Acta Psychologica 177 (2017) 30–35

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Where is the locus of the lowercase advantage during sentence reading?☆

Manuel Perea[a,*], Eva Rosa[b], Ana Marcet[a]

[a] Universitat de València, Valencia, Spain
[b] Universidad Católica de Valencia, Valencia, Spain

ARTICLE INFO

Keywords:
Eye movements
Reading
Word-frequency
Letter case

ABSTRACT

While most models of visual word identification and reading posit that a word's visual codes are rapidly transformed onto case-invariant representations (i.e., table and TABLE would equally activate the word unit corresponding to "table"), a number of experiments have shown a lowercase advantage in various word identification and reading tasks. In the present experiment, we examined the locus of this lowercase advantage by comparing the pattern of eye movements when reading sentences in lowercase vs. uppercase. Each sentence contained a target word that was high or low in word-frequency. Overall, results showed faster reading times for lowercase than for uppercase sentences. More important, while the word-frequency effect was sizeable in the first-fixation durations on the target word, the lowercase advantage only arose in the gaze durations (i.e., the sum of durations of first-pass fixations on the target word, including refixations). Furthermore, we found an effect of word-frequency, but not of letter case, in the first-fixation duration on target words with multiple first-pass fixations. Taken together, these findings suggest that the lowercase advantage reflects operations that do not occur in the initial contact with the lexical entries.

1. Introduction

The examination of the effects of typographical factors during reading (e.g., font [table vs. table], letter spacing [table vs. t a b l e], letter size [table vs. table], presence/absence of serifs [table vs. table], printed/handwritten format [table vs. table], letter case [table vs. TABLE], among others) has typically been disregarded in the literature on eye movements and reading. As Slattery (2016) pointed out, this was probably due to the implicit assumption that typographical factors do not modulate the main effects of interest—lexical or linguistic (e.g., see McClelland & Rumelhart, 1981). However, a number of recent experiments have shown that typographical factors may interact with lexical/linguistic processes during sentence reading (e.g., inter-letter/inter-word spacing; Slattery, Yates, & Angele, 2016; font: Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Rayner, Slattery, & Bélanger, 2010; Slattery & Rayner, 2010; printed vs. handwritten format; Perea, Marcet, Uixera, & Vergara-Martínez, 2017).

In the present study, we examined the time course of the effect of letter case (lowercase vs. uppercase; e.g., table vs. TABLE) during sentence reading. Current computational models of eye-movement control in reading (e.g., E-Z Reader model, Reichle, Pollatsek, Fisher, & Rayner, 1998; SWIFT model, Engbert, Nuthmann, Richter, & Kliegl, 2005) as well as contemporary models of visual word recognition (e.g., spatial coding model, Davis, 2010) remain agnostic as to how and when the visual signal from words is mapped onto case-invariant orthographic representations. Indeed, many models of visual word recognition employ the Rumelhart and Siple (1974) font, which is confined to uppercase letters. Nonetheless, leading neural (non-implemented) accounts of letter/word processing assume that the visual information from the words' constituent letters is rapidly transformed onto case-invariant orthographic representations (see Dehaene, Cohen, Sigman, & Vinckier, 2005; Grainger, Rey, & Dufau, 2008). Thus, these accounts would predict that table and TABLE activate the same lexical/semantic units at approximately the same time. Support for this view comes from an influential eye-movement experiment conducted by McConkie and Zola (1979; see also Rayner, McConkie, & Zola, 1980). In the McConkie and Zola (1979) experiment, participants read sentences presented in alternating case. When the saccade reached the following word, the text was presented in the reverse case (e.g., the target word tAbLe would be printed TaBlE when in the parafovea) or not (i.e., tAbLe would always be printed as tAbLe). Importantly, fixation durations were similar in the two conditions and, furthermore, participants did not notice the display changes, thus suggesting that the codes across saccades were orthographic (i.e., case-invariant) rather than visual.

☆ The research reported in this article has been partially supported by Grants PSI2014-53444-P and BES-2015-07414 from the Spanish Ministry of Economy and Competitiveness. We thank Denis Drieghe and Eyal Reingold for helpful and constructive comments on an earlier version of this paper.

* Corresponding author at: Departamento de Metodología, Av. Blasco Ibáñez, 21, 46010 Valencia, Spain.
E-mail address: mperea@uv.es (M. Perea).

http://dx.doi.org/10.1016/j.actpsy.2017.04.007
Received 19 October 2016; Received in revised form 3 April 2017; Accepted 18 April 2017

Likewise, Reingold, Yang and Rayner (2010) manipulated word-frequency and case alternation (i.e., an extreme manipulation of letter case; e.g., tAbLe vs. table) in a sentence reading experiment and found that while the first-fixation duration on the target word was longer for alternating-case than for lowercase words, the effect of case alternation vanished when considering the initial duration of multiple fixations—-note that this measure was sensitive to word-frequency. Reingold et al. (2010) concluded that the "fast acting lexical process is sensitive to word frequency and apparently largely insensitive to case alternation" (p. 1680)—that is, the effects of case alternation would occur on later attentional, lexical and/or post-lexical processes. Converging evidence of the rapid mapping from visual codes onto case-invariant representations has also been obtained with the masked priming paradigm (i.e., a technique designed to examine the early processes underlying word recognition). Jacobs, Grainger and Ferrand (1995) found remarkably similar lexical decision times for cross-case identity prime-target pairs (e.g., table-TABLE) and for same-case identity prime-target pairs (e.g., TABLE-TABLE) (see also Bowers, Vigliocco, & Haan, 1998; Perea, Jiménez & Gómez, 2014, for additional evidence). Similarly, Forster (1998) and Perea, Vergara-Martínez, and Gomez (2015) found that alternating-case identity primes were as effective as lowercase identity primes with the masked priming technique (i.e., tAbLe-TABLE and table-TABLE produced equivalent lexical decision times; see also Brysbaert, Speybroeck, & Vanderelst, 2009, for an analogous effect with acronyms). Taken together, these findings strongly suggest that letter case does not play a major role at the earliest phases of lexical processing.

Importantly, a number of experiments have examined whether letter case (lowercase vs. uppercase) modulates the response times in single-presentation word identification tasks and whether this effect interacts with word-frequency (i.e., an index of word identification). As can be seen in Table 1, the vast majority of experiments showed faster word identification times to lowercase than to uppercase words (i.e., a lowercase advantage), but whether or not letter case and word-frequency interact is unclear. Additionally, a lowercase advantage has also been reported when silently reading continuous text. In an influential study, Tinker and Paterson (1928) compared texts presented in lowercase vs. uppercase and found a 13.4% advantage in reading speed in favor of the text presented in lowercase (see also Tinker, 1955, for a similar finding). Tinker and Paterson concluded: "Text printed in all capitals is less legible than material in lower case letters and slows down speed of reading to a very marked degree" (p. 368)—a confound in this experiment, however, was that the uppercase text covered 35% more horizontal space than the lowercase text.

Table 1
Magnitude of the lowercase advantage (i.e., response times [RT] uppercase-lowercase) in word recognition experiments that compared letter case (lowercase vs. uppercase) and word-frequency (low-frequency vs. high-frequency).

	Lowercase advantage ($RT_{uppercase–lowercase}$)	
	High-frequency words	Low-frequency words
Paap et al. (1984, Exp. 3)		
Lexical decision	16	13
Mayall and Humphreys (1996, Exp. 1)		
Lexical decision	4	38
Naming	7	15
Semantic categorization (Living vs. nonliving)	− 18	40
Mayall and Humphreys (1996, Exp. 2)		
Semantic categorization (Living vs nonliving)	52	26
Human vs. nonhuman)	28	21
(Indoor vs. outdoor)	48	27
Mayall and Humphreys (1996, Exp. 3)		
Naming	15	21.5
Semantic categorization (Living vs. nonliving)	24.5	7
Mayall and Humphreys (1996, Exp. 4)		
Lexical decision	10.5	24
Perea and Rosa (2002, Exp. 2)		
Lexical decision	3.5	28

While the above-cited experiments showed a lowercase advantage in word identification times and in reading times, the locus of this effect remains uncertain. One possibility is that lowercase letters could be psychophysically more distinctive than uppercase letters, and hence, one would expect an early effect of letter case; however, Paap, Newsome, and Noel (1984) presented evidence against this interpretation. A second possibility is that ascending/descending segments of lowercase consonants (e.g., elephant) may help encoding the skeletal consonant-vowel orthographic code (see Grainger & Dufau, 2012), thus producing a processing advantage for lowercase words. However, in a lexical decision experiment with adult skilled readers, Lavidor (2011) found similar word identification times for "flat" words (e.g., camera) and for "non-flat" words (e.g., bishop). A third option is that while the initial contact with the lexical entries is not affected by letter case, later in lexical processing, words printed in their usual case (i.e., lowercase) may enjoy an advantage when the word's abstract units are mapped back onto the visual input (see Besner, 1983, for a similar reasoning to explain the locus of case alternation)—note that this interpretation would be consistent with the presence of faster word recognition times of brand names when printed in their prototypical case (e.g., adidas faster than ADIDAS and IKEA faster than ikea; see Gontijo & Zhang, 2007; Perea, Jiménez, Talero, & López-Cañada, 2015).

Clearly, a sentence reading experiment in which the participant's eye movements are registered offers at least two advantages over word identification experiments: 1) the scenario is more ecological (i.e., reading for comprehension); and 2) it may be used to gather early/late eye-movement measures on a target word embedded in the sentences, thus providing valuable information on the time course of the effect-s—word recognition tasks only provide a "response time" at the end of processing.

The research question of the current study is when letter case (lowercase vs. uppercase) affects eye-movement control during sentence reading. We compared sentences printed with lowercase vs. uppercase letters (e.g., "`If a lion could talk, we could not understand him`" vs. "`IF A LION COULD TALK, WE COULD NOT UNDERSTAND HIM`") while the participants' eye movements were registered—note that the above-cited reading studies (e.g., Tinker, 1955; Tinker & Paterson, 1928) did not register the participants' eye movements. Moreover, unlike Tinker and Paterson (1928; Tinker, 1995), we used a monospaced font (`Courier New`) so that each sentence occupied the same horizontal space regardless of letter case. To track the time course of letter case in early and late eye-movement measures and its relationship with word-frequency (i.e., an index of lexical processing), a target word of high vs. low frequency was included in each sentence (e.g., see Rayner, Fischer, & Pollatsek, 1998; Reingold et al., 2011, among others, for a similar approach).

The predictions of the experiment will be presented in the context of a leading model of eye-movement control during reading, the E-Z Reader model (Reichle et al., 1998; see also Reichle & Sheridan, 2015, for a recent overview of the model). (Note that other models [e.g., the SWIFT model, Engbert et al., 2005] would produce similar predictions.) This model assumes two stages of lexical processing. First, there is an initial familiarity check (L1 stage) that starts when allocation of attention is located on a target word. The L1 stage is completed when the word is about to be identified and then a saccadic movement is programmed to the following word—note that the L1 stage of word n + 1 may start when the eyes are still on word n (or even earlier sometimes). If the L1 stage were ended after the labile component of saccade programming has been completed, the saccade would be programmed to the same word, thus producing a refixation (see Reichle, Rayner, & Pollatsek, 1999, for discussion). There is a second stage (L2) responsible for the identification of the word ("completion of lexical access"). When this stage is completed, attention shifts to the following word so that the L1 stage would start on the word n + 1. Finally, failure to integrate the lexical/linguistic information may produce regressions to earlier words in the sentence (Reichle, Warren, & McConnell, 2009). The E-Z Reader model can readily accommodate the presence of word-frequency effects in early eye movement measures, as the L1 stage is modulated by word-frequency. Of note, when parafoveal information is available, the word-frequency effect arises in the first-fixation duration on the target word because high-frequency words may have been partially preprocessed in the parafovea—when there is no parafoveal information available, first-fixation durations are similar for high- and low-frequency words (Inhoff & Rayner, 1986). Regardless of the acquired parafoveal information, the word-frequency effect occurs in gaze durations (i.e., the sum of first-pass fixations, including refixations) because low-frequency words are refixated more often than high-frequency words. This can be readily explained in the *E*-Z Reader model: high-frequency words are more likely to complete the L1 stage during the labile component of saccadic programming (Reichle et al., 1999; see also Sheridan & Reichle, 2015, Simulation 2). In addition, the word-frequency effect may also affect the completion of the lexical access (L2 stage), and this may lead to slower fixations in the word n + 1 when the target word is of low frequency (i.e., spillover effects). Finally, failure to integrate low-frequency words in the syntactic/semantic context may produce regressions back to the target word and an increase of the word-frequency effect in total time (i.e., the sum of all fixation durations, including regressions).

Where is the locus of the lowercase advantage during sentence reading? There are three non-exclusive options (see Sheridan & Reingold, 2013, for an analysis of the lexical-processing stages in the E-Z Reader model). The first option is that the reading cost arises in the initial access to the lexical entries in the parafovea: this would produce faster first-fixation durations for lowercase than for uppercase target words. This outcome would pose some problems for those accounts that assume a rapid mapping of visual codes onto case-invariant orthographic codes in lexical processing (e.g., Dehaene et al., 2005; Grainger et al., 2008). Note, however, that previous research suggests that the initial contact with the lexical entries is not modulated by letter case (e.g., Forster, 1998; Jacobs, Grainger, & Ferrand, 1995; McConkie & Zola, 1979; Perea et al., 2015; Reingold et al., 2010) so that one would expect a word-frequency effect of similar magnitude for lowercase and uppercase words in the first-pass fixation on the target word, together with a null or negligible effect of letter case. The second option is that the familiarity checking is completed more rapidly for lowercase words than for uppercase words. As rapid completion of this stage allows programming the saccade to the following word (i.e., during the labile stage of saccade programming), lowercase words would be less frequently refixated than uppercase words.[1] As a result, a lowercase advantage would arise in the gaze durations on the target word (i.e., shorter gaze durations for lowercase than for uppercase words). A third possibility is that the lowercase advantage occurs late in processing, either during the completion of lexical access (i.e., L2 stage in the E-Z Reader model) or via at a post-lexical integration mechanism (e.g., if uppercase words were more difficult to integrate in the context than lowercase words). If this were so, the effect would occur in late eye movement measures such as the percentage of regressions back to the target word (i.e., more regressions for uppercase than for lowercase words), and in the total time on the target word (i.e., the sum of all fixations, including regressive saccades).

Finally, we acknowledge that the predictions regarding the interaction between word-frequency and letter case are not straightforward. As shown in Table 1, several word recognition experiments reported greater word-frequency effects for uppercase than for lowercase words, but the overall evidence was not conclusive. Furthermore, two factors may affect the same stage in the E-Z Reader model (e.g., word-frequency and predictability affect the L1 stage) and show additive effects—indeed, word-frequency and predictability show a recursive additive pattern in the literature (see Staub, 2015). For that reason, the critical issue in the present experiment is not the additivity/interaction of the effects of letter case and word-frequency, but rather the comparison of the time course of the two effects. Specifically, if word-frequency (i.e., an index of lexical processing), but not letter case, influences very early eye-movement measures (i.e., first-fixation duration on the target word), this would demonstrate that the effect of letter case reflects operations that occur relatively late in lexical processing (see Inhoff & Rayner, 1986, for a similar reasoning). As in the Reingold et al. (2010) experiment, we examined the duration of the initial fixation on target words with multiple fixations. The rationale is the following: if only word-frequency exerts an effect on this dependent variable, this would mean that letter case does not affect the first contact with the lexical units.

2. Method

2.1. Participants

Twenty undergraduate students from the University of Valencia, all of them native speakers of Spanish with normal vision, participated in the experiment in exchange of a small gift. None of them reported having any speech/reading problems.

2.2. Apparatus

To register the individuals' eye movements, we employed a video-based eye-tracking device with a 500 Hz sample rate (Eyelink II, SR Research Ltd., Canada). The average gaze position error was < 0.5° with a 3 ms delay. A 22-inch CRT ViewSonic Professional series P225f monitor was used to present the sentences.

2.3. Materials

We employed 120 sentence frames taken from the Perea and Acha (2009) experiment. Each sentence frame contained a low- or high-frequency target word with the same number of letters, such as "Marco ha trabajado como joyero/médico durante toda su vida" [Marco has worked as a jeweler/doctor throughout his life] and "Mi madre preguntó al joyero/médico si aquel diploma era original" [My mother asked the jeweler/doctor if that certificate was original] [joyero {jeweler} is a low-frequency word and médico{doctor} is a high-frequency word]. High-frequency target words had an average frequency of 87.3 per million (range: 23–253) and a mean number of letters of 7.3 (range: 6–9), whereas low-frequency target words had a mean frequency of 4.5 per million (range: 0.2–20) and a mean number of letters of 7.3 (range: 6–9) in the B-Pal Spanish database (Davis & Perea, 2005). To avoid the repetition of target words and sentence frames, we created two counterbalanced sets of 120 sentences. For instance, half of the participant read the word "joyero" in the sentence "Marco ha trabajado como joyero durante toda su vida", whereas the other half read "joyero" in the sentence "Mi madre

[1] In original version of the E-Z Reader model (Reichle et al., 1999), refixations were explained by means of corrective saccades when the initial landing site was far from the center of the word. However, simulations on the model failed to capture that low-frequency words are refixated more frequently than high-frequency words (Sheridan & Reichle, 2015). Sheridan and Reichle (2015) included additional assumptions that captured the effect, but they acknowledged that "there may be multiple mechanisms that actually produce refixations in human readers (…) that are not captured by the model's relatively simple assumptions" (p. 26) (see also White, 2008, for a similar conclusion when examining the higher refixation rates for orthographically unfamiliar words than for orthographically familiar words).

preguntó al joyero si aquel diploma era original". Each participant received 60 sentences in lowercase and 60 sentences in uppercase. The sentences were easy to comprehend and the target words were not predictable (see Perea & Acha, 2009, for details). The sentences were presented in a monospaced font, 14-pt Courier New (i.e., each sentence occupied the same horizontal space in lowercase and uppercase).

2.4. Procedure

Testing was individual. Participants were seated approximately 60 cm from the computer monitor in a dimly lit room. A chinrest was used to reduce head motion. Participants were instructed to read individual sentences for comprehension. Before starting the experiment, the eye-tracker was calibrated using a 9-dot matrix and we presented 8 practice sentences. The scheme of a given trial was the following: 1) there was a fixation point (a black square) on the left side of the screen, coinciding with the location of the first letter of each sentence; 2) once the participant looked at the square, the sentence was presented until the participant read it and pressed a button on a gamepad; and 3) participants were presented with a yes/no comprehension question to verify that they were reading for comprehension—this occurred on 20% of the sentences. Calibration was checked before each trial and the eye-movement device was recalibrated when necessary. Each participant received the sentences in a different random order.

2.5. Data analyses

We analyzed global and local eye-movement measures. For the global measures, the fixed factor was letter case (lowercase, uppercase) and the dependent variables were total reading time (in ms) and number of fixations. For the local measures on the target word, the fixed factors were letter case (lowercase, uppercase) and word-frequency (low, high), and the dependent measures were: first-fixation duration (the duration of the first-pass fixation on the target word), single fixation duration (the duration of the first-pass fixation on the target word when it is only fixated once), gaze duration (the sum of the durations of the first-pass fixations on the target word before leaving it), total time (the sum of all fixation durations on the target word, including regressions), the probability of first-pass refixations on the target word, and the probability of regressions back to the target word. All fixations shorter than 80 ms that were within one letter from the following/previous fixation were combined into that fixation. Furthermore, to reduce the influence of outliers on fixation durations, individual fixations beyond the 80–800 ms cutoff were excluded from the fixation duration analyses. Finally, those fixation durations beyond 3 standard deviations from the participant's grand mean were also excluded from the analyses.

3. Results

Accuracy rates for the comprehension questions were above 92% (range: 83.3–100%). The averages of the local measures are displayed in Table 2. To examine the effects of word-frequency (high, low) and letter case (lowercase, uppercase) on the first-fixation duration, gaze durations, and total time, we employed linear mixed effects models using the R package (R Core Team, 2016)—each fixed factor was coded as -0.5 and 0.5. Fixation durations were log transformed, so that the resulting data would be closer to the Gaussian distribution. When converged, we employed the maximal random-effect structure model; when not, we reduced the random structure until the model successfully converged. Significance (p) values were obtained using the lmerTest package (Kuznetsova, Brockhoff & Christensen, 2016). Binomial data (i.e., probability of refixations; probability of regressions back to the target word) were modeled similarly except that we employed generalized linear mixed models (glmer) in R. We also examined two global dependent variables (overall reading time; number of fixations) by using letter case as a fixed factor with the maximal random-effect structure model. Unsurprisingly, overall reading times were slower for uppercase sentences than for lowercase sentences (2052 vs. 2147 ms, respectively), $\beta = 0.047$, $t = 3.74$, $p = 0.001$. In addition, the number of fixations was slightly smaller for lowercase than for uppercase sentences (9.04 vs. 9.36, respectively), $\beta = 0.32$, $t = 2.44$, $p = 0.024$.

3.1. First-fixation durations

First-fixation durations on the target word were, on average, 15.5 ms shorter for high- than for low-frequency words, $\beta = 0.051$, $t = 3.08$, $p = 0.004$. There was a small 5.5 ms advantage of lowercase over uppercase words, but it was not significant, $\beta = 0.020$, $t = 1.46$, $p = 0.15$. There were no trends of an interaction between the two factors, $t < 0.22$.

3.2. Single fixation durations

Single fixation durations on the target word were, on average, 18 ms shorter for high- than for low-frequency words, $\beta = 0.080$, $t = 3.82$, $p < 0.001$. The 9 ms advantage of lowercase over uppercase words was significant, $\beta = 0.044$, $t = 3.00$, $p = 0.004$. There were no trends of an interaction between the two factors, $t < 0.78$. Similarly to Reingold, Yang, and Rayner (2010), we also examined the duration of the first fixations on the target words with multiple first-pass fixations. This analysis showed a 23-ms effect of word-frequency (215 vs. 238 ms for high- and low-frequency words, respectively), $\beta = 0.070$, $t = 2.48$, $p = 0.02$, whereas the 6-ms difference between lowercase and uppercase words (223 vs. 229 ms, respectively) did not approach significance, $\beta = 0.017$, $t < 1$—there were no signs of an interaction between the two factors, $t < 1$.

3.3. Gaze durations

Gaze durations on the target word were, on average, 54 ms shorter for high- than for low-frequency words, $\beta = 0.12$, $t = 3.84$, $p < 0.001$, and 31 ms shorter for lowercase than for uppercase words, $\beta = 0.08$,

Table 2
Averages of local measures for each experimental condition: first fixation duration (in ms), single fixation (in ms), gaze duration (in ms), total time (in ms), probability of refixating the target word, and probability of regressions back to the target word.

	First-fixation duration		Single fixation duration		Gaze duration		Total time		Probability of first-pass refixations on target word		Probability of regressions back to target word	
	HF	LF	HF	LF	HF	LF	HF	LF	HF	LF	HF	LF
Lowercase	239	254	254	269	301	347	356	413	0.27	0.35	0.101	0.118
Uppercase	244	260	260	281	324	386	385	458	0.34	0.40	0.113	0.143

Note: HF refers to high-frequency words and LF refers to low-frequency words.

$t = 4.23$, $p < 0.001$. Again, there were no trends of an interaction between the two factors, $t < 0.73$.

3.4. Probability of first-pass refixations

Low-frequency words were refixated more often than high-frequency words, $\beta = 0.28$, $t = 1.96$, $p = 0.050$, and uppercase words were refixated more often than lowercase words, $\beta = 0.36$, $t = 3.75$, $p < 0.001$. The interaction between the two factors did not approach significance, $t < 0.84$.

3.5. Total time

Total times on the target word were, on average, 65 ms shorter for high- than for low-frequency words, $\beta = 0.15$, $t = 3.99$, $p < 0.001$, and 37 ms shorter for lowercase than for uppercase words, $\beta = 0.08$, $t = 3.56$, $p < 0.001$. The interaction between the two factors was not significant, $t = 1.34$, $p = 0.18$.

3.6. Probability of regressions back to the target words

None of the effects was significant (all $ps > 0.12$).

4. General discussion

The main goal of the present eye-movement experiment was to examine the locus of the lowercase advantage during sentence reading. Unsurprisingly, at the global level, we found longer reading times for the sentences written in uppercase than for the sentences written in lowercase, thus replicating earlier research by Tinker (1955); Tinker & Paterson, 1928). The reading cost was small (around 4.6%) but significant. Tinker (1955; Tinker & Paterson, 1928) found a larger reading cost (around 10–14%) but their fonts were not monospaced—-note that in their experiments, uppercase text covered more horizontal space than lowercase text so any comparisons between the two conditions could be due to letter case or to differences in horizontal space (see Perea, Giner, Marcet, & Gomez, 2016, for evidence of a reading cost for text with extra inter-letter spacing). Nonetheless, the key issue at stake here was the examination of the time course of the lowercase advantage during sentence reading and its relation with an index of lexical processing, namely, the word-frequency effect.

Let's consider firstly the time course of the effect of word-frequency. In the first-fixation durations on the target word (i.e., an index of early lexical processing), we found a significant 15.5 ms word-frequency effect that increased to 54 ms in the gaze durations. This is the typical pattern of word-frequency effects and it is fully consistent with E-Z Reader model and other models of eye-movement control during reading. With respect to the time course of the effect of letter case, we found a nonsignificant 5.5 ms lowercase advantage in the first-fixation durations on the target word. The same pattern occurred when we measured the first-fixation duration on target words with multiple first-pass fixations: we found a significant 23-ms word-frequency effect accompanied by a small, nonsignificant lowercase advantage (see Reingold et al., 2010, for a similar finding with alternating case words). Taken together, these findings suggest that the initial lexical processing of the target word in the parafoveal/fovea is, to a large degree, insensitive to letter case. Thus, the effect of word-frequency arises earlier in lexical processing than the effect of letter case. This pattern of data is consistent with those models of visual word recognition that propose that visual codes are quickly mapped onto case-invariant orthographic units (Dehaene et al., 2005; Grainger et al., 2008).

Given that the lowercase advantage was negligible at the very early stages of lexical processing, where is its locus? We found a small, but significant 9 ms lowercase advantage when the target word was only fixated once. More important, we found a sizeable 31-ms lowercase advantage in the gaze durations on the target words, as words in uppercase were more likely to be refixated than the words in lowercase (see Table 2).[2] Importantly, the lowercase advantage did not increase when considering a late measure of eye movements in reading such as the total time on the target word (i.e., a 35-ms lowercase advantage). Indeed, there were no signs of an effect of letter case in the percentage of regressions back to the target word. That is, uppercase words do not require re-inspection more frequently than lowercase words (i.e., the lowercase advantage does not arise at a syntactic/semantic integration level). Finally, the lowercase advantage was approximately similar in magnitude for high- and low-frequency words in all eye movement measures.

Before examining why uppercase words may produce higher refixation rates than lowercase words, it may be relevant to compare the present pattern of data with those experiments that manipulated the difficulty of the font during sentence reading. For instance, Slattery and Rayner (2010) found, together with an effect of word-frequency, an effect of font (Times faster than Harrington and Script MT [two unfamiliar and difficult-to-process fonts]) of around 20 ms in the first-fixation duration, which increased to 40–48 ms in gaze duration (see also Rayner et al., 2006). Similarly, Perea et al. (2017) found, together with a word frequency effect, a 19 ms advantage of printed words over easy handwritten words in the first-fixation duration, which increased to 79 ms in gaze duration. That is, difficult-to-process fonts/formats hindered the initial contact with the lexical entries. As a result, the effect of font/format occurred in the first-fixation durations to the target words. This is a different scenario from letter case, where the both lowercase and uppercase words [e.g., table vs. TABLE]) are easily legible and the initial access to the lexical entries does not seem to be affected by this factor (see also Perea et al., 2015; Reingold et al., 2010, for similar claims).

In the present experiment, the bulk of the lowercase advantage occurred because uppercase words were refixated more often than lowercase words—note that the lowercase advantage also occurred, but to a small degree, in the fixation durations of those target words that were only fixated once. One potential explanation is that the initial familiarity check (i.e., the stage that which initiates a forward saccade) takes into account the match between the abstract lexical representations and the visual input. As the sense of “familiarity” would be higher for those items that are presented in the usual case, the signaling that lexical access is imminent would be more likely to occur during the labile component of saccade programming for lowercase than for uppercase words, thus producing fewer refixations. Indeed, previous research has shown that factors other than word-frequency may affect the probability of refixation (e.g., morphemic composition: Hyönä & Pollatsek, 1998; orthographic familiarity: White, 2008). As Reichle, Tokowicz, Liu, and Perfetti (2011) indicated, skilled adult readers may have learned to use various types of information—including global familiarity—that can be used to predict when a word's meaning is imminent. The present experiment suggests that the degree of familiarity induced by the archetypal letter case may be one of these elements. Indeed, as indicated in the Introduction, word recognition times to brand names are faster when presented in their archetypal case than when presented in a less familiar case (IKEA faster than ikea; see Gontijo & Zhang, 2007; Perea et al., 2015). Further experimentation is necessary to directly test this observation during normal sentence reading.[3]

[2] The initial landing position on the target word was not responsible for this effect, as it was similar for lowercase and uppercase words (2.51 vs. 2.52, respectively, $\beta = 0.06$, $SE = 0.007$, $t < 1$).

[3] As one might argue that the lowercase advantage may just be due to familiarity, we conducted some post hoc analyses to examine whether the effect was reduced in the second half of the experiment when compared to the first half. While numerically there were some hints of an interaction, the pattern of data was not stable to reach statistical significance. Further research should directly examine whether the lowercase advantage is reduced in a blocked design with lowercase vs. uppercase sentences.

In sum, the present experiment showed that the bulk of the lowercase advantage during sentence reading arises only after the lexical entries have been accessed: while the word-frequency effect is sizeable in the first-fixation durations on the target word, the effect of letter case (i.e., a lowercase advantage) only arises significantly in the gaze durations. These findings are consistent with those neural models of letter/word recognition that assume a rapid conversion from visual codes onto case-invariant representations (e.g., Dehaene et al., 2005; Grainger et al., 2008). Notably, models of word recognition and reading need to take into account that, during the course of lexical processing, these case-invariant units will be mapped back onto the visual input (see Besner, 1983; Stone & Van Orden, 1994). Additional research using event-related potentials may be particularly useful to further track the time course of the lowercase advantage during word recognition and reading.

References

Besner, D. (1983). Basic decoding components in reading: Two dissociable feature extraction processes. *Canadian Journal of Psychology*, *37*, 429–438. http://dx.doi.org/10.1037/h0080739.

Bowers, J. S., Vigliocco, G., & Haan, R. (1998). Orthographic, phonological, and articulatory contributions to masked letter and word priming. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1705–1719. http://dx.doi.org/10.1037/0096-1523.24.6.1705.

Brysbaert, M., Speybroeck, S., & Vanderelst, D. (2009). Is there room for the BBC in the mental lexicon? On the recognition of acronyms. *Quarterly Journal of Experimental Psychology*, *62*, 1832–1842. http://dx.doi.org/10.1080/17470210802585471.

Core Team, R. (2016). *R: A language and environment for statistical computing.* Vienna: R Foundation for Statistical Computing.

Davis, C. J. (2010). The spatial coding model of visual word identification. *Psychological Review*, *117*, 713–758. http://dx.doi.org/10.1037/a0019738.

Davis, C. J., & Perea, M. (2005). BuscaPalabras: A program for deriving orthographic and phonological neighborhood statistics and other psycholinguistic indices in Spanish. *Behavior Research Methods*, *37*, 665–671. http://dx.doi.org/10.3758/bf03192738.

Dehaene, S., Cohen, L., Sigman, M., & Vinckier, F. (2005). The neural code for written words: A proposal. *Trends in Cognitive Sciences*, *9*, 335–341. http://dx.doi.org/10.1016/j.tics.2006.02.006.

Engbert, R., Nuthmann, A., Richter, E. M., & Kliegl, R. (2005). SWIFT: A dynamical model of saccade generation during reading. *Psychological Review*, *112*, 777–813. http://dx.doi.org/10.1037/0033-295X.112.4.777.

Forster, K. I. (1998). The pros and cons of masked priming. *Journal of Psycholinguistic Research*, *27*, 203–233. http://dx.doi.org/10.1023/A:1023202116609.

Gontijo, P. F. G., & Zhang, S. (2007). The mental representation of brand names: Are brand names a class by themselves? In T. M. Lowrey (Ed.), *Psycholinguistic phenomena in marketing communications* (pp. 23–37). Hillsdale, NJ: Erlbaum.

Grainger, J., & Dufau, S. (2012). The front end of visual word recognition. In J. S. Adelman (Vol. Ed.), *Visual word recognition: Models and methods, orthography and phonology. Vol. 1,* (pp. 159–184). Hove, England: Psychology Press.

Grainger, J., Rey, A., & Dufau, S. (2008). Letter perception: From pixels to pandemonium. *Trends in Cognitive Sciences*, *12*, 381–387. http://dx.doi.org/10.1016/j.tics.2008.06.006.

Hyönä, J., & Pollatsek, A. (1998). Reading Finnish compound words: Eye fixations are affected by component morphemes. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1612–1627. http://dx.doi.org/10.1037/0096-1523.24.6.1612.

Inhoff, A. W., & Rayner, K. (1986). Parafoveal word processing during eye fixations in reading: Effects of word frequency. *Perception & Psychophysics*, *40*, 431–439. http://dx.doi.org/10.3758/bf03208203.

Jacobs, A. M., Grainger, J., & Ferrand, L. (1995). The incremental priming technique: A method for determining within-condition priming effects. *Perception & Psychophysics*, *57*, 1101–1110. http://dx.doi.org/10.3758/bf03208367.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2016). lmerTest: Tests for random and fixed effects for linear mixed effect models (lmer objects of lme4 package): R package version 2.0–30. Retrieved form: https://cran.r-project.org/web/packages/lmerTest/index.html.

Lavidor, M. (2011). Whole-word shape effect in dyslexia. *Journal of Research in Reading*, *34*, 443–454. http://dx.doi.org/10.1111/j.1467-9817.2010.01444.x.

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*, 278–294. http://dx.doi.org/10.1037/0278-7393.22.2.278.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part 1. An account of basic findings. *Psychological Review*, *88*, 375–407. http://dx.doi.org/10.1037/2F0033-295X.88.5.375.

Paap, K. R., Newsome, S. L., & Noel, R. W. (1984). Word shape's in poor shape for the race to the lexicon. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 413–428. http://dx.doi.org/10.1037/0096-1523.10.3.413.

Perea, M., & Acha, J. (2009). Space information is important for reading. *Vision Research*, *49*, 1994–2000. http://dx.doi.org/10.1016/j.visres.2009.05.009.

Perea, M., Giner, L., Marcet, A., & Gomez, P. (2016). Does extra interletter spacing help text reading in skilled adult readers? *The Spanish Journal of Psychology*, *19*(e26), 1–7. http://dx.doi.org/10.1017/sjp.2016.28.

Perea, M., Jiménez, M., & Gómez, P. (2014). A challenging dissociation in masked identity priming with the lexical decision task. *Acta Psychologica*, *148*, 130–135. http://dx.doi.org/10.1016/j.actpsy.2014.01.014.

Perea, M., Marcet, A., Uixera, B., & Vergara-Martínez, M. (2017). Eye movements when reading sentences with handwritten words. *Quarterly Journal of Experimental Psychology.*. http://dx.doi.org/10.1080/17470218.2016.1237531.

Perea, M., & Rosa, E. (2002). Does "whole word shape" play a role in visual word recognition? *Perception & Psychophysics*, *64*, 785–794. http://dx.doi.org/10.3758/bf03194745.

Perea, M., Vergara-Martínez, M., & Gomez, P. (2015). Resolving the locus of cAsE aLtErNaTiOn effects in visual word recognition: Evidence from masked priming. *Cognition*, *142*, 39–43. http://dx.doi.org/10.1016/j.cognition.2015.05.007.

Rayner, K., Fischer, M. H., & Pollatsek, A. (1998). Unspaced text interferes with both word identification and eye movement control. *Vision Research*, *38*, 1129–1144. http://dx.doi.org/10.1016/s0042-6989(97)00274-5.

Rayner, K., McConkie, G. W., & Zola, D. (1980). Integrating information across eye movements. *Cognitive Psychology*, *12*, 206–226. http://dx.doi.org/10.1016/0010-0285(80)90009-2.

Rayner, K., Reichle, E. D., Stroud, M. J., Williams, C. C., & Pollatsek, A. (2006). The effect of word frequency, word predictability, and font difficulty on the eye movements of young and older readers. *Psychology and Aging*, *21*, 448–465. http://dx.doi.org/10.1037/0882-7974.21.3.448.

Rayner, K., Slattery, T. J., & Bélanger, N. N. (2010). Eye movements, the perceptual span, and reading speed. *Psychonomic Bulletin & Review*, *17*, 834–839. http://dx.doi.org/10.3758/PBR.17.6.834.

Reichle, E. D., Pollatsek, A., Fisher, D. L., & Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological Review*, *105*, 125–157. http://dx.doi.org/10.1037/0033-295x.105.1.125.

Reichle, E. D., Rayner, K., & Pollatsek, A. (1999). Eye movement control in reading: Accounting for initial fixation locations and refixations within the E-Z Reader model. *Vision Research*, *39*, 4403–4411. http://dx.doi.org/10.1016/s0042-6989(99)00152-2.

Perea, M., Jiménez, M., Talero, F., & López-Cañada, S. (2015). Letter-case information and the identification of brand names. *British Journal of Psychology*, *106*, 162–173. http://dx.doi.org/10.1111/bjop.12071.

Reichle, E. D., Tokowicz, N., Liu, Y., & Perfetti, C. A. (2011). Testing an assumption of the E-Z Reader model of eye-movement control during reading: Using event-related potentials to examine the familiarity check. *Psychophysiology*, *48*, 993–1003. http://dx.doi.org/10.1111/j.1469-8986.2011.01169.x.

Reichle, E. D., & Sheridan, H. (2015). E-Z Reader: An overview of the model and two recent applications. In A. Pollatsek, & R. Treiman (Eds.), *Oxford handbook of reading* (pp. 277–292). Oxford, UK: Oxford University Press.

Reingold, E. M., Yang, J., & Rayner, K. (2010). The time course of word frequency and case alternation effects on fixation times in reading: Evidence for lexical control of eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, *36*, 1677–1683. http://dx.doi.org/10.1037/a0019959.

Rumelhart, D. E., & Siple, P. (1974). Process of recognizing tachistoscopically presented words. *Psychological Review*, *87*, 99–118. http://dx.doi.org/10.1037/h0036117.

Sheridan, H., & Reichle, E. D. (2015). An analysis of the time course of lexical processing during reading. *Cognitive Science*, *40*, 522–553. http://dx.doi.org/10.1111/cogs.12246.

Sheridan, H., & Reingold, E. M. (2013). A further examination of the lexical-processing stages hypothesized by the E-Z Reader model. *Attention, Perception, & Psychophysics*, *75*, 407–414. http://dx.doi.org/10.3758/s13414-013-0442-0.

Slattery, T. J. (2016). Eye movements: From psycholinguistics to font design. In M. C. Dyson, & C. Y. Yuen (Eds.), *Digital fonts and reading* (pp. 54–78). Singapore: World Scientific. http://dx.doi.org/10.1142/9789814759540_0004.

Slattery, T. J., & Rayner, K. (2010). The influence of text legibility on eye movements during reading. *Applied Cognitive Psychology*, *24*, 1129–1148. http://dx.doi.org/10.1002/acp.1623.

Slattery, T. J., Yates, M., & Angele, B. (2016). Interword and interletter spacing effects during reading revisited: Interactions with word and font characteristics. *Journal of Experimental Psychology: Applied*, *22*, 406–422. http://dx.doi.org/10.1037/xap0000104.

Staub, A. (2015). The effect of lexical predictability on eye movements in reading: Critical review and theoretical interpretation. *Language and Linguistics Compass*, *9*, 311–327. http://dx.doi.org/10.1111/lnc3.12151.

Stone, G. O., & Van Orden, G. C. (1994). Building a resonance framework for word recognition using design and system principles. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 1248–1268. http://dx.doi.org/10.1037/0096-1523.20.6.1248.

Tinker, M. A. (1955). Prolonged reading tasks in visual research. *Journal of Applied Psychology*, *39*, 444–446. http://dx.doi.org/10.1037/h0041553.

Tinker, M. A., & Paterson, D. G. (1928). Influence of type form on speed of reading. *Journal of Applied Psychology*, *12*, 359–368. http://dx.doi.org/10.1037/h0073699.

White, S. J. (2008). Eye movement control during reading: Effects of word frequency and orthographic familiarity. *Journal of Experimental Psychology: Human Perception and Performance*, *34*, 205–223. http://dx.doi.org/10.1037/0096-1523.34.1.205.

McConkie, G. W., & Zola, D. (1979). Is visual information integrated across successive fixations? *Perception & Psychophysics*, *25*, 221–224. http://dx.doi.org/10.3758/bf03202990.