LANGUAGE, COGNITION AND NEUROSCIENCE
2023, VOL. 38, NO. 2, 127–138
https://doi.org/10.1080/23273798.2022.2093390

Routledge
Taylor & Francis Group

REGULAR ARTICLE

Letter rotations: through the magnifying glass and What evidence found there

María Fernández-López[a], Pablo Gómez[b] and Manuel Perea[a,c]

[a]Universitat de València, València, Spain; [b]California State University San Bernardino, Palm Desert, CA, USA; [c]Universidad Nebrija, Madrid, Spain

ABSTRACT
Expert readers have a wide tolerance for distortions of the letters that make up a word. Nevertheless, the limits of this invariance are still under debate. To scrutinise this issue, we focused on a single parameter, letter rotation, as it serves to disentangle the predictions from neurally-inspired models of word recognition. Whereas the Local-Combination-Detector (LCD) model predicts invariance up to 45°, the SERIOL model predicts a linear cost until 60°. To test these predictions, Experiments 1 and 2 employed four rotation angles (0°, 22.5°, 45°, 67.5°) in lexical decision and semantic categorisation. The cost was minimal at 22.5°, sizeable at 45°, and considerably large at 67.5°. In Experiment 3, we focused on four moderate rotation angles (<45°). We found a gradual reading cost that increased at 45°. Thus, while there is a resilience limit around 45° favouring LCD, less steep angles also produce a reading cost, backing the SERIOL model.

ARTICLE HISTORY
Received 8 February 2022
Accepted 15 June 2022

KEYWORDS
Rotation; letter detectors; orthographic processing; letter distorsion; letter identity

One of the most remarkable skills of expert readers is their ability to quickly identify words despite their multiple variations in physical appearance. Indeed, heavily distorted words are used to differentiate between human and computer-based character extraction (e.g. CAPTCHA; see Hannagan et al., 2012, for evidence). Thus, it is not surprising that all leading models of visual-word recognition in alphabetical languages assume that the variations from the perceptual signal (e.g. rabbit, *rabbit*, rabbit, Rabbit, RABBIT) are distilled into an abstract representation during the earliest moments of processing. In these models, the elements responsible for accessing lexical memory are layers of abstract letter detectors (e.g. rabbit and *rabbit* would activate the same abstract letter units; see Grainger, 2018, for review).

The main goal of this paper is to examine to what degree the letter detectors in the word recognition system tolerate the degradation of the sensory input during lexical access. Given that the distortion of the physical signal of written text occurs along many different dimensions (i.e. all forms of bad penmanship can be bad in their own way), in this article, we focused on a single parameter of distortion: letter rotation. This decision has an added advantage: several neurally-inspired models of visual-word recognition (e.g. Local Combination Detector [LCD] model; Dehaene et al., 2005; Serial Encoding Regulated by Inputs to Oscillations within Letter units [SERIOL] model, Whitney, 2001) make precise claims on the impact of rotation angle on the resilience of letter detectors during word processing. In the following paragraphs, we offer a short overview of these two models, then we review the existing literature, and finally, we present a rationale for the three experiments reported in the paper.

The LCD model, postulated by Dehaene et al. (2005), is a hierarchical neurally-inspired model that explains word recognition via a series of local combinations of detectors that are sensitive to increasingly larger fragments of words, from shape fragments to complete words (see Figure 1 in Dehaene et al., 2005). Crucially, at the level in which abstract representations of letters are recognised, the detectors are invariant to changes in size or format (i.e. a A a **A** and *a* share the same abstract units). Nevertheless, the model postulated that letter rotation hinders the normal mapping of the letter features: "letter detectors should be disrupted by rotation (> 40°)" (Dehaene et al., 2005, p. 340). Specifically, the LCD model assumes that the visual word recognition system moves from the parallel encoding of letters to an effortful serial processing strategy for rotation angles above 40°–45°. Notably, it is assumed that rotation angles below that boundary would

CONTACT María Fernández-López Maria.Fernandez@uv.es Departamento de Metodología and ERI-Lectura, Universitat de València, 46010 València, Spain
Supplemental data for this article can be accessed https://doi.org/10.1080/23273798.2022.2093390

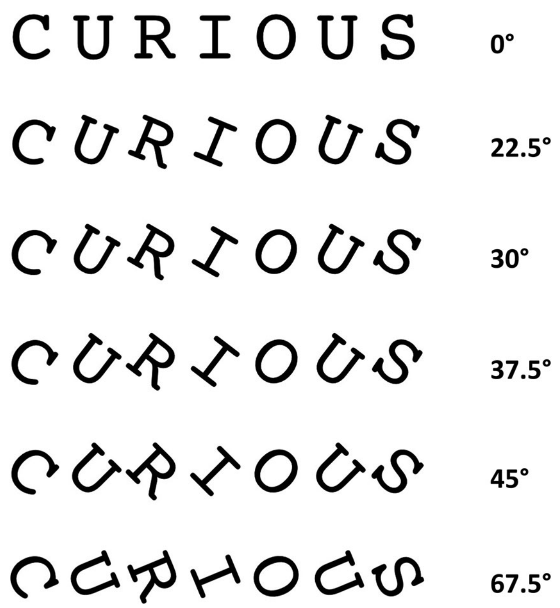

Figure 1. Rotation angles employed in the experiments. Letters in Experiment 1 and 2 were rotated 0°, 22.5°, 45°, and 67.5°. Letters in Experiment 3 were rotated 22.5°, 30°, 37.5°, and 45°.

induce “no measurable cost” (Vinckier et al., 2006, p. 2006; see also Cohen et al., 2008).

The SERIOL model (Whitney, 2001) is a theoretical framework that describes how word recognition is achieved via a series of processing layers. Specifically, the process of abstract letter identification depends on the activation of the nodes representing each letter, and this activation depends on the input provided by the letter feature level. The SERIOL model assumes that when the letters are rotated, the sensory input activates less the letter nodes, thus producing a reading cost as a function of rotation angles (i.e. degradation increases and the input decreases). Importantly, whereas this cost would be relatively small for moderate rotation angles, Whitney (2002) assumed that there would be a threshold at around 60° of rotation above which the input levels would not be sufficient to encode the word constituent letters automatically. Specifically, rotation angles above 60° would require extra top-down attentional processing (e.g. via activation in parietal areas in the brain) to guide a more letter-by-letter encoding. In this latter scenario, there would be a substantial delay in lexical access.

Although the LCD and SERIOL models share several principles concerning the role of rotation angle during word recognition, they vary in two crucial aspects. First, the boundary for the resilience of abstract letter detectors is lower in the LCD model than in the SERIOL model (around 45° vs. 60°, respectively). Second, in the LCD model, abstract letter detectors are assumed to be unaffected by moderate rotation angles (less than 40°−45°; an “invariance-with-limits perspective”, Kim & Straková, 2012). In contrast, the SERIOL model predicts a gradual, increased cost as a function of rotation angle up to the boundary level of 60°.

In the present experiments, we aimed to disentangle the predictions of these models. Importantly, our interest is in the rotation of individual letters within words rather than the rotation of the whole word. The reason is that when a word is rotated as a whole, readers could rotate the entire stimulus to the canonical position and then process it as usual (i.e. one movement of mental rotation; see Whitney, 2002; Gómez & Perea, 2014, for discussion). Indeed, recent research has repeatedly shown that the rotation of the whole word produces sizable masked identity priming even at angles of 90° or greater (see Benyhe & Csibri, 2021; Perea et al., 2018; Yang & Lupker, 2019). By contrast, the rotation of the individual letters within a word involves the disruption of trans-letter features (i.e. features that are larger than letters but smaller than words; Mayall & Humphreys, 1996). Thus, the effect letter-by-letter word rotation represents a more stringent test of the LCD and SERIOL models than whole-word rotation.

Somewhat surprisingly, only a few studies have directly examined the claims of the LCD and SERIOL models concerning the resilience of letter detectors to the rotation of individual letters. One of the exceptions is the study conducted by Kim and Straková (2012). They recorded the event-related potentials (ERP) during a lexical decision task (i.e. a word vs. nonword discrimination task). The items’ letters were presented in 0°, 22.5°, 45°, 67.5°, or 90°, and each word/nonword was presented for 200 ms. Kim and Straková focused on two early time windows (P1 [95-125 ms] and N170 [160-225 ms]). When considering the peak latencies, they found that angle rotation produced a linear increase on both P1 and N170 components. When considering amplitudes, they found a quadratic component of angle rotation for the P1 component: a rise between 0° and 22.5°, which remained stable until 67.5°, and then a decrease in amplitude at the 90° rotation. For the N170 component, they considered sub-windows. In the 160–190 ms interval, they found both an increase in linear and quadratic components from 0°−22.5° and 22.5°−45°, stable from 45°−67.5°, and a decrease from 67.5°−90°. In the 195–225 ms interval, they found a linear increase in all consecutive rotation angles.

Kim and Straková (2012) concluded that the increased amplitudes and delayed peaks with relatively moderate rotation angles (i.e. well below 45°) posed problems for the LCD model. However, a potential interpretive issue from the Kim and Straková (2012) experiment is that, to reduce the motor artifacts in the ERP signal, lexical decision responses had to be made after a cue presented 850 ms after the disappearance of the target. Therefore, they did not record a direct measure of the impact of letter rotation on the speed of lexical access; in other words, we cannot know whether the rotation effects are encapsulated in the encoding process, or instead, they cascade into the lexical processes. Indeed, they found remarkably similar word response times for 0° and 67.5° rotations. Thus, the effect of letter rotations in the ERPs at moderate angles (e.g. 22.5°) might be accounted for by changes in the visual appearance rather than a delay in lexical access (see Vergara-Martínez et al., 2015, for discussion).

In a more recent study, Blythe et al. (2019) measured participants' eye movements when reading sentences in which the individual letters within words were rotated (30°, 60°) or not. They found an overall reading cost on sentence reading for the words with 30° letters and an even larger one for the words with 60° letters. They also examined whether rotation angle interacted with word frequency by embedding a high- vs. low-frequency target word in each sentence. Their logic was that if rotation angle affected lexical processing, one would expect an interaction (i.e. greater word-frequency effects for the more degraded, 60° words). Results showed additive effects of rotation angle and word-frequency in the first-fixation duration on the target word (30° < 60°; high-frequency < low-frequency; i.e. the magnitude of word frequency effects was relatively consistent across all manipulations on these duration measures). Instead, gaze durations (i.e. the sum of fixation durations before leaving the target word) and total fixation durations (i.e. the sum of all fixations in the target word) showed an interaction between the two factors. Compared to the canonical 0° condition, the difference between high- and low-frequency target words increased in the 30° condition and even more in the 60° condition.

As reading was impaired even by relatively small rotations (i.e. 30°), Blythe et al. (2019) concluded that rotations hamper letter detectors at angles below 45° during sentence reading and, as a result, the LCD predictions concerning letter rotations should be revised. Indeed, the gradual cost of letter rotation fits better with the SERIOL model. Nevertheless, the experiment conducted by Blythe et al. (2019) does not inform us as to whether the effect of letter rotation occurs in the first moments of processing (i.e. as posited by the LCD and SERIOL models) or at a later point during the integration processes—note that participants could have adjusted their eye movement pattern to the rotation angle of the sentences.

To shed light on this latter issue, Fernández-López et al. (2021) conducted a parafoveal preview experiment using Rayner's (1975) gaze-contingent boundary change paradigm during sentence reading. Crucially, the letters of the fixated target word and the rest of the sentence were in the upright orientation. The parafoveal preview was either identical or unrelated to the target word, and its letters were rotated 15°, 30°, 45°, or 60°. Results showed that the advantage of the identity preview condition in eye fixation times on the target word decreased progressively as a function of the rotation angle: the identity advantage was sizeable for 15° and 30°, weak for 45°, and absent for 60° (e.g. the benefit in single fixation durations was 26, 13, 7, and 3 ms, respectively). Thus, the cost of letter rotation of parafoveal previews during sentence reading increased as a function of rotation angle, being substantial after 45°, providing empirical support to the LCD model. However, Fernández-López et al. (2021) measured the effects of the preview-on-target integration rather than directly measuring the impact of the rotation angle on eye movement measures. Furthermore, the previews were presented in the parafovea, where the quality of the spatial information is lower than in the fovea. As a result, it is difficult to completely ascertain whether the cost of letter rotations at 45° or above reflects the system bounds on early orthographic processing in a standard foveal scenario or whether it reflects structural limitations of parafoveal processing.

Taken together, previous research has shown that although there is a boundary beyond which processing words with rotated letters becomes effortful, relatively small rotation angles may also produce some reading cost. Although some of these findings favour the SERIOL model (e.g. a gradual cost of the transpositions at rotation angles less than 40-45°), the evidence is scarce and subject to alternative interpretations (e.g. a modulation in early ERPs does not imply a cost in lexical access; see Vergara-Martínez et al., 2015, for discussion). Furthermore, the evidence on the existence of a specific boundary that critically hampers the workings of letter detectors and consequent word recognition is not conclusive either. Crucially, a limiting issue in most of the previous experiments on this issue was the lack of a lexical factor in their design—the exception was Blythe et al. (2019). As a result, it is complicated to ascertain whether the impact of letter rotation is perceptual (visually) or linguistically mediated. To infer the effect of letter rotation on lexical processing, we did include word frequency as a factor in the experiments.

In the present study, we conducted three experiments that examined in detail the cost of one type of perceptual degradation (letter rotation) on lexical access. In Experiment 1, we conducted a lexical decision experiment with high- and low-frequency words using rotation angles of 0°, 22.5°, 45°, and 67.5°. The manipulation of word-frequency allowed us to examine whether the impact of letter rotation is on an early encoding phase (i.e. additive effects of rotation angle and word-frequency), or whether its impact also carries on to subsequent lexical processing (i.e. more frequent words would be less affected by steeper rotations because of top-down lexical feedback). Experiment 2 was parallel to Experiment 1, except that we used a task that directly taps onto the access to lexical-semantic memory: semantic categorisation (i.e. asking participants whether the presented item referred to an animal name or not). Notably, the use of different tasks in Experiment 1 (lexical decision) and Experiment 2 (semantic categorisation) allowed us to explore whether the effect of angle rotation varies across tasks that tap into different processes. Finally, Experiment 3 was designed to examine in detail the effect of rotation angle in the region of 45° and below (i.e. 22.5°, 30°, 37.5°, and 45°), as this is the threshold boundary proposed by the LCD model.

We can envision three scenarios concerning Experiment 1 (lexical decision task). First, if there is a gradual, purely linear increment in the word response times across the various rotation angles (0°, 22.5°, 45°, and 67.5°), it would pose problems for both LCD and SERIOL models. Second, if word response times are similar for the 0° and 22.5° rotation angles and then there is a dramatic increase at the 45° and 67.5° rotation angles, this outcome would favour the predictions of the LCD model. Third, a linear increase in word recognition times at the 0°, 22.5°, and 45° angles, and then a dramatic increase at the 67.5° angle, would favour the predictions of the SERIOL model. In addition, an interaction between rotation angle and word frequency would suggest that the effect of rotation angle spilled over lexical processes. In this latter scenario, top-down processes from the lexical level from high-frequency words may outweigh the harmful effects of perceptual degradation (see Vergara-Martínez et al., 2021, for evidence with handwritten words).

Experiment 1 (lexical decision task)

Methods

Participants

Sixty individuals took part in the experiment (mean age = 29 years-old; SD = 5.57; 39 women). With this sample size, we had 1,800 observations per condition, which is in line with the suggestion from Brysbaert and Stevens (2018) for small effects. Participants were recruited with Prolific Academic, a UK-based online crowd working platform (http://prolific.ac). Only English native speakers with no reading problems and normal/corrected vision could participate. All participants gave informed consent before the experiment and received monetary compensation. This and the following experiments obtained ethical approval from the Research Ethics Committee of the University of Valencia and followed the requirements of the Helsinki Convention.

Materials

We employed the 120 high-frequency and 120 low-frequency English words used by Aschenbrenner and Yap (2019). These two sets of words had been matched on a number of relevant psycholinguistic variables (e.g. number of letters, number of syllables, number of morphemes, OLD20, number of orthographic neighbours, number of phonological neighbours, and PLD20), while differing (see Table 1 of Aschenbrenner & Yap, 2019) in SUBTLEX word frequency (Brysbaert & New, 2009). We also employed the 240 orthographically legal pseudowords selected by Aschenbrenner and Yap (2019)—these stimuli had been created with Wuggy (Keuleers & Brysbaert, 2010). The letters of each item (either words o pseudoword) could be presented in four different rotation angles (see Figure 1): 0° (i.e. canonical presentation), 22.5°, 45°, or 67.5°. We created four lists to counterbalance the stimuli across rotation angle (e.g. the word CURIOUS could be at 0° in List 1, at 22.5° in List 2, at 45° in List 3, and 67.5° in List 4)—participants were randomly assigned to each list.

Procedure

The script was written in Psychopy 3 software (Peirce & MacAskill, 2018) and was conducted online using Pavlovia (www.pavlovia.org). Before the experiment, all participants filled out a questionnaire with demographic data (age, gender, education level) via LimeSurvey (www.limesurvey.org). Participants were advised to do the experiment in a quiet room without distractions. Their task was to decide whether the presented item was a word or not by pressing the "yes" (M) and "no" (Z) keys on the keyboard as quickly and accurately as

Table 1. Mean Response Times (in ms) and percent errors (in %) in each of the conditions in Experiment 1 (Lexical Decision Task).

		Rotation angle			
		0°	22.5°	45°	67.5°
Words	High Freq	608 (1.7)	608 (1.7)	657 (3.7)	781 (7.6)
	Low Freq	638 (4.0)	647 (3.4)	696 (4.7)	830 (8.7)
Frequency effect		30 (2.3)	39 (1.7)	39 (1)	49 (1.1)
Nonwords		719 (5.6)	748 (6.9)	819 (6.6)	985 (9.7)

possible. Within a given trial, a fixation cross was presented in the centre of the screen for 500ms. Then, the target item, always in capital letters, was presented until a response was made or 2 sec had passed. We included 16 practice trials before the 480 experimental trials. There were brief breaks after every 100 trials. Altogether, the experiment took 18–20 min to complete.

Results and Discussion

For the analyses of the response times (RTs), we excluded the error responses (4.4% for words; 7.2% for pseudowords) and the very brief responses (less than 250 ms; 1 observation [less than 0.004%]). Time-outs after 2000 ms (0.17% for words, 0.55% for pseudowords) were coded as errors. Table 1 presents the mean correct RTs and error percentage in each experimental condition.

The latency and the accuracy data were fitted with Bayesian linear-mixed effects models, using the *brms* package (Bürkner, 2021) in R (R Core Team, 2021). For the fits, we employed the exgaussian distribution for the latency data, thus capturing the skew of the RT data, and the Bernoulli distribution for the binary accuracy data. We conducted separate analyses for word and nonword trials. The fixed effect factors for the word trials were the Rotation angle of the items' letters (0°, 22.5°, 45°, and 67.5°, where the canonical 0° was the reference level) and Word-frequency (high vs. low; encoded as −0.5 and 0.5). For the nonword trials, the only fixed factor was Angle, but the general procedure was the same as that for the word trials. In all statistical analyses, we employed the maximal random-effect structure allowed in the design:

DV ~ Rotation Angle * Word Frequency +

(1 + Rotation Angle * Word Frequency | subject) +

(1 + Rotation Angle | item)

To examine the nature of the function of the reading cost due to rotation angle (i.e. linear, quadratic, cubic) in the latency data, we conducted parallel Bayesian linear mixed-effects models with the difference that the fixed factor Rotation Angle was coded using polynomial contrasts.

In all cases, we carried out 5,000 iterations for each model—1,000 were for warmup—using four chains. All models fit adequately ($\hat{R} = 1.00$ in all cases). The complete output of the models in this and subsequent experiments is available at https://osf.io/fc3xz/?view_only = e3452260fa4d4b4398363c0d83a0696d. For the fixed effects, we report an estimate of the mean of the posterior distribution for each parameter (*b* parameter), together with its standard error (*SE*) and 95% credible interval (95% CrI) based on the quantiles of the distribution of the posterior estimates. Bayesian models do not report a *p* value for each effect, instead, the estimate plausible values for the parameters given the data that is available. In other words, they are used to estimate the size of an effect. When such plausible values (as described by the Credible intervals) do not contain zero, we deem the effect to be larger than zero.

Word stimuli

Response Times. We found evidence of an effect of word-frequency, *b* = 24.13, *SE* = 4.08, 95%CrI [16.03, 32.09]: responses were 39 ms faster for high-frequency words than for low-frequency words. Regarding the effect of rotation angle, words with 22.5° letters were responded to only minimally slower (5 ms) than those with 0° letters, *b* = 4.95, *SE* = 2.85, 95%CrI [−0.56, 10.48]. Words with 45° letters were responded 54 ms slower than those with 0°, *b* = 41.32, *SE* = 3.55, 95%CrI [34.35, 48.30]. Finally, words with 67.5° letters were responded to 183 ms slower than those with 0°, *b* = 116.80, *SE* = 6.51, 95%CrI [103.84, 129.60]. None of the rotation angle effects interacted with word-frequency (all *b*s < 7.71; all 95%CrIs crossed zero).

The trend analyses showed clear evidence of linear and quadratic components of rotation angle (linear: *b* = 86.26, *SE* = 4.81, 95%CrI [76.95, 95.81], quadratic: *b* = 35.25, *SE* = 3.05, 95%CrI [29.33, 41.27]). These effects did not interact with word-frequency (all *b* values of the interaction were less than 5 ms and their 95%CrIs crossed zero).

Accuracy. We found a main effect of word-frequency, *b* = −0.94, *SE* = 0.27, 95%CrI [−1.49, −0.40]: responses were 2% less error prone for high-frequency than for low-frequency words. Concerning the effect of rotation angle, we did not find differences between the accuracy on responses to 0° and 22.5° words, *b* = 0.34, *SE* = 0.37, 95%CrI [−0.36, 1.13]—this effect did not interact with word-frequency, *b* = 0.15, *SE* = 0.36, 95%CrI [−0.55, 0.84]. Moreover, words with 45° letters were responded a 7% less accurately than those with 0°, *b* = −0.74, *SE* = 0.29, 95%CrI [−1.31, −0.16]—this effect interacted with word-frequency, *b* = 0.74, *SE* = 0.32, 95%CrI [0.11, 1.38], showing that the word-frequency effect was smaller with 45° letters. Finally, words composed of 67.5° letters were responded a 4.7% less accurately than those with 0°, *b* = −1.67, *SE* = 0.27, 95%CrI [−2.20, −1.16]—this effect also interacted with word-frequency, *b* = 0.78, *SE* = 0.31, 95%CrI [0.18, 1.39], showing that the word-frequency effect was smaller with 67.5° letters.

Nonword stimuli

Response Time analysis. Pseudowords composed of 22.5° letters were responded 29 ms more slowly than those with 0°, $b = 16.33$, $SE = 2.81$, 95%CrI [10.84, 21.88]. The latency cost increased to 100 ms for the pseudowords with 45° letters, $b = 56.38$, $SE = 4.26$, 95% CrI [48.04, 64.74], and even more, 266 ms, for the pseudowords with 67.5° letters, $b = 143.49$, $SE = 9.85$, 95% CrI [123.89, 163.11].

The trend analyses showed clear evidence of linear and quadratic components of rotation angle (linear: $b = 105.30$, $SE = 6.97$, 95%CrI [91.77, 119.02], quadratic: $b = 35.31$, $SE = 3.77$, 95%CrI [27.85, 42.66]). We also found some evidence of a small cubic component, $b = 5.38$, $SE = 2.34$, 95%CrI [0.83, 9.90].

Accuracy analysis. We did not find evidence of differences in accuracies between 0° and 22.5°, $b = -0.17$, $SE = 0.15$, 95%CrI [−0.46, 0.12], and 0° and 45°, $b = -0.21$, $SE = 0.15$, 95%CrI [−0.49, 0.09]. Nevertheless, responses to pseudowords with 67.5° letters were 3.1% more error prone than responses to pseudowords with 0°, $b = -0.63$, $SE = 0.14$, 95%CrI [−0.90, −0.34].

The present experiment revealed that word identification times increased nonlinearly at the steeper rotation angles: when compared to the canonical 0° format, the reading cost was minimal for the words with 22.5° letters (4 ms), it increased to 54 ms for the words with 45° letters, and considerably more, to 183 ms, for the words with 67.5° letters. This reading cost was not accompanied by a larger word-frequency effect (see Gomez & Perea, 2014, for a similar pattern when rotating whole words in a lexical decision task). Overall, these increases can be modeled by a combination of linear and quadratic components (see Figure 2). The analyses of the error rates showed a similar pattern: the percentage of errors was similar for the 0° (2.9%) and 22.5° (2.6%) angles, and then increased for the 45° angle (4.2%) and even more for the 67.5° angle (8.2%).

The pseudoword data revealed an analogous pattern, except that the effects of rotation angle were steeper than those for words. We found a sizeable cost (29 ms) for the pseudowords with 22.5° letters compared to those with 0° letters. Relative to this canonical 0° format, the cost increased to a much larger degree for the 45° (100 ms) and the 67.5° (266 ms). Thus, rotation angle hinders pseudowords to a greater degree than words. To obtain statistical support of this dissociation, we conducted an analysis with Lexicality (word vs. pseudoword) and Rotation angle as polynomial contrasts. We found evidence of a greater cost for pseudowords than for words in the linear component (interaction Angle x Lexicality) ($b = 12.53$, $SE = 6.22$, 95%CrI [0.38, 24.71]).

In sum, the present experiment showed a sizable reading cost of rotation angle for words at the 45° angle (54 ms; 1.4% errors) and, much more dramatically, at the 67.5° angle (183 ms; 5.3% errors), but not at the 22.5° angle (5 ms; −0.3% errors). This pattern in word responses favours the predictions of the LCD model. However, pseudowords showed greater reading costs than words, including the 22.5° rotation angle (29 ms; 1.3% errors). One explanation for this dissociation is that some top-down feedback from the lexical level could have partly overridden the cost of letter rotation at moderate angles.

The question now is whether rotation angle also affects a recognition task that requires word identification at a semantic level. Experiment 2 was designed to examine the resilience of word recognition to letter rotation using a task that is less sensitive to purely visual elements and more on access to meaning in lexical memory (semantic categorisation task: "is the word an animal name?") (see Perea et al., 2020, for discussion). As the number of animal names is limited, the ratio between animal and non-animal words was 1:2 instead of 1:1. Previous semantic categorisation experiments have used a similar design and found a very similar pattern for animal and non-animal words and no signs of a "no" bias (e.g. see Perea et al., 2022). Furthermore, we must keep in mind that, in Experiment 2, the focus was on the role of rotation angle for the same class of stimuli rather than a comparison of "yes" and "no" responses, which were analyzed separately.

Experiment 2 (semantic categorisation task)

Method

Participants

The number of participants, sampled from the same population as Experiment 1, was increased to 80 (mean age = 29 years old; SD = 5.41; 60 women) so that the number of observations per condition was comparable to that of Experiment 1—note that the number of trials per condition was smaller than in Experiment 1 (see the Materials subsection below).

Materials

For the non-animal words, we used a subset of 184 words from the set of high- and low-frequency words from Experiment 1 (92 high-frequency words and 92 low-frequency words). The reason is that we excluded those words which referred to animal

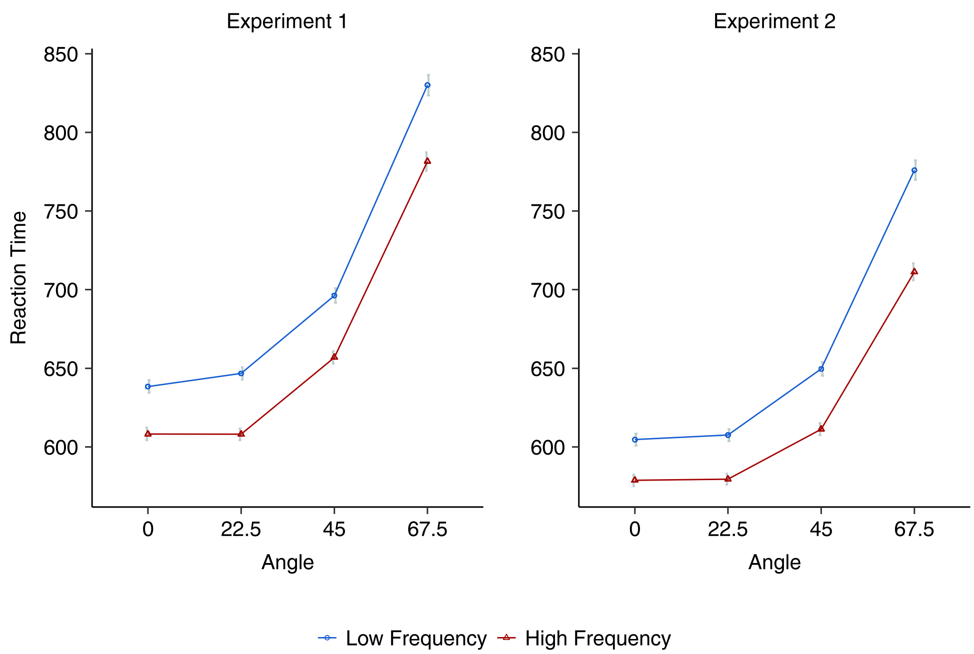

Figure 2. Reaction times (in ms) for high- and low-frequency words across the different rotation angles in Experiment 1 (Lexical Decision Task) and Experiment 2 (Semantic Categorisation Task). The brackets reflect the standard errors. Note that these analyses were based on "yes" responses in Experiment 1 and on "no" responses (i.e. non-animal words) in Experiment 2.

names or were closely related to animals (e.g. mother, mountain, food). We also selected a set of 92 words for the animal words, thus keeping the 2:1 ratio used in previous experiments (e.g. Perea et al., 2020, 2022). The number of letters of the animal words (M = 5.3; range: 3-9) was similar to that of the non-animal words (high-frequency words: M = 5.3, range: 3-8; low-frequency words: M = 5.3, range: 3-9). The animal words had an ample range of word-frequency in the SUBTLEX database (M = 11.84 per million; range: 0.61-192.84).

Procedure

It was parallel to Experiment 1, except that the participants were asked to decide whether the item referred to an animal name (press "M") or not (press "Z").

Results and Discussion

The analyses plan was the same as in Experiment 1. Although the main focus was on non-animal words (i.e. the set of high vs. low-frequency words from Experiment 1), we also analyzed the data from the animal words for completeness. For the non-animal words, the fixed factors were Angle and Word-frequency; for the animal words, the fixed factor was Angle. Table 2 displays the mean RT and error rate in each experimental condition.

Non-animal words

Response Time analysis. We found that responses were 40 ms faster for high- than for low-frequency words., $b = 19.44$, $SE = 3.86$, 95%CrI [11.94, 26.96]: Regarding rotation, words with 22.5° letters were responded only 2 ms slower than those with 0°, $b = 2.18$, $SE = 2.98$, 95% CrI [−3.71, 8.07]—this effect did not interact with word-frequency, $b = -0.17$, $SE = 4.25$, 95%CrI [−8.46, 8.11]. Words with 45° letters were responded 39 ms more slowly than those with 0°, $b = 41.32$, $SE = 3.54$, 95%CrI [17.52, 31.40]—this effect did not interact with word-frequency, $b = 8.03$, $SE = 4.88$, 95%CrI [−1.52, 17.56]. Finally, words with 67.5° letters were responded to152 ms slower than those with 0°, $b = 85.19$, $SE = 6.61$, 95%CrI [72.07, 98.24]—this effect did interact with word frequency, $b = 24.83$, $SE = 8.40$, 95%CrI [8.22, 41.27]: the difference between responses to high and low frequency words was 39 ms greater when the letters were rotated 67.5° than when presented at 0°.

Table 2. Mean Response Times (in ms) and percent errors (in %) in each of the conditions in Experiment 2 (Semantic Categorisation Task).

		Rotation angle			
		0°	22.5°	45°	67.5°
Non-Animal	High Freq	579 (1.6)	580 (1.0)	611 (1.4)	711 (2.7)
	Low Freq	605 (1.8)	608 (1.8)	650 (2.6)	776 (4.0)
Frequency effect		26 (0.2)	28 (0.8)	39 (1.2)	65 (1.3)
Animal		618 (9.7)	629 (11.1)	652 (9.4)	709 (11.0)

The trend analyses showed evidence of both linear a quadratic components of rotation angle (linear: $b = 61.71$, $SE = 4.68$, 95%CrI [52.43, 70.89], quadratic: linear: $b = 29.15$, $SE = 3.22$, 95%CrI [22.85, 35.46]). In addition, word-frequency interacted with the linear component of rotation angle, $b = 17.93$, $SE = 5.68$, 95%CrI [6.80, 29.02]—the evidence of a quadratic component was weak (i.e. 95%CrI crossed zero), $b = 8.02$, $SE = 4.39$, 95% CrI [−0.50, 16.74].

Accuracy analysis. We did not find evidence of an effect of word-frequency, $b = -0.06$, $SE = 0.33$, 95%CrI [−0.70, 0.59]. Regarding rotation, words with 22.5° letters and words with 45° letters, were responded as accurately as those with 0°, (0° vs 22.5°, $b = 0.71$, $SE = 0.40$, 95%CrI [−0.02, 1.55]; 0° vs 45° $b = 0.34$, $SE = 0.36$, 95%CrI [−0.33, 1.10]). However, responses to words with 67.5° letters were 2.2% more error prone than responses to words with 0°, $b = -0.61$, $SE = 0.30$, 95% CrI [−1.21, −0.02]. None of the rotation angle effects interacted with word-frequency (all *b*s < 0.54; all 95% CrIs crossed zero).

Animal words

Response Time analysis. Relative to the words with 0° letters, we found a cost that increased with rotation angle: 11 ms for 22.5°, $b = 11.48$, $SE = 2.65$, 95%CrI [6.31, 16.66]; 34 ms for 45°, $b = 27.41$, $SE = 3.09$, 95%CrI [21.36, 33.48]; and 91 ms for 67.5°, $b = 64.76$, $SE = 4.11$, 95%CrI [56.75, 72.84].

The trend analyses revealed evidence of both linear a quadratic components of rotation angle (linear: $b = 46.87$, $SE = 3.22$, 95%CrI [40.70, 53.27], quadratic: $b = 12.78$, $SE = 2.12$, 95%CrI [8.59, 17.00]).

Accuracy analysis. We did not find evidence of differences in accuracy relative to the words with 0° in any of the three angles (all *b*s < 0.23; all 95%CrIs crossed zero).

The pattern of word recognition times for the non-animal words in the semantic categorisation task mimicked that of the word recognition times in the lexical decision task. There was a minimal cost from 0° to 22.5° rotation angles (2 ms) that increased at the 45° rotation angle (39 ms) and was even more dramatic at the 67.5° rotation angle (152 ms). In addition, the effect of word-frequency increased for the words with 67.5° letters relative to the canonical 0° format (65 vs. 26 ms, respectively), thus suggesting that the encoding cost of 67.5° words also affected lexical processes. Error rates on non-animal names were very low (2.1%) and only showed a small disadvantage at the 67.5° angle relative to the 0° angle (3.4% vs. 1.7%, respectively).

The pattern of data for animal words was similar to that for non-animal words except that there was a small reading cost for the words composed of 22.5° letters relative to the canonical format (11 ms); this cost increased for the 45° angle (34 ms) and even more for the 27.5° angle (91 ms). The error rates did not show differences across rotation angles.

In sum, the effect of rotation angle in the range between 0° and 67.5° is remarkably similar in lexical decision and semantic categorisation tasks, reflecting both linear and quadratic components. The reading cost from 0° to 22.5° rotation angle was minimal, sizeable for the words with 45° letters, and substantial for the 67.5° angle (see Figure 2 for a comparison of the two experiments).

While the overall pattern in Experiments 1 and 2 is generally consistent with the claims of Dehaene et al.'s LCD model, we found some gradual increases as a result of rotation angle in some conditions, even for moderate rotations that deserve further scrutiny. To further study this issue, we designed Experiment 3. The objective was to examine with a magnifying glass the effects of letter rotation at angles of up to 45° in a semantic categorisation task. For this purpose, in Experiment 3, we chose four angles of rotation whose difference was almost indiscernible (i.e. 7.5°): 22.5°, 30°, 37.5°, and 45°.

The key question in Experiment 3 was whether there is an "abrupt" boundary at around 45° in which rotation angle makes word recognition substantially less automatic, or whether there is a gradual linear cost as a function of rotation angle at moderate angles. If there is a critical boundary level at around 40-45° at which letter detectors cannot efficiently deal the sensory input—as predicted by the LCD model, we would expect negligible increases from the 22.5° up to 37.5° rotation angle and then a large increase at the 45° angle (i.e. a quadratic component). Alternatively, rotation angles below 45° could produce a small but steady accumulative reading cost in each step—as predicted by the SERIOL model. In this latter case, we would expect a linear (but not quadratic) component of the rotation angle.

Experiment 3

Method

Participants

We recruited 80 new participants (mean age = 29 years old; SD = 5.42; 66 women) from the same population as in the previous experiments—note that the sample size was the same as in Experiment 2.

Materials and procedure

They were the same as in Experiment 2, except that the rotation angles were 22.5°, 30°, 37.5°, and 45°.

Results and Discussion

The analysis plan was the same as in Experiment 2. Table 3 presents the averages per condition in the latency and error data.

Non-animal words

Response Time analysis. We found evidence of an overall effect of word-frequency, $b = 17.13$, $SE = 3.91$, 95%CrI [9.56, 24.90]: responses to low-frequency words were 25 ms slower than responses to high-frequency words. Regarding the rotation angle effect, when comparing to responses with 22.5° rotated letters, words with 30° letters produced a minimal cost (5 ms), $b = 2.26$, $SE = 2.98$, 95%CrI [−3.13, 7.58], that slightly grew for words with 37.5° rotated letters (8 ms), $b = 8.41$, $SE = 2.81$, 95%CrI [2.95, 13.98]. Importantly, for words with 45° rotated letters, the cost increased sharply (29 ms), $b = 20.08$, $SE = 3.08$, 95%CrI [14.04, 26.21]. None of these effects interacted with word-frequency (all *b*s < 4, all 95%CrI crossed zero).

This pattern was confirmed by the trend analyses, which showed evidence of linear and quadratic components of rotation angle (linear: $b = 14.75$, $SE = 2.27$, 95%CrI [10.29, 19.22], quadratic: $b = 4.72$, $SE = 2.01$, 95%CrI [0.76, 8.67]). There were no signs of an interaction of rotation angle with word-frequency (all *b*'s < 2.27).

Accuracy analysis. We did not find evidence of an effect of word-frequency, $b = -0.38$, $SE = 0.41$, 95%CrI [−1.19, 0.42]. We did not find evidence of an effect of rotation relative to 22.5° letters in any of the three angles (all bs < 0.39, all 95%CrI crossed zero) or an interaction between word-frequency and rotation angle (all *b*s < 0.83, all 95%CrI crossed zero).

Animal words

Response Time analysis. Relative to the words with 22.5° letters, there were no differences when the letters were rotated at 30° (5 ms), $b = 2.55$, $SE = 2.65$, 95%CrI [−1.38, 8.63]. We found some cost of rotation at 37.5° (8 ms), $b = 6.97$, $SE = 2.77$, 95%CrI [1.54, 12.41], which abruptly increased at the angle of 45° (23 ms), $b = 18.60$, $SE = 2.56$, 95%CrI [13.62, 23.65].

The trend analyses again revealed evidence of both linear and quadratic components (linear: $b = 13.16$, $SE = 2.09$, 95%CrI [9.01, 17.34], quadratic: linear: $b = 4.18$, $SE = 2.10$, 95%CrI [0.11, 8.33]), but not a cubic component ($b = .91$, $SE = 1.78$, 95%CrI [−1.59, 5.42]).

Accuracy analysis. There were no differences in accuracy of the various angle conditions relative to the 22.5° words (all bs < 0.30, all 95%CrI crossed zero).

The present experiment showed small changes in word response times across rotation angles, except for the more abrupt change at the 45° angle. Compared to the 22.5° baseline, the recognition times for non-animal words increased 5, 8, and 29 ms when the letters were rotated 30°, 37.5°, and 45°. We found a parallel pattern for animal words: recognition times increased in 5, 8, and 23 ms. This pattern reveals a combination of linear and quadratic components, suggesting that (1) there is something special at a rotation angle of around 45° (i.e. the quadratic component predicted by the LCD model) and (2) there is a gradual cost in lower rotation angles (i.e. the linear component posited by the SERIOL model).

Table 3. Mean Response Times (in ms) and percent errors (in %) in each of the conditions in Experiment 3 (Semantic Categorisation Task).

		Rotation angle			
		22.5°	30°	37.5°	45°
Non-Animal	High Freq	588 (0.9)	583 (1.3)	590 (0.7)	606 (1.2)
	Low Freq	600 (1.4)	615 (1.1)	614 (1.5)	639 (2.0)
Frequency effect		12 (0.5)	32 (−0.2)	24 (0.8)	33 (0.8)
Animal		620 (10.0)	625 (9.1)	628 (9.3)	643 (8.6)

General Discussion

In the present study, we designed three experiments to test the predictions of the LCD and SERIOL models concerning the resilience of letter detectors to rotation at relatively moderate angles. The LCD model (Dehaene et al., 2005) assumes invariance up to around rotation angles around 40°–45° after which the resilience of letter detectors drops abruptly, whereas the SERIOL model (Whitney, 2002) postulates a gradual increase of word processing cost with rotation angle (at least until an abrupt shift at around 60°).

When using a relatively large range of rotation angles (0°, 22.5°, 45°, and 67.5°; i.e. a difference of 22.5° in each step), we found a linear cost and a quadratic cost in the word response times in lexical decision (Experiment 1) and semantic categorisation (Experiment 2). Relative to the canonical format (0°), the cost was minimal for the 22.5° words, substantial for the 45° words, and dramatically large for the 67.5° words (see Figure 2). The dramatic cost at a 67.5° angle was also accompanied by a greater word-frequency effect in the semantic categorisation task (Experiment 2) relative to the canonical format (65 vs. 26 ms, respectively). This increase in the word-frequency effect was much smaller for moderate angles (i.e. 28 and 38 ms at the 30° and 45° angles, respectively), and the pattern was similar (but weaker) in the lexical decision task (Experiment 1). This pattern suggests that, at a steep angle, like 67.5°, participants might have engaged in extra top-down processing to help access lexical-semantic information. Another indication of lexical involvement in the effects of letter rotation is that, in the lexical decision task (Experiment 1), we found that the effect of letter rotation was larger for pseudowords (0° vs. 22.5°: 29 ms; 22.5° vs. 45°: 100 ms; 45° vs. 67.5°: 266 ms) than for words (0° vs. 22.5°: 5 ms; 22.5° vs. 45°: 54 ms; 45° vs. 67.5°: 183 ms). To further examine the complexities of rotation angles at around 45°, we conducted a third experiment using rotation angles at or below that threshold (i.e. 22.5°, 30°, 37.5°, and 45°; a difference of 7.5° in each step) with a semantic categorisation task. Results showed both a gradual linear increase of the cost due to letter rotation and an extra bump for the 45°.

What are the implications of these findings for the LCD and SERIOL models? On the one hand, the LCD model can readily capture the abrupt cost in word recognition times when the letters are rotated at 45° relative to more moderate values (i.e. 22.5°, 30°, or 37.5°) and the dramatic increase at 67.5° angle. In the LCD model, when the capacity of the ventral pathway is surpassed (e.g. via visual degradation such as letter rotations above 40-45°), the cognitive system requires some extra top-down processes via the engagement of the dorsal parietal cortex to recognise written words (see Vinckier et al., 2006). However, this model cannot easily accommodate the gradual cost of rotation angles below 45° (i.e. the LCD model assumes an all-or-none edge at around 40-45°). On the other hand, the SERIOL model can easily capture the gradual cost of letter rotations at moderate angles (i.e. below 45°) and with the dramatic increase in word recognition times at the 67.5° angle (see Figure 2). However, it cannot easily capture the bump in the cost of letter rotations at around 45° (i.e. the model would have predicted a gradual increase until a bump at around 60-70° angle). Thus, one way to reconcile these models is, for the LCD model, to assume a gradual (not all-none) cost of letter rotation model and, for the SERIOL model, to assume the nuances of rotations at around 45°. Notably, the reduced effects of letter rotation for words when compared to pseudowords even for moderate angles suggests that words benefited from lexical feedback, thus helping to achieve a more stable representation even after moderate degraded conditions (see Woolnough et al., 2021, for evidence of feedback from lexical to orthographic processing in the ventral visual pathway using direct intracranial recordings).

The present data fit well with previous research across various paradigms. In a lexical decision experiment, Kim and Straková (2012) found that increasing letter-rotation led to monotonic increases in the P1 and N170 (i.e. ERPs that mark the beginning of word-form analysis) amplitudes up to 45°–67.5°. Notably, they found an effect of letter rotation relative to the canonical format for 22.5° words (i.e. well below 45°), and suggested that moderate deviation from preferred stimulus properties (<45°–67.5°) could recruit additional processing resources to cope with distorted stimuli. Likewise, during sentence reading, Blythe et al. (2019) found a reading cost in fixation durations when letters were rotated 30° relative to the canonical 0° format—this effect was dramatically larger when for 60° words. Similarly, in a parafoveal preview paradigm during sentence reading, Fernández-López et al. (2021) found that the benefit of parafoveal previews was sizeable at rotation angles of 15°. This parafoveal benefit decreased at 30°, even more so at 45°, and was absent at 60°.

Thus, considering the previous and present empirical evidence across a variety of paradigms on the processing of rotated letters, we propose that (i) even moderate letter rotations produce a (small) cost in word processing; (ii) this cost increases nonlinearly, while being manageable, at around 45°, and (iii) this cost increases dramatically around 60° or larger. In the latter scenario, to cope with the visual distortion caused by the rotation angle, individuals are likely to use more effortful processing of the stimuli through increased parietal activation (see Cohen et al., 2008; Whitney, 2010; see also Vergara-Martínez et al., 2021, for a similar reasoning for handwritten words).

The experiments with rotated letters used in the present paper explore the interaction between linguistic and spatial factors. These two types of process have garnered significant attention by scholars interested in gender-based differences. Mental rotation tasks with visual objects tend to yield gender differences in favour of males (e.g. Christie et al., 2013; Jansen & Heil, 2009; but see Rahe et al., 2021), whereas linguistic tasks tend to favour females (e.g. Heinzel et al., 2013; Kimura & Seal, 2003; Murre et al., 2013). We appreciate a suggestion by a Reviewer to explore if the effects of letter rotation are modulated by individual differences such as gender. Notably, these analyses are exploratory and post-hoc, as the theoretical models guiding the present research do not make any predictions on the modulating role of factors based on individual differences such as gender.

To examine the role of gender differences on letter rotation, we focused on the data of Experiment 1 (i.e. the experiment in which gender was approximately balanced). These analyses are provided in Appendix A (online supplementary material). In a nutshell, we found that while the basic findings were qualitatively the same regardless of gender, the effect of letter rotations of 45° or higher was stronger for male than for female participants (see Yang et al., 2022, for a processing advantage of females over males when processing mirrored words). This same pattern occurred for both word and nonword stimuli. Intriguingly, response times to the intact stimuli (both words and nonwords) were remarkably similar for male and female participants (see Table A1 in Appendix A, online supplementary material). We prefer to be cautious at interpreting these gender differences, as they might be related to reading exposure rather than gender because, in general, women read more than men. Another potential explanation stems from the fact that women show greater bilateralization in both language and spatial tasks than men (Van Dyke et al., 2009; Vogel et al., 2003). This might lead to an advantage in tasks that require simultaneous spatial and linguistic processing (see Yang et al., 2022). Further research is necessary to examine this timely issue.

To sum up, we conducted three experiments to shed light on the processing of letter rotation and discerning between the predictions of two neurally-inspired models of word recognition (LCD model, SERIOL model). We found that the cost elicited by rotation angle increases smoothly at angles below 45°, as proposed by the SERIOL model. The letter detectors reach a resilience limit at around 45° (consistent with the LCD model), and the cost becomes dramatic at steeper angles (e.g. 67.5°). We also found that lexical factors could partly outweigh the harmful effects of letter rotation (i.e. these effects were smaller for words than for pseudowords). We propose combining the assumptions from these models to build a more comprehensive explanation of how rotation angle, and more generally, visual distortion, hampers word recognition.

The stimuli, scripts, and data of the three experiments are available at: https://osf.io/fc3xz/?view_only=e3452260fa4d4b4398363c0d83a0696d.

Acknowledgments

This study was supported by the Spanish Ministry of Science and Innovation (grants PRE2018-083922, PSI2017-86210-P, and PID2020-116740GB-I00 [MCIN/ AEI/10.13039/ 501100011033]). We would like to thank Andrew Aschenbrenner and Melvin Yap for sharing their word and pseudoword stimuli with us.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Spanish Ministry of Science and Innovation: [Grant Number PID2020-116740GB-I00,PRE2018-083922,PSI2017-86210-P].

References

Aguasvivas, J., Carreiras, M., Brysbaert, M., Mandera, P., Keuleers, E., & Duñabeitia, J. A. (2020). How do spanish speakers read words? Insights from a crowdsourced lexical decision megastudy. *Behavior Research Methods*, *52*(5), 1867–1882. https://doi.org/10.3758/s13428-020-01357-9

Aschenbrenner, A. J., & Yap, M. J. (2019). The influence of relatedness proportion on the joint relationship among word frequency, stimulus quality, and semantic priming in the lexical decision task. *Quarterly Journal of Experimental Psychology*, *72*(10), 2452–2461. https://doi.org/10.1177/1747021819845317

Benyhe, A., & Csibri, P. (2021). Can rotated words be processed automatically? Evidence from rotated repetition priming. *Memory & Cognition*, *49*(6), 1163–1171. https://doi.org/10.3758/s13421-021-01147-4

Blythe, H. I., Juhasz, B. J., Tbaily, L. W., Rayner, K., & Liversedge, S. P. (2019). Reading sentences of words with rotated letters: An eye movement study. *Quarterly Journal of Experimental Psychology*, *72*(7), 1790–1804. https://doi.org/10.1177/1747021818810381

Brysbaert, M., & New, B. (2009). Moving beyond kučera and francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavior Research Methods*, *41*(4), 977–990. https://doi.org/10.3758/BRM.41.4.977

Brysbaert, M., & Stevens, M. (2018). Power analysis and effect size in mixed effects models: A tutorial. *Journal of Cognition*, *1*, 9. https://doi.org/10.5334/joc.10

Bürkner, P. (2021). Bayesian item Response Modeling in R with brms and Stan. *Journal of Statistical Software*, *100*(5), 1–54. https://doi.org/10.18637/jss.v100.i05

Christie, G. J., Cook, C. M., Ward, B. J., Tata, M. S., Sutherland, J., Sutherland, R. J., & Saucier, D. M. (2013). Mental rotational ability is correlated with spatial but not verbal working memory performance and P300 amplitude in males. *PLOS ONE*, *8*(2), e57390. https://doi.org/10.1371/journal.pone.0057390

Cohen, L., Dehaene, S., Vinckier, F., Jobert, A., & Montavont, A. (2008). Reading normal and degraded words: Contribution of the dorsal and ventral visual pathways. *Neuroimage*, *40*(1), 353–366. https://doi.org/10.1016/j.neuroimage.2007.11.036

Dehaene, S., & Cohen, L. (2007). Response to carreiras et al: The role of visual similarity, feedforward, feedback and lateral pathways in reading. *Trends in Cognitive Sciences*, *11*(11), 456–457. https://doi.org/10.1016/j.tics.2007.08.009

Dehaene, S., Cohen, L., Sigman, M., & Vinckier, F. (2005). The neural code for written words: A proposal. *Trends in Cognitive Sciences*, *9*(7), 335–341. https://doi.org/10.1016/j.tics.2005.05.004

Fernández-López, M., Mirault, J., Grainger, J., & Perea, M. (2021). How resilient is reading to letter rotations? A parafoveal preview investigation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *47*(12), 2029–2042. https://doi.org/10.1037/xlm0000999

Gomez, P., & Perea, M. (2014). Decomposing encoding and decisional components in visual-word recognition: A diffusion model analysis. *Quarterly Journal of Experimental Psychology*, *67*(12), 2455–2466. https://doi.org/10.1080/17470218.2014.937447

Grainger, J. (2018). Orthographic processing: A 'mid-level' vision of reading: The 44th Sir frederic bartlett lecture. *Quarterly Journal of Experimental Psychology*, *71*(2), 335–359. https://doi.org/10.1080/17470218.2017.1314515

Hannagan, T., Ktori, M., Chanceaux, M., & Grainger, J. (2012). Deciphering CAPTCHAs: What a turing test reveals about human cognition. *PLOS ONE*, *7*(3), e32121. https://doi.org/10.1371/journal.pone.0032121

Heinzel, S., Metzger, F. G., Ehlis, A. C., Korell, R., Alboji, A., Haeussinger, F. B., … & TREND Study Consortium. (2013). Aging-related cortical reorganization of verbal fluency processing: A functional near-infrared spectroscopy study. *Neurobiology of Aging*, *34*(2), 439–450. https://doi.org/10.1016/j.neurobiolaging.2012.05.021

Jansen, P., & Heil, M. (2009). Gender differences in mental rotation across adulthood. *Experimental Aging Research*, *36*(1), 94–104. https://doi.org/10.1080/03610730903422762

Keuleers, E., & Brysbaert, M. (2010). Wuggy: A multilingual pseudoword generator. *Behavior Research Methods*, *42*(3), 627–633. https://doi.org/10.3758/BRM.42.3.627

Kim, A. E., & Straková, J. (2012). Concurrent effects of lexical status and letter-rotation during early stage visual word recognition: Evidence from ERPs. *Brain Research*, *1468*, 52–62. https://doi.org/10.1016/j.brainres.2012.04.008

Kimura, D., & Seal, B. N. (2003). Sex differences in recall of real or nonsense words. *Psychological Reports*, *93*(1), 263–264. https://doi.org/10.2466/pr0.2003.93.1.263

Lerma-Usabiaga, G., Carreiras, M., & Paz-Alonso, P. M. (2018). Converging evidence for functional and structural segregation within the left ventral occipitotemporal cortex in reading. *Proceedings of the National Academy of Sciences*, *115*(42), E9981–E9990. https://doi.org/10.1073/pnas.1803003115

Mayall, K., & Humphreys, G. W. (1996). Case mixing and the task-sensitive disruption of lexical processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*(2), 278–294. https://doi.org/10.1037/0278-7393.22.2.278

Murre, J. M., Janssen, S. M., Rouw, R., & Meeter, M. (2013). The rise and fall of immediate and delayed memory for verbal and visuospatial information from late childhood to late adulthood. *Acta Psychologica*, *142*(1), 96–107. https://doi.org/10.1016/j.actpsy.2012.10.005

Peirce, J. W., & Macaskill, M. R. (2018). *Building experiments in PsychoPy*. Sage.

Perea, M., Fernández-López, M., & Marcet, A. (2020). Does CaSeMiXinG disrupt the access to lexico-semantic information? *Psychological Research*. *84*(4), 981–989. https://doi.org/10.1007/s00426-018-1111-7

Perea, M., Labusch, M., & Marcet, A. (2022). How are words with diacritical vowels represented in the mental lexicon? Evidence from spanish and German. *Language, Cognition and Neuroscience*, *37*, 457–468. https://doi.org/10.1080/23273798.2021.1985536

Perea, M., Marcet, A., & Fernández-López, M. (2018). Does letter rotation slow down orthographic processing in word recognition? *Psychonomic Bulletin & Review*, *25*(6), 2295–2300. https://doi.org/10.3758/s13423-017-1428-z

R Core Team (2021). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Rahe, M., Ruthsatz, V., & Quaiser-Pohl, C. (2021). Influence of the stimulus material on gender differences in a mental-rotation test. *Psychological Research*, *85*(8), 2892–2899. https://doi.org/10.1007/s00426-020-01450-w

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology*, *7*, 65–81. https://doi.org/10.1016/0010-0285(75)90005-5

Van Dyke, S. A., Zuverza, V., Hill, L. A., Miller, J. B., Rapport, L. J., & Whitman, R. D. (2009). Gender differences in lateralized semantic priming. *Developmental Neuropsychology*, *34*(4), 381–392. https://doi.org/10.1080/87565640902964516

Vergara-Martínez, M., Gomez, P., Jiménez, M., & Perea, M. (2015). Lexical enhancement during prime-target integration: ERP evidence from matched-case identity priming. *Cognitive, Affective, & Behavioral Neuroscience*, *15*(2), 492–504. https://doi.org/10.3758/s13415-014-0330-7

Vergara-Martínez, M., Gutierrez-Sigut, E., Perea, M., Gil-López, C., & Carreiras, M. (2021). The time course of processing handwritten words: An ERP investigation. *Neuropsychologia*, *159*, 107924. https://doi.org/10.1016/j.neuropsychologia.2021.107924

Vinckier, F., Naccache, L., Papeix, C., Forget, J., Hahn-Barma, V., Dehaene, S., & Cohen, L. (2006). "What" and "where" in word reading: Ventral coding of written words revealed by parietal atrophy. *Journal of Cognitive Neuroscience*, *18*(12), 1998–2012. https://doi.org/10.1162/jocn.2006.18.12.1998

Vogel, J. J., Bowers, C. A., & Vogel, D. S. (2003). Cerebral lateralization of spatial abilities: A meta-analysis. *Brain and Cognition*, *52*(2), 197–204. https://doi.org/10.1016/S0278-2626(03)00056-3

Whitney, C. (2001). How the brain encodes the order of letters in a printed word: The SERIOL model and selective literature review. *Psychonomic Bulletin & Review*, *8*(2), 221–243. https://doi.org/10.3758/BF03196158

Whitney, C. (2002). An explanation of the length effect for rotated words. *Cognitive Systems Research*, *3*(1), 113–119. https://doi.org/10.1016/S1389-0417(01)00050-X

Whitney, C. (2010). *One mechanism or two: A commentary on reading normal and degraded words*. Unpublished manuscript. http://www.cs.umd.edu/~shankar/cwhitney/selected-publications.html

Woolnough, O., Donos, C., Rollo, P. S., Forseth, K. J., Lakretz, Y., Crone, N. E., … Tandon, N. (2021). Spatiotemporal dynamics of orthographic and lexical processing in the ventral visual pathway. *Nature Human Behaviour*, *5*(3), 389–398. https://doi.org/10.1038/s41562-020-00982-w

Yang, H., & Lupker, S. J. (2019). Does letter rotation decrease transposed letter priming effects? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *45*(12), 2309–2318. https://doi.org/10.1037/xlm0000697

Yang, H., Reid, J. N., Kong, P., & Chen, J. (2022). Mirror generalization during early word recognition. *Journal of Psycholinguistic Research*, *51*, 543–561. https://doi.org/10.1007/s10936-022-09857-9