AMERICAN PSYCHOLOGICAL ASSOCIATION

Journal of Experimental Psychology: Learning, Memory, and Cognition

ISSN: 0278-7393

2022, Vol. 48, No. 12, 1995–2003
https://doi.org/10.1037/xlm0001179

Effects of Letter Case on Processing Sequences of Written Words

Colas Fournet[1], Jonathan Mirault[1], Manuel Perea[2, 3], and Jonathan Grainger[1, 4]
[1] Laboratoire de Psychologie Cognitive, Centre National de la Recherche Scientifique, Aix-Marseille University
[2] Departamento de Metodología and ERI-Lectura, Universitat de València
[3] Centro de Investigación Nebrija en Cognición, Universidad Antonio de Nebrija
[4] Institute of Language, Communication and the Brain, Aix-Marseille University

In four experiments, we investigated the impact of letter case (lower case vs. UPPER CASE) on the processing of sequences of written words. Experiment 1 used the rapid parallel visual presentation (RPVP) paradigm with postcued identification of one word in a five-word sequence. The sequence could be grammatically correct (e.g., “the boy likes his bike”) or be an ungrammatical reordering of the same words (e.g., “his boy the bike likes the”). We replicated the standard sentence superiority effect (more accurate identification of target words when embedded in a grammatically correct sequence compared with ungrammatical sequences), and also found that lowercase presentation led to higher word identification accuracy, but equally so for the grammatical and ungrammatical sequences. This pattern suggests that the lowercase advantage was mostly operating at the level of individual word identification. The following three experiments used the grammatical decision task to provide an examination of letter case effects on more global sentence processing measures. All these experiments revealed a significant lowercase advantage in grammatical decisions, independently of the nature of the ungrammatical sequence (Experiments 2 and 3) and independently of whether or not the letter case manipulation was blocked (Experiment 4). The size of the effects observed in grammatical decisions again points to individual word identification as the primary locus of the lowercase advantage. We conclude that letter case mainly affects early visuo-orthographic processing and access to case-independent letter and word identities.

Keywords: grammatical decisions, letter case, reading, sentence superiority

There is a long-standing debate on whether or not letter case (lowercase vs. UPPERCASE)[1] has a significant impact on the ease with which skilled readers process single words. Given that most reading involves text with lowercase letters, one might have expected that reading words printed in lowercase would be much easier than reading words printed in uppercase. However, evidence from the single word reading literature remains ambiguous at present, although it should be mentioned that relatively few studies have actually focused on the basic lower vs. uppercase comparison. For example, Paap et al.’s (1984) influential study examined the impact of shape frequency (the pattern of ascending, descending, and neutral letters: e.g., *t*, *g*, and *n*, respectively) on the processing of lowercase text and found no evidence for an impact of this variable. On the other hand, in a comparison of lowercase and uppercase presentation, Perea and Rosa (2002) did find a significant lowercase advantage in a lexical-decision task (in response times [RTs]), but only for relatively unfamiliar words. Moreover, when measured as a percentage of average RT (averaged across the lowercase and uppercase conditions) the effect was rather small (2.45%). This lowercase advantage in single word lexical decision in Spanish was replicated by Vergara-Martínez et al. (2020), but again the size of the effect was small (1.99%). Contrary to those findings, however, Lété and Pynte (2003) failed to find a lowercase advantage in a lexical-decision task in French but did find that shape frequency modulated performance to lowercase words.

Evidence from sentence reading, on the other hand, is relatively unambiguous. Early studies (e.g., Tinker, 1955, 1963; Tinker & Paterson, 1928) reported a sizable advantage (close to 14%) in reading times for sentences written in lowercase compared with uppercase text. In his influential book on text legibility, Tinker (1963) explained this lowercase advantage by the pattern of ascending/descending letters in lowercase words providing some useful “characteristic word forms” (p. 34), thus making them easier to read than

This article was published Online First August 29, 2022.
Jonathan Grainger https://orcid.org/0000-0002-6737-5646
Before starting the experiment, participants accepted an online informed-consent form. Ethics approval was obtained from the “Comité de Protection des Personnes SUD-EST IV” (17/051).

We thank Camille Reynaud for help with stimulus selection, and Ken Paap and Nicolas Dumay for constructive feedback on an earlier version. This study was supported by Grant 742141 from the European Research Council (ERC). The authors declare no conflicts of interest.

All data and materials are available at osf.io/m3y2z (Fournet et al., 2022).
Correspondence concerning this article should be addressed to Jonathan Grainger, Laboratoire de Psychologie Cognitive, Centre National de la Recherche Scientifique, Aix-Marseille University, 3, place Victor Hugo, Marseille 13331, France. Email: i.jonathan.grainger@gmail.com

[1] Here we will not consider studies investigating the impact of aLtErNaTiNg case presentation given the evidence that this is likely driven by low-level visual factors such as perceptual grouping (e.g., Mayall and Humphreys, 1996).

uppercase words. However, as noted above, this explanation was ruled-out by Paap et al. (1984). Furthermore, recent research (Perea et al., 2017) has shown that the lowercase advantage in total reading times is smaller than those early estimates. One possible reason for the larger lowercase advantage in the early studies by Tinker and colleagues is that they used fonts that were not monospaced, so that uppercase words occupied more horizontal space than lowercase words. Notably, when measuring eye-movement patterns on a single target word embedded in a sentence, Perea et al. (2017) found a sizable lowercase advantage (9.57%) on gaze durations (i.e., the sum of eye fixations on the target stimulus), but this advantage was much smaller (2.23%) on first-fixation durations (i.e., first of several fixations on the word) and single-fixation durations (3.44%). Of note, the lowercase advantage did not increase when considering the total fixation time (i.e., including those fixations resulting from regressions) on the target word (9.62%).

In the present study, we first examined the extent to which letter case impacts on the sentence superiority effect (Snell & Grainger, 2017). According to Perea et al. (2017), the lowercase advantage seen in gaze durations during sentence reading points to individual word identification processes as the locus of the effect. We should therefore find a lowercase advantage in word-in-sentence identification, in conditions where participants do not have to read the entire sentence, and where brief stimulus presentation and postmasking makes complete sentence reading difficult. However, if lowercase presentation also facilitates more global sentence processing (i.e., beyond single word identification) one might expect to observe an interaction between letter case and the sentence superiority effect. We see two possible scenarios here. One possibility is that lowercase presentation, by facilitating global sentence processing, leads to a larger sentence superiority effect. However, it is also possible that top-down support from sentence-level representations when processing correct sentences could reduce the sentence superiority effect by facilitating individual word identification. Anticipating the results, in Experiment 1 we failed to observe an interaction between letter case and sentence superiority. This provided the motivation for Experiments 2–4 where we investigated the impact of letter case on a more direct measure of global sentence reading by using the grammatical decision task (Mirault et al., 2018; Mirault & Grainger, 2020). In this task, participants are instructed to decide as rapidly and as accurately as possible if a sequence of words is grammatically correct or not and can be considered to be the sentence-level equivalent of the lexical-decision task. If letter case impacts reading beyond the level of single words, we expected to see proportionally larger effects of this manipulation in grammatical decisions to sequences of words compared with lexical decisions to isolated words (Perea & Rosa, 2002).[2]

General Method

Participants

For each experiment we first screened participants using the following criteria: (a) native speakers of French; (b) between 18 and 65 years old; and (c) no diagnosed reading impairment. Participants could only participate in one of the four experiments. Participants received £5 in compensation. The purpose of the experiment was not revealed to participants. Prior to initiation of the experiment, participants were informed that data would be collected anonymously, and they then provided informed consent for participation, as well as information concerning age, native language, and gender. Ethics approval was obtained from the Comité de Protection des Personnes SUD-EST IV (17/051).

Apparatus and Stimuli

All experiments were created using LabVanced (Finger et al., 2017), and the Prolific platform (Palan & Schitter, 2018) was used to recruit participants. Only MacOS, PC-Windows, and PC-Linux operating systems were allowed, and only Chrome, Firefox, Microsoft Edge, Safari, and Opera browsers were accepted. Stimuli were presented in Courier New font size 24.

General Procedure

Installed in front of their personal computer, participants were asked to click on the computer screen to launch the experiment. After that, they were shown the complete set of instructions for the experiment on a single page. Once they had read and understood the instructions, the participant could start the practice trials by pressing the space key. The practice session was composed of 16 trials that were representative of the conditions tested in the main experiment but were not included in the main experiment. Once the practice session was complete, participants were prompted to press the space key when they were ready to begin the main experiment. A break was proposed every 50 trials.

Analyses

We used linear mixed effects (LME) models to analyze RTs (recorded in all experiments except for Experiment 1) and generalized (logistic) linear mixed effects (GLME) models to analyze accuracy, with participants and items as crossed random effects (Baayen et al., 2008; Barr et al., 2013). The models were fitted with the lmer function (for LME) and the glmer function (for GLME) from the lme4 package (Bates et al., 2015) in the R statistical computing environment (R Core Team, 2021). We report regression coefficients (b), standard errors (SE) and z values. Fixed effects were deemed reliable if $|z| > 1.96$ (Baayen, 2008). We used the maximal random structure model that converged (Barr et al., 2013), and this included by-participant and by-item random intercepts in all analyses that we report for this and the following experiments. See Fournet al. (2022) for all stimuli and data which are available at: osf.io/m3y2z.

[2] Note that in Experiments 2–4 (grammatical decision task) we do not test for an interaction between effects of letter case and grammaticality given that responses to grammatical and ungrammatical sequences are not directly comparable. We aimed to compare the size of the lowercase advantage in grammatical decisions with that reported previously in single word lexical decisions.

Experiment 1

Method

Participants

Eighty participants (29 females) took part in Experiment 1. Their age ranged from 19 to 57 years (M = 28.09 years; SD = 8.73).

Design and Stimuli

We constructed 200 sentences in French each consisting of five words with an average word length of 4.12 letters (SD = .56). The average word frequency in Zipf values was 4.80 (SD = .63; New et al., 2004). All sequences were grammatically correct. From these base sentences, we created an ungrammatical sequence by scrambling the order of the words in the corresponding base sentence (see Table 1). The scrambling involved a change in position for all words in the base sentence except for the designated target word (located at either the second, third, or fourth position in the sentence). Thus, the same target word was tested at the same position in both a correct sentence and the corresponding ungrammatical sequence. The set of grammatically correct sentences and ungrammatical sequences were tested in both lowercase and uppercase (see Table 1) leading to a 2 (grammaticality) × 2 (case) factorial design. A Latin square design was used such that each of the four types of sequence derived from the same base sentence was tested with different participants, but each participant was tested in all four conditions across different base sentences. Thus, four counterbalanced lists were created, and participants were randomly assigned to one of the lists. There were 50 trials per condition per participant, and therefore a total of 200 trials per participant. Target location was randomly at position 2, 3, or 4 on each trial, and different words were tested at the different positions.

Procedure

Each trial started with two vertical bars for 500 ms indicating the center of the upcoming sequence of words. Participants were instructed to focus their attention between the two vertical bars. Then the sequence of words was displayed for a duration of 200 ms. After that, a sequence of hash marks (#), each one corresponding to a letter in the sequence of word, was presented for 500 ms as a mask (each letter is converted to "#"). The location of the to-be-identified target word was indicated by underlining the corresponding string of hashes. Finally, a response box was added to the screen with hash marks and underline cue and remained on screen until participants responded by typing (with their computer keyboard) the word they thought had been present at the cued location and confirmed their response with the enter key. The procedure is illustrated in Figure 1

Table 1
Examples of the Different Sequences of Words Tested in Experiment 1 (Target = "Boy/BOY")

Grammatical	
Lowercase	The boy likes his bike
Uppercase	THE BOY LIKES HIS BIKE
Scrambled	
Lowercase	His boy bike likes the
Uppercase	HIS BOY BIKE LIKES THE

Note. Examples are in English for convenience, but the experiment was conducted in French. The experiment used a monospaced font which is not the case in the examples here. Further note that the first letter was capitalized in the lowercase condition.

Scoring

Participants' responses were analyzed automatically using the algorithm developed by Mirault et al. (2021), which counts minor spelling or typographical errors and morphological changes (e.g., plural form instead of singular) as correct.

Results and Discussion

The dataset for analysis was composed of 16,000 observations, which exceeds the recommendation of Brysbaert and Stevens (2018). Condition means are shown in Table 2. There was a significant effect of Letter Case (b = .44, SE = .05, z = 9.61), with fewer errors in the lowercase condition compared with the uppercase condition. We also replicated the sentence superiority effect, with greater accuracy in correct sentences compared with ungrammatical sequences (b = −.93, SE = .12, z = 7.44). The interaction was not significant (b = .15, SE = .09, z = 1.63).

Given the absence of a significant interaction between letter case and grammaticality, the results of Experiment 1 suggest that letter case is having most of its impact at the level of individual word identification rather than sentence-level processing. In line with this conclusion is the fact that the effects of letter case were even numerically greater in the ungrammatical sequences compared with the grammatical sequences (expressed as a percentage of average performance in the grammatical and ungrammatical conditions, the case effect was 4.43% for grammatical sequences and more than twice that, 9.63%, for ungrammatical sequences). This suggests that top-down sentence-level constraints were facilitating target word identification, hence reducing the lowercase advantage on single word identification.

However, the task used in Experiment 1 did focus on processing at the individual word level, given that participants only had to identify a single word in each sequence. Therefore, to test for effects of letter case on processing at the sentence level, Experiment 2 uses the grammatical decision task with the same materials.

Experiment 2

Method

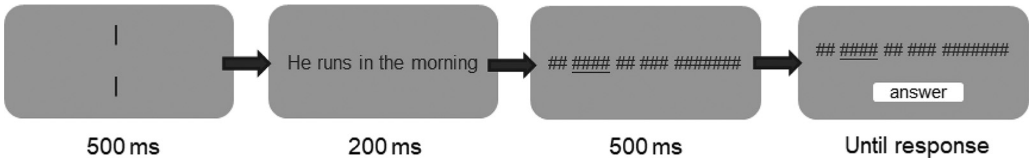
Participants

Eighty participants (36 females) took part in Experiment 2. Their age ranged from 18 to 58 years (M = 29.3 years; SD = 8.51).

Design and Stimuli

We used the same set of stimuli as in Experiment 1. Examples of the four types of word sequences are shown in Table 1. As in Experiment 1, four counterbalanced lists were created, and participants were randomly assigned to one of the lists. As such, all word sequences derived from the same base sentence were presented in all conditions (grammatical lowercase, grammatical uppercase, ungrammatical lowercase, ungrammatical uppercase) across different participants, and every participant saw all four conditions but with different word sequences.

Figure 1
Procedure of One Trial in Experiment 1 With an Example of a Grammatically Correct Word Sequence Presented in Lowercase and With the Target Word ("Runs") in Position 2



Procedure

In this and the following experiments participants had to perform a grammatical decision task. That is, they were instructed to determine as rapidly and as accurately as possible whether the sequence of words formed a grammatically correct sentence or not. Participants were instructed to first focus on the central fixation cross and then press the right arrow key on their computer keyboard if they thought that the word sequence was grammatically correct, or to press the left arrow if not. They received feedback in the form of a green circle (correct response) or a red cross (incorrect response) shown for 500 ms. After this feedback, a blank screen was presented for 200 ms before the next trial. The procedure is illustrated in Figure 2.

Results and Discussion

We analyzed RTs for correct responses and percent errors. Prior to analysis, one participant was excluded due to excessive errors (>25%). Then we removed 2.09% of the trials with excessively long or short RTs (3,000 ms < RT > 100 ms). The remaining dataset was composed of 15,469 observations, a number that largely exceeds the recommendation of Brysbaert and Stevens (2018).

Response Time

Prior to analysis, we excluded trials with incorrect responses (4.5%) and RT values lying beyond 2.5 standard deviations from the grand mean (3.52%). The remaining dataset was composed of 14,253 observations. The grammatical and ungrammatical trials were analyzed separately. Condition means are reported in Table 3.

Grammatical Trials. For the grammatical sequences, the dataset was composed of 7272 observations. We found a significant effect of Letter Case (b = .01, SE = .00, t = 5.21), with longer RTs to sentences presented in uppercase compared with lowercase.

Table 2
Average Accuracy (in %) per Experimental Condition in Experiment 1

Condition	Average accuracy	CI
Grammatical		
Lowercase	85.82	1.09
Uppercase	82.10	0.95
Case effect	3.72	
Ungrammatical		
Lowercase	75.65	0.99
Uppercase	68.70	1.09
Case effect	6.95	

Note. CIs are within-participant 95% confidence intervals (Cousineau, 2005).

Ungrammatical Trials. For ungrammatical sequences, the dataset was composed of 6,981 observations. Similarly to the grammatical trials, we found a significant effect of Letter Case (b = .02, SE = .00, t = 6.61), indicating that participants took more time to decide that uppercase sequences were ungrammatical compared with lowercase sequences.

Error Rate

The dataset for the error rate analysis was composed of 15,469 observations. We ran separate GLMMs for the grammatical and ungrammatical trials. Condition means are shown in Table 4.

Grammatical Trials. For grammatical trials, the dataset was composed of 7,755 observations. The effect of Letter Case was not significant (b = −.07, SE = .18, z = .37).

Ungrammatical Trials. For ungrammatical trials, the dataset was composed of 7,714 observations. The effect of Letter Case was again not significant (b = −.20, SE = .14, z = 1.40).

Although the effect of letter case was significant in RTs in Experiment 2, the magnitude of the effect is rather small, and much smaller than that seen in gaze durations on single words in the Perea et al. (2017) study. Expressed as a percentage of the average RT in the grammatical and ungrammatical conditions, the effect was 3.07% for grammatical trials and 3.34% for ungrammatical trials in Experiment 2, whereas the effect in gaze durations in the Perea et al. study was 9.57%. Indeed, the size of the effects are more in line with the effects on first fixation durations in the Perea et al. study, and the effects on lexical decision RTs in the Perea and Rosa (2002) study. This might be attributable to the superficial nature of processing performed to make a grammatical decision. Therefore, in Experiment 3 we increased the difficulty of grammatical decisions by using transposed-word ungrammatical sequences that are known to be particularly difficult to judge as being ungrammatical. Mirault et al. (2018) compared grammatical decisions to two types of ungrammatical sequence—one formed by transposing two adjacent words in a correct sentence (e.g., *The white was cat big*), and one where the transposition of any two words would not generate a correct sentence (e.g., *The white was cat slowly*). Deciding that transposed-word sequences were ungrammatical was more difficult compared with the corresponding control sequences.

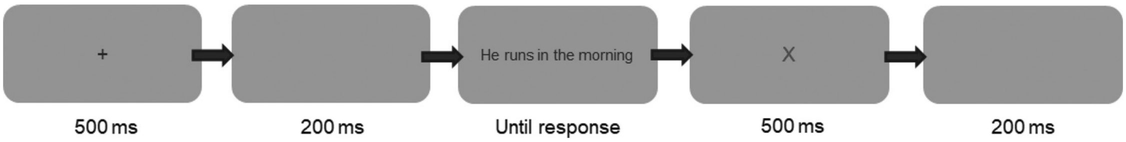
Experiment 3

Method

Participants

Eighty participants (37 females) took part in Experiment 3. Their age ranged from 18 to 58 years (M = 28.16 years; SD = 8.95).

Figure 2
Procedure of One Trial in Experiment 2, With an Example of a Grammatically Correct Sentence Presented in Lowercase



Design and Stimuli

We used the same set of 200 grammatical sentences as in Experiments 1 and 2, but this time the ungrammatical sequences were constructed by transposing two adjacent words in the grammatical sentences. This was designed to make the grammatical decision task harder. Because the sequences were five words long, one of the four possible adjacent transpositions (1 and 2/2 and 3/3 and 4/4 and 5) was randomly chosen to create the associated ungrammatical sequence. See Table 5 for example stimuli.

Procedure

The procedure was the same as in Experiment 2.

Results and Discussion

Prior to analysis, two participants were excluded, with an average accuracy less than 75%. Four items were also removed again because of accuracy less than 75%. Then, we deleted 3.31% of the trials with excessively short or long RTs (i.e., < 100 ms or > 4,000 ms). The remaining dataset was composed of 14,923 observations, a number that largely exceeds the recommendation of Brysbaert and Stevens (2018).

Response Time

Prior to analysis we excluded trials with incorrect responses (7.24%) and values lying beyond 2.5 standard deviations from the grand mean (2.99%). The remaining dataset was composed of 13,428 observations. The grammatical and ungrammatical trials were analyzed separately. Condition means are reported in Table 6.

Grammatical Trials. For grammatical trials, the dataset was composed of 7,113 observations. We found a significant effect of Letter Case ($b = .02$, $SE = .00$, $t = 6.48$), with longer RTs for sentences presented in uppercase compared with lowercase.

Ungrammatical Trials. For ungrammatical trials, the dataset was composed of 6,315 observations. As for the grammatical trials, we found a significant effect of Letter Case ($b = .01$, $SE = .00$, $t = 4.89$), indicating that participants took more time to respond to uppercase sequences than lowercase sequences.

Error Rate

The dataset for Error Rate was composed of 14,923 observations. We ran separate GLMM for the grammatical and ungrammatical trials. Condition means are shown in Table 7.

Grammatical Trials. For grammatical trials, the dataset was composed of 7,494 observations. The effect of Letter Case was not significant ($b = -.36$, $SE = .21$, $z = 1.66$).

Ungrammatical Trials. For ungrammatical trials, the dataset was composed of 7,429 observations. Again, the effect of Letter Case was not significant ($b = -.05$, $SE = .12$, $z = .47$).

Although we did succeed in increasing the difficulty of the grammatical decision task in Experiment 3 compared with Experiment 2 (i.e., overall slower RTs and more errors), this did not lead to a greater lowercase advantage. Expressed as a percentage of the average RT in the grammatical and ungrammatical conditions, the lowercase advantage was 3.68% for grammatical trials and 2.68% for ungrammatical trials in Experiment 3, compared with 3.07% for grammatical trials and 3.34% for ungrammatical trials in Experiment 2. The lowercase advantage seen in grammatical decisions is therefore quite small in magnitude and would appear to be insensitive to task difficulty. Moreover, the observed difficulty in processing all uppercase stimuli in Experiments 1–3 could be attributed to these being intermixed with the more familiar lower-case stimuli. Therefore, in Experiment 4 we examined whether blocking the case manipulation might increase the ease of responding to uppercase stimuli when these are presented in

Table 3
Average RTs (in ms) per Experimental Condition in Experiment 2

Condition	Average RT	CI
Grammatical		
Lowercase	994	11.15
Uppercase	1,024	10.08
Case effect	31	
Ungrammatical		
Lowercase	1,090	10.29
Uppercase	1,128	11.92
Case effect	37	

Note. RT = response time. CIs are within-participant 95% confidence intervals (Cousineau, 2005).

Table 4
Average Error Rates (in %) per Experimental Condition in Experiment 2

Condition	Average ER	CI
Grammatical		
Lowercase	3.70	0.69
Uppercase	3.53	0.73
Case effect	−0.17	
Ungrammatical		
Lowercase	5.04	0.76
Uppercase	5.63	0.64
Case effect	0.59	

Note. ER = error rate. CIs are within-participant 95% confidence intervals (Cousineau, 2005).

Table 5
Examples of the Different Conditions Sequences of Words Tested in Experiment 3

Grammatical	
Lowercase	The boy likes his bike
Uppercase	THE BOY LIKES HIS BIKE
Ungrammatical	
Lowercase	The likes boy his bike
Uppercase	THE LIKES BOY HIS BIKE

Note. Examples are in English, but the experiment was conducted in French. The experiment used a monospaced font which is not the case in the examples here. Further note that the first letter was capitalized in the lowercase condition.

the same block of trials and prior to presentation of the lowercase stimuli, hence even further reducing the effects of letter case on grammatical decisions. More specifically we tested whether effects of letter case would interact with block order—that is, whether participants first saw the uppercase stimuli before the lowercase stimuli, or vice versa.

Experiment 4

Method

Participants

One hundred sixty participants (79 females) took part in Experiment 4. Their age ranged from 18 to 64 years (M = 31.85 years; SD = 10.71).

Design and Stimuli

We used the same set of stimuli as in Experiment 3. Examples of the four types of word sequences are shown in Table 5.

Procedure

The procedure was the same as for Experiments 2 and 3 except that the Letter Case manipulation was now blocked. Participants therefore received all the lowercase trials in one block and all the uppercase trials in a different block, and Block Order was counterbalanced across participants. A break was proposed at the end of the first block.

Analyses

The same analyses as for Experiments 2 and 3 were performed except that for this experiment, because participants only received one block order, Block Order was not included as a by-participant random slope.

Table 6
Average RTs (in ms) per Experimental Condition in Experiment 3

Condition	Average RT	CI
Grammatical		
Lowercase	1,221	15.07
Uppercase	1,266	11.90
Case effect	45	
Ungrammatical		
Lowercase	1,323	13.75
Uppercase	1,359	12.99
Case effect	36	

Note. RT = response time. CIs are within-participant 95% confidence intervals (Cousineau, 2005).

Table 7
Average Error Rates (in %) per Experimental Condition in Experiment 3

Condition	Average ER	CI
Grammatical		
Lowercase	2.52	0.88
Uppercase	3.63	0.72
Case effect	1.11	
Ungrammatical		
Lowercase	11.63	1.02
Uppercase	11.27	1.02
Case effect	−0.36	

Note. ER = error rate. CIs are within-participant 95% confidence intervals (Cousineau, 2005).

Results and Discussion

No participant was excluded prior to analysis, but four items were removed because of high error rates (>25%). Then, we removed trials (2.97%) with excessively short or long RTs (100 ms < RTs > 3,000 ms). The remaining dataset was composed of 30,429 observations, a number that largely exceeds the recommendation of Brysbaert and Stevens (2018).

Response Time

Prior to analysis, we excluded incorrect trials (7.66%) and values beyond 2.5 standard deviation from the grand mean (2.94%). The remaining dataset was composed of 27,271 observations. We ran separate LME models for grammatical and ungrammatical trials. Condition means are reported in Table 8.

Grammatical Trials. For grammatical trials, the dataset was composed of 14,361 observations. There was a significant effect of Letter Case (b = .02, SE = .00, t = 7.42), with longer RTs in the uppercase sequences compared with lowercase sequences. The effect of Block Order was not significant (b = .01, SE = .01, t = .85), and neither was the interaction (b = .00, SE = .01, t = .81).

Ungrammatical Trials. For ungrammatical trials, the dataset was composed of 12,910 observations. As for the grammatical sequences, there was a significant effect of Letter Case (b = .02,

Table 8
Average RTs (in ms) per Experimental Condition in Experiment 4

	Lowercase First		Uppercase First	
Condition	Average RT	CI	Average RT	CI
Grammatical				
Lowercase	1,203	10	1,226	10
Uppercase	1,275	13	1,278	11
Case effect	72		52	
Ungrammatical				
Lowercase	1,321	13	1,291	10
Uppercase	1,352	13	1,355	11
Case effect	31		64	

Note. RT = response time. CIs are within-participant 95% CIs (Cousineau, 2005).

Table 9
Average Error Rates (in %) per Experimental Condition in Experiment 4

Condition	Lowercase First		Uppercase First	
	Average ER	CI	Average ER	CI
Grammatical				
Lowercase	3.36	0.65	2.97	0.57
Uppercase	3.75	0.73	3.99	0.59
Case effect	0.39		1.02	
Ungrammatical				
Lowercase	12.53	0.67	11.84	0.67
Uppercase	11.14	0.92	11.97	0.65
Case effect	−1.39		0.13	

Note. ER = error rate. CIs are within-participant 95% confidence intervals (Cousineau, 2005).

SE = .00, t = 5.43), with longer RTs to uppercase sequences than lowercase sequences. The effect of Block Order was not significant (b = .00, SE = .01, t = .33), but there was a significant interaction between Letter Case and Block Order (b = .01, SE = .01, t = 2.21), reflecting the fact that the lowercase advantage was greater when participants first received the uppercase block (see Table 8).

Error Rate

The dataset for Error rate was composed of 30,429 observations. The grammatical and ungrammatical trials were analyzed separately. Condition means are shown in Table 9.

Grammatical Trials. For grammatical trials, the dataset was composed of 15,245 observations. There was no significant effect of Letter Case (b = −.21, SE = .13, z = 1.54). Neither the effect of Block order (b = −.15, SE = .16, z = .92) nor the interaction of Block order and Letter Case was significant (b = −.19, SE = .19, z = 1.01).

Ungrammatical Trials. For ungrammatical trials, the dataset was composed of 15,184 observations. The effect of Letter Case was not significant (b = .08, SE = .05, z = 1.48). Neither was the effect of Block order (b = −.04, SE = .14, z = .27) nor the interaction between letter case and bloc order (b = −.18, SE = .11, z = 1.69).

The results of Experiment 4 clearly demonstrate that presenting the uppercase stimuli prior to the lowercase stimuli in separate blocks of trials did not reduce the lowercase advantage. Indeed, when expressed as a percentage of the average RT in the grammatical and ungrammatical conditions, the lowercase advantage was even slightly greater than in the previous experiments (where case was mixed from trial-to-trial) for the grammatical trials (5.13%) and remained about the same (3.93%) for the ungrammatical trials. Nevertheless, this lowercase advantage, seen now in three grammatical decision experiments, is relatively small compared with the advantage seen in gaze durations on target words during sentence reading (Perea et al., 2017). Instead, the size of the lowercase advantage in grammatical decision RTs aligns more with the effects seen on first fixation and single fixation measures in Perea et al. (2017), and the effects seen in single word lexical decision RTs (Perea & Rosa, 2002; Vergara-Martínez et al., 2020).

General Discussion

The present series of four experiments examined the nature of the effects of letter case (lowercase vs. uppercase) when processing sequences of words. Experiment 1 used an RSVP technique with the postcued identification of one of the five words in the sentence with an aim to test whether the sentence superiority effect (i.e., more accurate decisions to grammatical vs. ungrammatical sentences) would be modulated by letter case. Results showed a substantial sentence superiority effect accompanied by a smaller effect of letter case, with higher accuracy for words presented in lowercase, and no interaction. The fact that grammaticality did not have a significant impact on performance in Experiment 1 suggests that the effects of letter case were operating at the level of individual word identification and not at the sentence-level. Furthermore, the fact that correct sentences generated a numerically smaller effect of letter case (expressed as a percentage of average performance, the lowercase advantage was 4.43% for the grammatical sequences and 9.63% for the ungrammatical sequences) could be taken as evidence that top-down constraints from sentence-level representations were reducing the bottom-up impact of letter case on individual word identification. A more global impact of letter case on sentence-level processing actually predicted the opposite pattern, with stronger effects of letter case in the grammatical sequences.

Experiments 2–4 provided a stronger focus on sentence-level processing by using the grammatical decision task. This also allowed us to obtain measures of case effects in RTs that are more directly comparable to prior observations of effects in fixation durations in sentence reading and in single word lexical decision latencies. In Experiment 2, we used the same set of items as in Experiment 1 and we found a small but reliable advantage for lowercase compared with uppercase presentation together with substantially faster responses to grammatically correct sentences. Experiment 3 was designed to test whether an increased difficulty in making grammatical decisions, by using transposed-word ungrammatical sequences, would produce a larger lowercase case advantage. Results replicated the findings of Experiment 2 but failed to show a notable increase in the size of the lowercase advantage. Expressed as a percentage of the average RT for grammatical and ungrammatical sequences, the lowercase advantage was 3.07% in Experiment 2 and 3.68% in Experiment 3 for grammatical trials and 3.34% in Experiment 2 and 2.68% in Experiment 3 for ungrammatical trials.

To examine whether the lowercase advantage in Experiment 3 could have been attributable to the difficulty in processing the uppercase sentences intermixed in the same blocks as the lowercase sentences, in Experiment 4 the lowercase and uppercase sequences were presented in different, counterbalanced blocks. Results essentially mimicked those of Experiment 3, thus ruling out an explanation of the case effect seen in Experiment 3 as being driven by list composition. In sum, all these experiments revealed a significant lowercase advantage in different tasks (word-in-sentence identification, grammatical decision). Importantly, this effect was independent of the nature of the ungrammatical sequences (easy vs. difficult), the nature of the composition of the list (mixed list of lowercase and uppercase sentences vs. blocked lists), and the order of the blocks (uppercase before lowercase or vice versa).

We therefore have clear evidence from four experiments for a lowercase advantage when processing sequences of written words. Crucially, our findings provide important information with respect to the locus of the lowercase advantage found in prior research in single word lexical decisions (Perea & Rosa, 2002; Vergara-Martínez et al., 2020) and with eye movement recordings during sentence reading (Perea et al., 2017). Prior results plus the present findings all point to individual word identification processes as the primary locus of the lowercase advantage in reading, with little or no role played by sentence-level processing. One particularly relevant prior study is that of Vergara-Martínez et al. (2020). In that study, letter case was manipulated in a lexical decision experiment with EEG recordings. The results revealed a significant impact of letter case for both words and nonwords in the N/P150 and N250 ERP components. This pattern suggests that letter case was affecting the early mapping of visual features onto abstract letter identities and the subsequent sublexical processing of orthographic information (see Grainger & Holcomb, 2009, for a discussion of the functional significance of the N/P150 and N250 components).

Following Vergara-Martínez et al. (2020), we therefore propose that the lowercase advantage is mainly driven by early visuo-orthographic processing of fixated words during reading. This early processing essentially involves the mapping of visual features onto the abstract letter identities that, combined with letter-position information, form the core of sublexical orthographic processing. It is this processing that would be facilitated by the vastly greater exposure skilled readers have with lowercase text. The advantage remains relatively small, because in the Roman alphabet the majority of uppercase letters share features with lowercase letters (b-B, c-C, etc.), and therefore the expertise gained by exposure to lowercase text transfers, to a certain extent, to the processing of uppercase text. Our results also suggest that the rather small lowercase advantage that arises during single word processing does not accumulate across multiple words in a sentence.[3] This could be attributable to the fact that sentence-level processing is mostly affected by the later stages of individual word processing that would be relatively insensitive to letter case (see Vergara-Martínez et al., 2020, for ERP evidence supporting this view). Evidence in support of this has also been found in masked priming studies demonstrating that masked repetition priming effects for word stimuli do not depend on whether or not primes and targets are presented in the same case (e.g., table-TABLE vs. TABLE-TABLE; Jacobs et al., 1995; Perea et al., 2015).

Taken together, these results suggest that some form of word-shape information (over and above word length information), that would only be available in lowercase format, is not having a significant impact on sentence-level processing. Moreover, the fact that we found effects in the range of those found in single word lexical decision studies suggests that our results are not driven by the parafoveal processing of word-shape information. That is, our results pose problems for the hypothesis that word-shape information would be mainly processed in the parafovea, where low-spatial frequency information would presumably have a greater impact on processing. Overall, our results fit best with models of reading in an alphabetic script that assign a key role for abstract letter identities in recognizing words (see McConkie & Zola, 1979; and Rayner et al., 1980; for early evidence using eye movements during reading), and a key role for word identification processes during sentence processing.

Nevertheless, some key questions remain open concerning the impact of letter case on reading. Under the hypothesis that the lowercase advantage is at least partly driven by a greater exposure to lowercase text, future studies could investigate the extent to which both word frequency (Perea & Rosa, 2002) and individual letter frequency (New & Grainger, 2011) modulate the lowercase advantage. The present study focused on the interplay between word identification and sentence reading. An interesting complementary line of research would be to focus on the interplay between letter identification and word recognition. New and Grainger (2011) found significant effects of letter frequency in an alphabetic decision task for both uppercase and lowercase isolated letters. Future research could therefore examine the extent to which the lowercase advantage for word recognition (Perea & Rosa, 2002; Vergara-Martínez et al., 2020) is driven by frequency effects operating at the letter level.

[3] We note nevertheless that the results of Perea et al. (2017) point to a cumulative effect driven by multiple fixations on a single word prior to leaving that word, hence leading to a greater effect in gaze durations. That is, although the lowercase advantage does not accumulate across different words, it can accumulate across multiple fixations within the same word.

Conclusions

In four experiments we found a small but significant effect of letter case (lowercase better than uppercase) when processing sequences of words. The overall pattern of effects as a function of the grammaticality of the sequence as well as the relatively small magnitude of the lowercase advantage all point to individual word identification processes as the locus of the effect. Combined with prior findings, we would argue that letter case mainly affects early visuo-orthographic processing, and that abstract letter identities rapidly dominate the processing of case-independent word identities which in turn dominate processing at the sentence-level, hence the rather small impact of letter case.

References

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language*, *59*(4), 390–412. https://doi.org/10.1016/j.jml.2007.12.005

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*(3), 255–278. https://doi.org/10.1016/j.jml.2012.11.001

Bates, D. J., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

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

Cousineau, D. (2005). Confidence intervals in within-subject designs: A simpler solution to Loftus and Masson's method. *Tutorials in Quantitative Methods for Psychology*, *1*(1), 42–45. https://doi.org/10.20982/tqmp.01.1.p042

Finger, H., Goeke, C., Diekamp, D., Standvoß, K., & König, P. (2017). LabVanced: a unified JavaScript framework for online studies. In *2017 International Conference on Computational Social Science IC2S2 (Cologne)*.

Fournet, C., Mirault, J., Perea, M., & Grainger, J. (2022, April 22). Effects of letter case on processing sequences of written words. osf.io/m3y2z

Grainger, J., & Holcomb, P. J. (2009). Watching the word go by: On the time-course of component processes in visual word recognition. *Language and Linguistics Compass*, *3*(1), 128–156. https://doi.org/10.1111/j.1749-818X.2008.00121.x

Jacobs, A. M., Grainger, J., & Ferrand, L. (1995). The incremental priming technique: A method for determining within-condition priming effects. *Perception & Psychophysics*, *57*(8), 1101–1110. https://doi.org/10.3758/BF03208367

Lété, B., & Pynte, J. (2003). Word-shape and word-frequency effects in lexical-decision and naming tasks. *Visual Cognition*, *10*(8), 913–948. https://doi.org/10.1080/13506280344000112

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

McConkie, G. W., & Zola, D. (1979). Is visual information integrated across successive fixations in reading? *Perception & Psychophysics*, *25*(3), 221–224. https://doi.org/10.3758/BF03202990

Mirault, J., & Grainger, J. (2020). On the time it takes to judge grammaticality. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, *73*(9), 1460–1465. https://doi.org/10.1177/1747021820913296

Mirault, J., Massol, S., & Grainger, J. (2021). An algorithm for analyzing cloze test results. *Methods in Psychology*, *5*, 100064. https://doi.org/10.1016/j.metip.2021.100064

Mirault, J., Snell, J., & Grainger, J. (2018). You that read wrong again! A transposed-word effect in grammaticality judgments. *Psychological Science*, *29*(12), 1922–1929. https://doi.org/10.1177/0956797618806296

New, B., & Grainger, J. (2011). On letter frequency effects. *Acta Psychologica*, *138*(2), 322–328. https://doi.org/10.1016/j.actpsy.2011.07.001

New, B., Pallier, C., Brysbaert, M., & Ferrand, L. (2004). Lexique 2: A new French lexical database. *Behavior Research Methods, Instruments, & Computers*, *36*(3), 516–524. https://doi.org/10.3758/BF03195598

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*(3), 413–428. https://doi.org/10.1037/0096-1523.10.3.413

Palan, S., & Schitter, C. (2018). Prolific - A subject pool for online experiments. *Journal of Behavioral and Experimental Finance*, *17*, 22–27. https://doi.org/10.1016/j.jbef.2017.12.004

Perea, M., & Rosa, E. (2002). Does "whole-word shape" play a role in visual word recognition? *Perception & Psychophysics*, *64*(5), 785–794. https://doi.org/10.3758/BF03194745

Perea, M., Jiménez, M., & Gomez, P. (2015). Do young readers have fast access to abstract lexical representations? Evidence from masked priming. *Journal of Experimental Child Psychology*, *129*, 140–147. https://doi.org/10.1016/j.jecp.2014.09.005

Perea, M., Rosa, E., & Marcet, A. (2017). Where is the locus of the lowercase advantage during sentence reading? *Acta Psychologica*, *177*, 30–35. https://doi.org/10.1016/j.actpsy.2017.04.007

R Core Team. (2021). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing.

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

Snell, J., & Grainger, J. (2017). The sentence superiority effect revisited. *Cognition*, *168*, 217–221. https://doi.org/10.1016/j.cognition.2017.07.003

Tinker, M. (1963). *Legibility of print*. Iowa State University Press.

Tinker, M. A. (1955). Prolonged reading tasks in visual research. *Journal of Applied Psychology*, *39*(6), 444–446. https://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*(4), 359–368. https://doi.org/10.1037/h0073699

Vergara-Martínez, M., Perea, M., & Leone-Fernandez, B. (2020). The time course of the lowercase advantage in visual word recognition: An ERP investigation. *Neuropsychologia*, *146*, 107556. https://doi.org/10.1016/j.neuropsychologia.2020.107556

Received April 25, 2022
Revision received July 6, 2022
Accepted July 15, 2022 ■