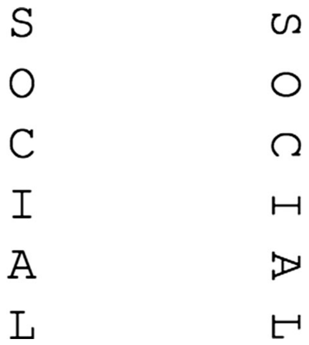

Fig. 1 Example of marquee and rotated text

Thus, in the present masked priming lexical decision experiment, we examined whether letter orientation in two vertical formats (marquee [upright letters] vs. rotated [rotated letters]) modulated the early orthographic processes underlying word recognition. As in Experiment 1 of Witzel et al. (2011), we examined not only the processing underlying letter position (i.e., masked transposed-letter priming: transposed-letter vs. replacement-letter conditions [*soical–SOCIAL* vs. *soaral–SOCIAL*]) but also the processes underlying letter identity (masked identity priming: identity vs. unrelated priming conditions [*social–SOCIAL* vs. *camión–SOCIAL*]; *camión* is the Spanish word for *truck*). This allowed us to examine the potential differences between marquee and rotated words when encoding letter identity and letter position in the early moments of word processing. The predictions are straightforward. If the letters that compose the rotated stimuli are not rapidly converted into ordinal orthographic representations, one would expect smaller masked priming effects for rotated than for marquee words—for marquee words we expect to replicate Witzel et al.’s (2011) findings. This outcome would favor those models that posit that the visual input from rotated stimuli takes time to encode (e.g., LCDs model, Dehaene et al., 2005; SERIOL model, Whitney, 2002). Alternatively, if readers can rapidly convert the visuospatial code into an abstract code regardless of the orientation (i.e., upright vs. rotated) of the visual objects that compose the vertical words, one would expect masked priming effects of similar magnitude for marquee and rotated words (see Hannagan, Ktori, Chanceaux, & Grainger, 2012, for masked priming effects with another type of distorted primes: CATCHAPs [e.g., ]). This latter finding would require some adjustments on those models that postulate an early encoding cost of letter rotation.

Method

Participants

The sample was composed of 32 first-year psychology students from the University of Valencia. They were native speakers of Spanish with normal/corrected vision and no reported reading problems.

Materials

We selected 240 words of five and six letters from the Spanish lexical database EsPal (subtitle module; Duchon, Perea, Sebastián-Gallés, Martín, & Carreiras, 2013). The average Zipf frequency was 4.80 (range: 3.65–6.96)—this corresponded to a mean frequency of 114.64 occurrences per million words (range: 4.42–1151.83), the mean OLD20 value was 1.52 (range: 1–2.85), and the mean number of letters was 5.55 (range: 5–6). Each target word—presented in uppercase—was preceded by a lowercase prime that could be (1) the same as the target word (identity condition: *social–SOCIAL*); (2) an unrelated word (unrelated condition; *camión–SOCIAL*); (3) a nonword prime created by transposing two internal letters from the target word (transposed-letter condition; e.g., *soical–SOCIAL*)—the letter transposition always involved two consonants or a consonant and a vowel (see Perea & Lupker, 2003); and (4) a nonword prime created by replacing two internal letters from the target word (replacement-letter condition; e.g., *soaral–SOCIAL*). The positions of the replaced letters were the same that were transposed in the transposed-letter condition, and the mean log bigram frequency was similar for transposed-letter and replacement-letter primes (1.997 vs. 1.997, respectively), $t(239) = 0.68$, $p > .49$. A set of 240 pseudoword foils was created from the target words using Wuggy (Keuleers & Brysbaert, 2010). The manipulation in the pseudoword trials was the same as that in the word trials (identity condition, unrelated condition, transposed-letter condition, replacement-letter condition). As the four prime–target conditions were presented in the marquee and rotated formats, we created eight lists so that each target appeared once in each list, but each time in a different priming/orientation condition. Four groups of participants were assigned to each list. The prime–target pairs in all conditions are available at http://www.uv.es/mperea/RotatedWords.pdf.

Procedure

Participants were tested in groups of three to seven participants a quiet room. We used DMDX software (Forster & Forster, 2003) to present the stimuli and register the participants' responses. Participants were instructed to respond, in each trial, if the presented string of letters was a Spanish word or not. To do this, they had to press either the "yes" or "no" buttons as quickly as possible while keeping a reasonably low error rate. The sequence of stimuli in each trial was the following: (1) a column of number signs (#s) was presented for 500 ms—the number of #s was matched with the number of letters of the target stimulus; (2) a lowercase prime replaced the mask for 50 ms (i.e., three refresh cycles in the CRT screen at 16.6 Hz); and (3) an uppercase target remained on the screen until the participant responded or 2,500 ms had passed. Response times were measured from the presentation of the target until the participant's response. All stimuli were presented in 12-pt Courier New typeface. Half of the participants received a first block of 240 trials (120 word trials and 120 nonword trials) with marquee stimuli and a second block of 240 trials with rotated stimuli, whereas the other half received the reversed order. The presentation of the trials in each block was randomized. A short practice phase preceded each block. The whole session lasted approximately 40 min.

Results

Both error responses (8.3% for words; 6.6% for pseudowords) and very short correct RTs (<250 ms; only four responses) were excluded from the latency analyses—note that the deadline for correct responses was 2,500 ms. The mean RTs for correct responses and percentage of errors for the word and pseudoword targets are presented in Table 1. As is customary in masked priming experiments, word trials and pseudoword trials were analyzed separately.

We conducted linear mixed-effects models on the latency data using the lme4 and lmerTest R packages (Bates, Mächler, Bolker, & Walker, 2015; Kuznetsova, Brockhoff, & Christensen, 2016; R Development Core Team, 2017). The fixed factors were format (marquee vs. rotated) and prime–target relationships (identity [ID], unrelated word [UN], transposed-letter [TL], and replacement-letter [RL]), whereas subjects and items were treated as random factors—both intercepts and slopes. For prime–target relationship, we focused on the two comparisons of interest: ID versus UN (i.e., masked identity priming) and TL versus RL (i.e., masked transposed-letter priming)—note that these two contrasts keep constant the lexical status of the primes (i.e., word primes for masked identity priming; nonword primes for masked transposed-letter priming). Response times were inverse transformed (−1000/RT) to reduce the positive skew of the raw RTs. We chose the

Table 1 Mean lexical decision times (in ms) and percentage error rates (in parentheses) for words and pseudowords in the experiment

	Marquee stimuli		Rotated stimuli	
	Identity	TL	Identity	TL
Word trials				
Related	947 (8.3)	956 (8.5)	936 (7.1)	933 (9.5)
Control	987 (8.3)	975 (9.2)	973 (7.5)	953 (7.6)
Priming	40 (0.0)	19 (0.7)	37 (0.4)	20 (-1.9)
Nonword trials				
Related	1221 (6.5)	1232 (5.8)	1227 (5.7)	1221 (7.1)
Control	1241 (8.3)	1225 (6.1)	1244 (7.8)	1225 (6.1)
Priming	20 (1.8)	-7 (0.3)	17 (1.9)	4 (-1.0)

Note. Control condition for the identity primes was an unrelated condition, whereas the control condition for the TL (transposed-letter) primes was a replacement-letter condition. The term *priming* refers to the difference between the control and related conditions

model with the more complex random effect structure that successfully converged. For the word trials, the model was LME_RT = lmer(−1000/RT ~ primetype × format + (1 + primetype|item) + (1 + primetype|subject), data = rotated_data). For the accuracy data, the analyses were parallel, except that we employed generalized linear effects models.

Word trials

On average, responses to target words were 15 ms faster in marquee than in rotated format, $t = -3.509$, $b = -0.0230$, $SE = 0.0065$, $p < .001$. The masked identity priming effect was sizeable (38.5 ms), $t = 4.008$, $b = -0.0200$, $SE = 0.0050$, $p < .001$, and similar in size for marquee and rotated words (40 ms vs. 37 ms, respectively; interaction: $p > .45$). The masked transposed-letter priming effect was also sizeable (19.7 ms), $t = -2.682$, $b = -0.0125$, $SE = 0.0047$, $p = .0075$, and again with similar priming effects for marquee and rotated words (19 ms vs. 20 ms; interaction: $p > .71$).

The analyses of the accuracy data showed that participants committed fewer errors for rotated than for marquee words, $z = 2.021$, $b = 0.1752$, $SE = 0.0867$, $p = .0433$. None of the other effects approached significance (all *p*s > .11).

Pseudoword trials

None of the effects on the latency or accuracy data approached significance, all *p*s > .12.

Discussion

We designed a masked priming lexical decision to determine whether or not the visual input from vertically rotated words is rapidly transformed into abstract orthographic representations—for comparison purposes, we included a vertical format with upright letters (marquee format). Results showed that both masked identity and masked transposed-letter effects were similar in magnitude in the two vertical formats (identity priming: 40 ms and 37 ms with marquee and rotated words, respectively; transposed-letter priming: 19 ms and 20 ms with marquee and rotated words, respectively).

The presence of robust masked priming effects with unfamiliar vertically presented words (both with upright and rotated letters; see Fig. 1) supports the view that "the orthographic code is independent of orientation and ordinal in nature" (Witzel et al., 2011, p. 920). Critically, the lack of a disruption in masked priming effects with rotated words poses some problems for those models that assume that "letter detectors" are negatively affected by stimulus rotation during the initial moments of letter/word processing (e.g., LCDs model; Dehaene et al., 2005). This claim, which was inspired by a study on the generalization at recognizing isolated objects at different orientations in macaques (Logothetis & Pauls, 1995), does not take into account the very distinct status of letters and words in the human brain (see Grainger, 2018). Keep in mind that there is an area in the human cortex that is dedicated to the processing of letters/words (the so-called visual word form area; e.g., see Baker et al., 2007; Dehaene et al., 2005, for fMRI evidence). A similar concern arises with the interpretation of the orientation effect being due to preliminary encoding processes to rotate the letter string to the horizontal orientation (Gomez & Perea, 2014; Whitney, 2002). For instance, Whitney (2002) stated that "subjects mentally rotated the string to the canonical horizontal orientation, and processed the string as usual" (pp. 116–117). However, as this alleged mental rotation requires time, one would have expected that the masked related primes were not as effective as those with upright letters (i.e., marquee format). Gomez and Perea (2014) shared Whitney's interpretation of an early encoding cost due to mental rotation. They found longer values of the T_{er} parameter in the diffusion model for rotated than for horizontal words, which they interpreted as an encoding cost for rotated strings. However, the current findings with the masked priming technique showed that some of the letter and letter order information is available quite early, and might not need to be mentally rotated into the canonical orientation.

Unsurprisingly, rotated (and marquee) words are identified more slowly than horizontal words in Indo-European languages (e.g., mean RTs for words above 900 ms; see Table 1), but the present experiment revealed that the locus of the effect is not at the very early access to the words units. This dissociation has some remarkable similarities with the effects of case alternation on word recognition: While alternating-case words (e.g., *rIgHt*) are identified much more slowly than lowercase (or uppercase) words (*right* or *RIGHT*), masked priming effects occur to the same degree for alternating-case primes and for lowercase primes (e.g., *rIgHt–RIGHT* is processed similarly as *right–RIGHT*; see Forster, 1998; Perea, Vergara-Martínez, & Gomez, 2015). A parsimonious explanation is that both the effects of orientation and case alternation occur late in processing, when the activated orthographic codes resonate against a visual input that is distorted and unfamiliar. This issue is a potential avenue for further research (e.g., combining masked priming with the recording of electrophysiological data).

While the main goal of this study was to examine the early moments of processing, we also compared the overall response times for the two vertical formats: marquee versus rotated. Responses to marquee words were slightly faster than the responses to rotated words (949 ms vs. 966 ms, respectively), whereas this difference was absent in pseudowords (1230 ms vs. 1227 ms, respectively). The advantage for marquee words was substantially smaller than that reported in previous experiments with unprimed paradigms (Byrne, 2002; Yu, Gerold, Park, & Legge, 2010) experiments. A reason for this apparent discrepancy is that marquee words occupied more vertical space than the rotated words in the Byrne (2002) and Yu et al. (2010) experiments (for illustration, see Fig. 1 in both articles). Keep in mind that letter-spacing beyond some limits (e.g., as in the word *h o u s e*) may hinder lexical access. The current experiment suggests that when vertical space is carefully controlled, lexical processing is comparable with marquee and rotated words.

To summarize, we conducted a masked priming experiment that showed that skilled adult readers quickly convert an unfamiliar visuospatial code in which letters were rotated 90° to a stable orthographic code during word recognition. Thus, letter detectors do not seem to be negatively affected by word rotation in the initial moments of processing, hence constraining the locus of the effect of stimulus orientation. This remarkable ability to process rotated letter strings is a demonstration of the resilience of the word identification system during reading.

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