Quartely Journal of Experimental Psychology, in press

Do handwritten words magnify lexical effects in visual-word recognition?

Manuel Perea [1 2], Cristina Gil-López [2], Victoria Beléndez [1], and Manuel Carreiras [2 3]

[1] Departamento de Metodología, Universitat de València, Valencia, Spain

[2] BCBL. Basque Center on Cognition, Brain, and Language, Donostia-San Sebastián, Spain

[3] IKERBASQUE, Basque Foundation for Science, Bilbao, Spain

Running Head: handwritten words and lexical access

Address for correspondence:

Manuel Perea

Departamento de Metodología

Av. Blasco Ibáñez, 21

46010 Valencia (Spain)

e-mail: mperea@valencia.edu

This research has been partially supported by grants PSI2014-53444-P and PSI2012-31448 from the Spanish Government and by grant ERC-2011-ADG-295362 from the European Research Council. We thank Anthony Barnhart, Sachiko Kinoshita, and an anonymous reviewer for helpful comments on an earlier version of this paper.

Abstract

An examination of how the word recognition system is able to process handwritten words is fundamental to formulate a comprehensive model of visual word recognition. Previous research has revealed that the magnitude of lexical effects (e.g., the word-frequency effect) is greater with handwritten words than with printed words. In the present lexical decision experiments, we examined whether the quality of handwritten words moderates the recruitment of top-down feedback, as reflected in word-frequency effects. Results showed a reading cost for difficult-to-read and easy-to-read handwritten words relative to printed words. But the critical finding was that difficult-to-read handwritten words, but not easy-to-read handwritten words, showed a greater word-frequency effect than printed words. Therefore, the inherent physical variability of handwritten words does not necessarily boost the magnitude of lexical effects.

Key words: visual-word recognition, handwritten words, word-frequency

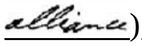
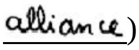
The vast majority of experiments on visual word recognition and reading employ printed words (e.g., animal) rather than handwritten words (e.g., animal). While using printed words is definitely appropriate when the research focus is on the role of lexico-semantic factors in visual word recognition, a detailed examination of how the word recognition system is able to process handwritten words is necessary to formulate a fully comprehensive model of visual word recognition at all levels, from features to letters and words (e.g., Davis, 2010). Furthermore, the recognition of handwritten words raises a number of fundamental questions on how the brain is able to cope with complex and variable stimuli. Indeed, handwritten words and printed words differ in a number of parameters (e.g., geometrical structure, see Hellige & Adamson, 2007), there may be lack of physical demarcation between the letters, and there is considerable intra- and inter-individual variability in the form of handwritten letters/words.

Corcoran and Rouse (1970) pioneered the systematic study of printed vs. handwritten words in visual word recognition. In their experiments, using a tachistoscope, participants were briefly presented with words, either printed or handwritten. Accuracy was the only dependent variable. In pure blocks of only-printed or only-handwritten words, Corcoran and Rouse reported that participants were more accurate at identifying printed words than handwritten words (41 vs. 26% of correct responses, respectively). These differences nearly vanished in the blocks with intermixed printed/handwritten words (19 vs. 14% of correct responses for printed and handwritten words, respectively). Corcoran and Rouse concluded: “the processes, whatever they may be, which occur in the perception of handwritten words may well be different from those underlying the recognition of printed letters” (p. 530). However, the presence of potential participants’ strategies in perceptual identification tasks makes it difficult to establish firm conclusions from these data (see also Manso De Zuniga, Humphreys, & Evett, 1991, for additional criticism).

To further scrutinize the differences of printed and handwritten words in visual-word recognition, Manso De Zuniga et al. (1991) manipulated the effect of script (printed vs. handwritten) in combination with a lexical factor, namely, word-frequency (low vs. high) in the most common laboratory visual-word recognition task: lexical decision (i.e., “is the stimulus a word?”). Script was manipulated between subjects in Experiment 3, whereas it was manipulated within subjects in Experiment 4. Unsurprisingly, results revealed longer word identification times for handwritten words than for printed words. More important, Manso De Zuniga et al. found that the effect of word-frequency (i.e., the difference in RTs/accuracy between the responses to low-frequency and high-frequency words) was greater for handwritten than for printed words (134 vs. 89 ms, respectively, in Experiment 3; 144 vs. 99 ms, respectively, in Experiment 4). Manso De Zuniga et al. (1991) explained their findings in terms of feedback from higher (lexical) levels of processing, producing a magnification of the word-frequency effect.

More recently, Barnhart and Goldinger (2010) conducted a systematic series of experiments that examined how the magnitude of various lexical effects (word-frequency, regularity, bidirectional consistency, and imageability) differed in printed and handwritten words (either naturally written or with an “assembled cursive” font). Consistent with the data reported by Manso De Zuniga et al. (1991), Barnhart and Goldinger (2010) found not only a “printed word” advantage but also a magnification of *all* lexical effects with handwritten words (see also Barnhart & Goldinger, 2013, for further evidence of an interaction of script [printed, handwritten] and word-frequency [low, high] with rotated words). This is consistent with the idea that “the human perceptual system is equipped to disambiguate handwritten words; it simply has to rely more heavily on top-down processes, relative to more prototypical word forms" (Barnhart & Goldinger, 2010, p. 921).

In the present series of lexical decision experiments, we examined whether the magnification of a lexical effect such as word-frequency with handwritten words is due to the inherent physical variability of all handwritten words, or whether it is due to the difficulty in processing handwritten words because of their noisy/ambiguous letter forms. Keep in mind that Barnhart and Goldinger (2010; see also Barnhart & Goldinger, 2013) employed "highly non-uniform and unfamiliar" handwritten words (p. 908; e.g.,  and  as instances of this and patch, respectively)—Manso de Zuniga et al. (1991) did not report examples of handwritten words. While an interaction between script (printed, handwritten) and word-frequency (low, high) is intuitive and consistent with interactive activation models (see Carreiras, Armstrong, Perea, & Frost, 2014, for a recent review), the story is more complex. A number of experiments have shown that stimulus quality (i.e., another perceptual factor) and word-frequency produce additive effects in the lexical decision task (i.e., significant main effects of stimulus quality and word-frequency and an absence of interaction between the two factors; see Balota, Aschenbrenner, & Yap, 2013, for discussion). As Balota et al. (2013) indicated, this additivity pattern "is challenging for the currently most successful models of visual word recognition, where there is a heavy reliance on interactive activation mechanisms (e.g., McClelland & Rumelhart, 1981)" (p. 1563). Indeed, the additivity of stimulus quality and word-frequency has often been interpreted as evidence against single-process models of visual word recognition (see, however, Plaut & Booth, 2006). Therefore, it is important to examine whether handwritten words (notwithstanding how easy to read they are) always produce a magnification of the word-frequency effect, or alternatively whether—as occurs with stimulus quality—easy-to-read handwritten words show additive effects of script [printed vs. handwritten] and word-frequency [low vs. high]). For comparison purposes, we also examined the parallel interaction with difficult-to-read handwritten words—for these words, we expect a magnification of the word-frequency effect, as in the experiments of Manso de Zuniga et al. (1991) and Barnhart and Goldinger (2010, 2013).

The empirical evidence concerning the reading cost of easy-to-read vs. difficult-to-read handwritten words is very scarce. In a recent fMRI experiment, Qiao et al. (2010) reported a dissociation between easy-to-read and difficult-to-read handwritten words on the pattern of brain activity during the recognition of visually presented words. The categorization of the handwriting styles as “difficult” or “easy” were made on the basis of a naming experiment that included six groups of handwritten words of different length written by six individuals. The group with the slower naming times on average was categorized as a “difficult-to-read” style (e.g., ), whereas the group with the shorter naming times was categorized as an “easy-to-read” style (e.g., ). In the fMRI experiment, Qiao et al. (2010) found that perception of handwritten words relied primarily on the same left-lateralized regions as printed words, including the left fusiform area, an area that has been repeatedly reported for reading words and nonwords (see Carreiras et al., 2014, for a review). But the critical finding was that while easy-to-read handwritten words produced additional activation in the right fusiform area relative to printed words, difficult-to-read handwritten words produced additional activation in a bilateral frontoparietal network relative to easy-to-read handwritten words (see Qiao et al., 2010, for further details). Thus, the Qiao et al. experiment suggests that, besides the common processes sustained by the reading network, the identification of difficult-to-read handwritten words may require additional attentional and top-down processes. In addition, it is important to note that easy-to-read handwritten words produce a reading cost at the earliest stages of lexical access relative to printed words. Gil-López, Perea, Moret-Tatay, and Carreiras (2011) found a 31-ms masked repetition priming effect with easy-to read handwritten primes on printed target words (e.g.,  -MELÓN) in a lexical decision task. The parallel priming effect when the primes were printed was 45 ms. Given that the masked priming lexical decision task taps into the initial stages of lexical access (see Forster, 1998), the reduction in the magnitude of the repetition priming effect reported by Gil-López et al. (2011) suggests that easy-to-read handwritten words slow down, to a certain degree, the initial access to the abstract representations in the mental lexicon.

To examine whether there is always a magnification of the word-frequency effect (i.e., the most studied lexical effect) with handwritten words, we conducted three lexical decision experiments. To that end, we employed difficult-to-read handwritten words and easy-to-read handwritten words. A preliminary question is how to categorize the handwritten styles as "easy-to-read" vs. "difficult-to-read" in a principled way. Unfortunately, the current implementation of the letter-feature level in models of visual word recognition does not include a fine-grained level of specificity that helps predict which features of a letter/word are more important than others (see Balota, Yap, & Cortese, 2006; Davis, 2010; Schomaker & Segers, 1999; see also Gauthier, Wong, Hayward, & Cheung, 2006, for a discussion on font tuning and letter expertise). In fact, the letter-feature level in the family of interactive activation models employs an all-uppercase font that is composed of unrealistic straight lines (Rumelhart & Sipple, 1974). Given these issues, Qiao et al. (2010) employed an empirical approach (i.e., naming times) to categorize the handwriting styles as "easy" or "difficult". Similarly to Qiao et al. (2010), we also used an empirical criterion to categorize the handwritten style as easy vs. difficult to read. In a pilot phase of the current research, we asked eight volunteers to write down ten sentences, and then we asked five naïf judges to choose in a 1-to-5 Likert scale the readability of the handwritten sentences. The volunteer with the worst penmanship (mean: 2.3) was the individual that wrote the "difficult-to-read" handwritten stimuli (e.g., boxeo, brazo, cocina, época, música, pésimo, puñal, tiempo, and torero), whereas the person with the best penmanship (mean: 4.2) was the individual that wrote the "easy-to-read" handwritten stimuli (e.g., boxeo, brazo, cocina, época, música, pésimo, puñal, tiempo, and torero) (see also Gil-López et al., 2011, for an empirical criterion to categorize "easy-to-read" handwritten words). What we should stress here is that our goal was not to provide a systematic examination of why some handwritten styles are more difficult than others. Instead, our goal was to examine whether there is an additive or an interactive pattern of script (handwritten, printed) and word-frequency (low, high) when the handwritten words are easy to read —for comparison purposes, we also examined the interaction between script and word-frequency for difficult-to-read handwritten words.

In Experiments 1 and 2, the two critical factors for the word stimuli were Script (printed, handwritten) and Word-frequency (low, high). We employed difficult-to-read handwritten word in Experiment 1 and easy-to-read handwritten words in Experiment 2. In Experiment 3, we employed all three scripts (i.e., easy-to-read handwritten words, difficult-to-read handwritten words, printed words) in a within-subject design. The predictions are clear. If the impaired processing in the initial formation of the orthographic code that occurs with handwritten words (e.g., Gil-López et al., 2011) produces an increased top-down lexical feedback, we expect a magnification of lexical effects (e.g., word-frequency) not only with difficult-to-read handwritten words but also with easy-to-read handwritten words. Alternatively, if the magnification of lexical effects with handwritten words is due to the difficulty of processing the word's constituent letters (i.e., noisy/ambiguous bottom-up input), the magnification of the word-frequency effect should occur for those handwritten words that are difficult to read but not for those handwritten words that are easy to read (i.e., additive effects of word-frequency and script for easy-to-read handwritten words). What we should note here is that Barnhart and Goldinger (2010) indicated in Footnote 1 that they included "computer-generated cursive" words and "human print" word in a pilot stage of their study. They added: "the computer-generated cursive and human print conditions produced results that were equivalent to the computer print condition and are thus excluded for brevity" (p. 908). No further information was provided, however, on the findings they obtained (i.e., whether there was an effect of script or whether there were additive effects of script and word-frequency).

In the current experiments, we report not only the analyses on the mean response times (RTs), but we also examined the RT distributions. Analyses on the RT distributions provide more constraining information on the nature of the effects under scrutiny than the analyses on the mean RTs (Ratcliff, Gomez, & McKoon, 2004; see also Gomez, Perea, & Ratcliff, 2013; Perea, Abu Mallouh, & Carreiras, 2013; Perea, Vergara-Martínez, & Gomez, 2015). First, an effect that only affects the early encoding (non-decisional) components of visual word recognition should produce changes in the mean RTs and are reflected as a *shift* of the RT distributions (i.e., similar magnitude of the effect across quantiles; e.g., identity vs. unrelated condition in masked priming; see Gomez et al., 2013; Perea, Vergara-Martínez, & Gomez, 2015; inter-letter spacing; Perea & Gomez, 2012; rotated words: Gomez & Perea, 2014). Second, an effect that affects the "quality of information" in a decision stage of the lexical decision task should produce not only changes in the mean RTs but also changes in the shape of the RT distributions (i.e., a greater magnitude of the effect in the higher quantiles than at the leading edge of the RT distribution) and more errors in the slower condition (e.g., the word-frequency effect; see Ratcliff et al., 2004).

Experiment 1 (difficult-to-read handwritten stimuli)

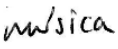
A second goal of Experiments 1 and 2 was to examine to what degree the processing differences between handwritten and printed words can be affected by the participants' strategies. As indicated earlier, Corcoran and Rouse (1970) reported that, in a perceptual identification task, the advantage of printed words on the handwritten words differs in blocked and mixed lists of handwritten/printed words. They suggested by the processing underlying the identification of perception of handwritten words might be quite different form the perception of printed words. Specifically, Corcoran and Rouse claimed: "the input is processed according to one procedure for handwriting and another for printing" (p. 530, but see Manso De Zuniga et al., 1991, for criticism). To re-examine this issue in a response time task, participants were presented with pure blocks of stimuli (handwritten or printed) and with mixed blocks composed of printed and handwritten stimuli (see Perea, Carreiras, & Grainger, 2004, for a similar procedure). If participants employ different procedures when processing handwritten words in pure and mixed lists—as suggested by Corcoran and Rouse, one would expect an interaction between Script and Block. Alternatively, if the visual word recognition system employs a single procedure for handwritten and printed words—as suggested by Manso De Zuniga et al. (1991), one would expect an effect of Script (printed, handwritten) that does not interact with Block.

Method

Participants

Forty psychology students from the University of Valencia, all of them native speakers of Spanish and with normal/corrected-to-normal vision, participated in the experiment for extra course credit.

Materials

We selected 320 words of five/six letters from the Spanish B-Pal database (Davis & Perea, 2005). One hundred sixty of these words were of high frequency (mean frequency per million words: 153.0) and the other 160 words of low frequency (mean 4.7 per million). The mean of Coltheart's N (i.e., a measure of neighborhood size; see Coltheart, Davelaar, Jonasson, & Besner, 1977) was 2.1 and 2.4 for the high- and low-frequency words, respectively. The number of letters was 5.5 in each frequency group. For the purposes of the lexical decision task, we employed 320 orthographically legal nonwords of the same length as the words. These nonwords were generated using Wuggy (Keuleers & Brysbaert, 2010). The list of words and nonwords is presented in the Appendix. Printed stimuli were presented written on a computer in Century size 16-pt. All the handwritten stimuli, both words and nonwords, were written by someone with bad penmanship (e.g., compare  and  with música and puñal, respectively; see Introduction). These handwritten stimuli were scanned and scaled to approximately match the printed stimuli dimensions. The stimuli were presented in pure/mixed blocks, mimicking the procedure used in blocking experiments of Perea et al. (2004). For each participant, there was a pure block with 160 printed stimuli (80 words and 80 nonwords) and a pure block with 160 handwritten stimuli (80 words and 80 nonwords). In addition, two mixed blocks consisting of an equal number of printed/handwritten stimuli were included. Assigning words to the conditions were arranged in a Latin-square manner. For example, if the word "animal" was presented printed on a pure block for Group 1, it would be presented handwritten in a pure block for Group 2, it would be presented printed on a mixed block for Group 3, and it would be presented handwritten on a mixed block for Group 4. All experimental participants received four blocks (two pure blocks [one handwritten and one printed]) and two mixed blocks. The order of the stimuli in each block was randomized for each participant.

Procedure

The experimental session took place individually in a quiet room. To present the stimuli on the computer screen and register the responses, we employed DMDX software (Forster & Forster, 2003). Here is the sequence of stimuli in each trial. A fixation point (‘‘+’’) was presented at the center of the screen for 750 ms. Then, a lowercase stimulus (word/nonword) was presented and remained on the screen until the participant’s response or 2.5 sec had passed. Participants were instructed to press the "sí" [yes] button when letter string formed a real Spanish word and the "no" button when the letter string did not form a word. This decision was to be made as rapidly and accurately as possible. There was a break after each block; thus, the 640 experimental trials were divided into four blocks of 160 trials. Each participant received a total of 20 practice trials prior to the experimental phase. The session lasted approximately 20 min.

Results and Discussion

Error responses (5.7% of the data) and correct RTs beyond the 250-1500 ms cutoffs (less than 1.6% of the data) were excluded from the latency analyses. The mean RTs and error percentages from the subject analysis are presented in Table 1. For the word data, separate ANOVAs were conducted on the mean RTs and error rate per condition based on a 2 (script: printed, handwritten) x 2 (word-frequency: low, high) design. For the nonword data, the only factor in the design was script (printed, handwritten). As indicated in the Method section, type of block (pure, mixed) was also a factor in the design. However, the statistical analyses of pure/mixed blocks revealed a similar pattern of data; thus, for simplicity's purposes, we don't include/report type of block in the statistical analyses. In this and subsequent experiments, List (list 1, list 2, list 3, list 4) was included as a (dummy) factor in the design to extract the error variance due to the lists (see Pollatsek & Well, 1995). The statistical analyses on the mean RTs were conducted over subjects ($F1$) and over items ($F2$). The RT distributions were examined using the .1, .3, .5, .7, and .9 quantiles (see Gomez et al., 2013; Perea et al., 2014, 2015, for a similar procedure) instead of the mean RTs.

Please insert Table 1 and Figure 1 around here

Word stimuli. The ANOVA on the mean RTs revealed an advantage of printed words over handwritten words (50 ms, $F1(1, 36) = 152.72$, $p < 0.001$, $F2(1, 318) = 189.6$, $p < 0.001$) and an advantage of high-frequency words over low-frequency words (63 ms, $F1(1, 36) = 216.44$, $p < 0.001$; $F2(1, 318) = 167.99$, $p < 0.001$). The interaction between the two factors was significant ($F1(1, 36) = 10.77$, $p = 0.002$; $F2(1, 318) = 8.56$, $p < 0.004$). This reflected that the size of the word-frequency effect was greater for handwritten words than for printed words (73 vs. 54 ms, respectively).

The ANOVA on the error data showed that participants committed more errors to handwritten words than to printed words (7.4 vs. 3.5%), $F1(1, 36) = 66.61$, $p < 0.001$, and participants committed more errors to low-frequency than to high-frequency words (8.1 vs. 2.8%), $F1(1, 36) = 123.93$, $p < 0.001$. The magnitude of the word-frequency effect was greater for handwritten than for printed words (6.7 vs. 3.9%, respectively), as deduced from an interaction between the two factors, *F*1(1, 36) = 12.24, *p* = 0.001.

Analyses of the RT distributions in Figure 1 reveal an advantage of printed words over handwritten words (*F*(1,36) = 136.81, *p* < .001) and an advantage of high-frequency words over low-frequency words (*F*(1,36) = 193.82, *p* < .001). As in the mean RT analysis, the effect of word-frequency was greater for handwritten words than for printed words (script x word-frequency interaction, *F*(1,36) = 16.64, *p* = .001). The advantage of printed words over handwritten words was greater in the higher than in the lower quantiles (30, 40, 52, 66, and 90 ms at the .1, .3, .5, .7, and .9 quantiles, respectively; script x quantile interaction, *F*(4,144) = 22.64, *p* < .001). Likewise, the advantage of high-frequency words over low-frequency words was greater in the higher quantiles than in the lower quantiles (38, 53, 67, 85, and 106 ms at the .1, .3, .5, .7, and .9 quantiles, respectively; word-frequency x quantile interaction, *F*(4,144) = 26.88, *p* < .001). Finally, the three-way interaction between script, word-frequency, and quantile was also significant (*F*(4,144) = 5.26, *p* = .001). This reflected that the effect of word-frequency across quantiles increased more sharply for handwritten words than for printed words (handwritten words: 42, 59, 77, 103, and 129 ms at the .1, .3, .5, .7, and .9 quantiles; printed words: 34, 46, 57, 68, and 82 ms, at the .1, .3, .5, .7, and .9 quantiles, respectively).

Nonword stimuli. The ANOVA on the latency data revealed that mean RTs were longer to handwritten nonwords than to printed nonwords (77 ms), *F*1(1, 36) = 125.21, *p* < 0.001; *F*2(1, 319) = 386.9, *p* < 0.001.

The analysis of the RT distributions for nonword stimuli showed an advantage of printed over handwritten nonwords (*F*(1,36) = 160.43, *p* < .001). This advantage increased at the higher quantiles (46, 66, 82, 105, and 160 ms at the .1, .3, .5, .7, and .9 quantiles, respectively; script x quantile interaction: *F*(4,144) = 47.73, *p* < .001).

The ANOVA on the error data only revealed that participants committed more errors to handwritten than to printed nonwords (6.8 vs. 5.4%, respectively), $F1(1, 36) = 7.66$, $p = 0.009$.

In sum, the present experiment revealed a substantial advantage of printed stimuli over difficult-to-read handwritten stimuli in the latency (mean RTs, distributions of RTs) and accuracy data for both words and nonwords. This was accompanied by a greater word-frequency effect for difficult-to-read handwritten than for printed words. Therefore, these data successfully replicated the pattern of data reported by Manso De Zuniga et al. (1991) and Barnhart and Goldinger (2010, 2013). Finally, the magnitude of the effects of word frequency and script was larger in the higher quantiles of the RT distributions. This strongly suggests that these effects were not just affecting a non-decisional encoding component of the word recognition stream, but rather a decision component (see Gomez & Perea, 2014). Finally, if block (pure, mixed) had been included in the statistical analyses for the word data, there would only be an overall 11-ms advantage in pure blocks over mixed blocks, but this was accompanied by more errors in pure blocks (1.1%; i.e., a speed-accuracy trade-off)—note that there were no signs of an interaction with script or word-frequency. This finding reinforces the idea that the visual word recognition system used a single procedure for both handwritten and printed words (Mason De Zuniga et al., 1991).

The question now is whether the magnification of the word-frequency effect occurs when the handwritten words are relatively easy to read. To that end, we designed Experiment 2. This experiment was parallel to Experiment 1 except that an individual with good penmanship wrote the handwritten words and nonwords. What we should stress here is that easy-to-read handwritten prime words can produce significant masked repetition effects in a lexical decision task (Gil-López et al., 2011). However, the magnitude of these effects was somewhat smaller than that with printed primes (31 vs. 45 ms, respectively). This suggests that there is some initial reading cost in the course of word processing due to the regularization of the handwritten stimuli. Thus, the question is whether or not this reading cost necessarily produces a magnification of lexical effects (i.e., word-frequency) relative to printed words.

Experiment 2 (easy-to-read handwritten stimuli)

Method

Participants

Forty students from the University of Valencia, all of them native speakers of Spanish, took part voluntarily in the experiment. None of them had taken part in Experiment 1.

Materials

They were the same as in Experiment 1, with the exception that the handwritten words were written by someone with better penmanship than in Experiment 1 (e.g., compare música and puñal with música and puñal; see details in the Introduction).

Procedure

It was the same as in Experiment 1.

Results and Discussion

Error responses (3.7% of the data) and correct RTs beyond the 250-1500 cutoffs (less than 2.1% of the data) were excluded from the RT analyses. The mean RTs and error percentages from the subject analysis are presented in Table 2. The statistical analyses paralleled those of Experiment 1. As occurred in Experiment 1, the pattern of findings was essentially the same in pure and mixed blocks—there were no signs of a main effect of block or an interaction with script or word-frequency.

Please insert Table 2 and Figure 2 around here

Word stimuli. The ANOVA on the mean RTs revealed that, on average, printed words were responded to faster than the handwritten words (24 ms), $F1(1, 36) = 34.08$, $p < 0.001$; $F2(1, 318) = 49.85$, $p < 0.001$, and high-frequency words were responded to faster than low-frequency words (59 ms), $F1(1, 36) = 274.85$, $p < 0.001$; $F2(1, 318) = 189.3$, $p < 0.001$. More important, unlike Experiment 1, there were no signs of a script x word-frequency interaction, both *F*s < 1: indeed, the size of the word-frequency effect was virtually the same for handwritten words and printed words (59 and 59 ms, respectively; unsurprisingly, the corresponding Bayesian $p(H_0/D)$ value for the lack of interaction is above .99).

As in Experiment 1, the analyses of the RT distributions revealed an advantage of printed words over handwritten words ($F1(1,36) = 30.76$, $p < .001$) and an advantage of high-frequency words over low-frequency words ($F1(1,36) = 223.36$, $p < .001$). However, unlike Experiment 1, there were no trends of an interaction between script and word-frequency ($F < 1$). The advantage of printed words over handwritten words increased in the higher quantiles (15, 21, 24, 29, and 42 ms at the .1, .3, .5, .7, and .9 quantiles, respectively; script x quantile interaction, $F1(1,36) = 3.39$, $p = .011$). The advantage of high-frequency words over low-frequency words was substantially greater in the higher than in the lower quantiles (36, 46, 61, 85, and 117 ms at the .1, .3, .5, .7, and .9 quantiles, respectively; word-frequency x quantile interaction, $F1(1,36) = 37.95$, $p < .001$). The three-way interaction between script, word-frequency, and percentile did not approach significance ($F1(1,36) = 1.06$, $p = .38$).

The ANOVA on the error data showed that participants committed more errors to handwritten words than to printed words (3.6 vs. 2.6%, respectively), $F1(1,36) = 11.26$, $p = 0.002$, and participants committed more errors on low-frequency words than high frequency words (5.0 vs. 1.2%), $F1(1,36) = 58.47$, $p < 0.001$. The interaction between the two factors was not significant ($p > .15$).

Nonword stimuli. The ANOVA on mean RTs revealed a 32-ms advantage of printed over handwritten nonwords, $F1(1, 36) = 11.58$, $p = 0.002$; $F2(1, 319) = 78.94$, $p< 0.001$.

The analysis of the RT distributions for nonword stimuli showed an advantage of printed nonwords over handwritten nonwords ($F(1,36) = 12.93$, $p < .001$). This advantage increased at the higher quantiles (19, 28, 35, 41, and 59 ms at the .1, .3, .5, .7, and .9 quantiles, respectively; script x quantile interaction: $F(4,144) = 6.41$, $p < .001$).

The ANOVA on the error data did not reveal any significant effects.

The current experiment showed that word (and nonword) identification times were faster for printed words than for easy-to-read handwritten words. This difference, while sizeable, was smaller than that obtained with difficult-to-read handwritten words in Experiment 1 (see Tables 1 and 2). Further, the magnitude of the effect of script increased at the higher quantiles, and there were more errors to handwritten than for printed stimuli. That is, the reading cost of easy-to-read handwritten stimuli relative to printed stimuli cannot be solely due to an early letter-encoding component. As indicated in the Introduction, if the effect of script had only occurred in an early encoding (non-decisional) component, there should have been a *shift* in the RT distributions and little/no effect in the error rates (see Gomez & Perea, 2014; Perea & Gomez, 2012, for instances of such effects). However, there was a change in the shape of the RT distributions (i.e., the slower condition also showed more positive asymmetry), and this was accompanied by more errors to handwritten stimuli than to printed stimuli. Therefore, the effect of script affected the “quality of information” in the decision process.

But the critical finding is that, despite the reading cost with easy-to-read handwritten words, the magnitude of the word-frequency effect was virtually the same for printed and handwritten words (see Table 2 and Figure 2). Therefore, the magnification of lexical effects is *not* an inherent characteristic of handwritten words. To empirically corroborate this conclusion, we conducted a combined analysis on the mean RTs of Experiments 1 and 2 (i.e., Experiment was included as a between-subjects factor in the design). The joint ANOVA on the RT data revealed a three-way interaction between Experiment, Script, and Word-frequency, $F1(1,72) = 7.19$, $p = .009$; $F2(1,318) = 4.08$, $p = .044$.

One potential limitation of Experiments 1 and 2 is that the manipulation of handwriting difficulty involved different samples of participants (difficult-to-read handwritten words vs. printed words in Experiment 1; easy-to-read handwritten words vs. printed words in Experiment 2). Experiment 3 was designed to replicate the main findings of Experiments 1 and 2 in a within-subject design. In Experiment 3, participants were presented with easy-to-read handwritten words, difficult-to-read handwritten words, and printed words. Thus, the factors were type of script and word-frequency (low- vs. high-frequency). Based on the findings of Experiments 1 and 2, we expect: 1) a greater word-frequency effect for difficult-to-read handwritten words than for printed words; and 2) a similar magnitude of the word-frequency effect for easy-to-read handwritten words and for printed words. (footnote 1)

Experiment 3 (printed, easy-to-read and difficult-to-read handwritten stimuli)

Method

Participants

Fifteen students from the same population as in Experiments 1 and 2 took part voluntarily in the experiment in exchange for extra course credit.

Materials

We used the same materials as in Experiments 1 and 2. Each stimulus could be presented: i) in an easy-to read handwritten form; ii) in a difficult-to read handwritten form; or iii) printed. Because the number of words (and nonwords) in Experiments 1 and 2 was not a multiple of 3 (320 words and 320 nonwords), we randomly chose a set of 312 words and 312 nonwords from Experiments 1-2 and created three lists in a Latin square manner. There were 52 items per condition for the word items (312 words, 6 conditions), and 104 items per condition for the nonword items (312 words, 3 conditions).

Procedure

It was the same as in Experiments 1 and 2, except that all trials were presented in random order.

Results and Discussion

Error responses (6.0% of the data) and correct RTs beyond the 250-1500 cutoffs (less than 1% of the data) were excluded from the latency analyses. The mean RTs and error percentages from the subject analysis are presented in Table 3. For the word data, separate ANOVAs were conducted on the mean RTs and error rate per condition based on a 3 (script: difficult-to-read handwritten, easy-to-read handwritten, printed) x 2 (word-frequency: low, high). For the nonword data, there was only one factor, script (difficult-to-read handwritten, easy-to-read handwritten, printed). The analyses on the

RT distributions were based on the .1, .3, .5, .7, and .9 quantiles.

Please insert Table 3 and Figure 3 around here

Word stimuli. The ANOVA on the mean RTs revealed faster response times for high-frequency words than for low-frequency words (50 ms, $F1(1, 12) = 180.7$, $p < 0.001$; $F2(1, 306) = 162.68$, $p < 0.001$). The main effect of script was also significant ($F1(2,24) = 55.4$, $p < 0.001$, $F2(2, 612) = 56.17$, $p < 0.001$: difficult-to-read handwritten [619 ms] > easy-to-read handwritten [587 ms] > printed [573 ms]; all *p*s < 0.016). Importantly, the interaction between script x word-frequency was significant, $F1(2,24) = 5.69$, $p = 0.008$; $F2(2, 612) = 3.81$, $p = 0.023$. This interaction reflected that the advantage of word-frequency effect was greater for difficult-to read handwritten words (63 ms) than for easy-to-read handwritten words (46 ms) or printed words (41 ms).

The analyses of the RT distributions revealed an advantage of high-frequency words over low-frequency words ($F1(1,12) = 103.29$, $p < .001$). The main effect of script was also significant ($F1(2,24) = 63.18$, $p < .001$): this reflected an advantage of printed over easy-to-read handwritten words, and in turn, an advantage of easy-to-read handwritten words over difficult-to-read handwritten words (see Figure 3). The interaction between script and word-frequency was significant ($F1(2,24) = 4.51$, $p = .02$). In addition, the advantage of high-frequency words over low-frequency words was substantially greater in the higher quantiles (22, 44, 59, 74, and 108 ms at the .1, .3, .5, .7, and .9 quantiles, respectively; word-frequency x quantile interaction, $F1(4,48) = 12.53$, $p < .001$), and the effect of script also increased in the higher quantiles (script x quantile interaction, $F1(8,96) = 2.65$, $p = .011$). Note that the effect of script across quantiles resembled that of Experiments 1 and 2: easy-to-read vs. printed words: 3, 19, 17, 19, and 22 ms at the .1, .3, .5, .7, and .9 quantiles; difficult-to-read vs. printed words: 29, 41, 47, 56, and 74 ms, at the .1, .3, .5, .7, and .9 quantiles.

The ANOVA on the error data revealed that participants committed more errors to low-frequency words than to high-frequency words, $F(1,12) = 43.75$, $p < 0.001$. The main effect of script was significant, $F(2,24) = 13.85$, $p < 0.001$ (difficult handwritten [9.2 %] > easy handwritten [4.9%] = printed [4.2%]; all *p*s < 0.004). Although the interaction between the two factors was not significant ($F(2,24) = 1.95$, $p = 0.16$), the pattern of data was parallel to that of the response times: the magnitude of the word-frequency effect was 8.0% for the difficult-to-read handwritten words, whereas it was 5.4% for the easy-to-read handwritten words and 5.0% for the printed words.

Nonword stimuli. The ANOVA on the mean RTs revealed an effect of script ($F1(2,28) = 24.02$, $p < 0.001$, $F2(2, 618) = 35.18$, $p < 0.001$: difficult handwritten [701 ms] > easy handwritten [677 ms] > printed [653 ms]; all *p*s < 0.005).

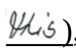
The analyses of the RT distributions revealed an effect script ($F1(2,24) = 35.19$, $p < 0.001$). This effect increased in the higher quantiles (script x quantile interaction: $F1(8,96) = 11.29$, $p < 0.001$).

The ANOVA on the error data did not reveal a significant effect of script ($F(2,28) = 1.49$, $p = 0.24$).

The present experiment replicated and extended the findings of Experiments 1 and 2 in a within-subject design. First, word (and nonword) identification times were longer for difficult-to-read handwritten stimuli than for the easy-to-read handwritten stimuli, and word identification times were longer for easy-to-read handwritten stimuli than for printed stimuli. Second, difficult-to-read handwritten words produced a magnification of lexical effects (i.e., a larger word-frequency effect) when compared to printed words. Third, easy-to-read handwritten words produced a word-frequency effect of similar magnitude as the printed words.

General Discussion

Why are word identification times faster for printed than for handwritten words? Manso De Zuniga et al. (1991) and Barnhart and Goldinger (2010, 2013) claimed that the natural physical ambiguity of handwritten words requires greater reliance on top-down processes. As a result, all lexical effects (e.g., the word-frequency effect) should be magnified in handwritten words relative to printed words. The present series of experiments qualify this claim. When the handwritten words are difficult to read, the word-frequency effect is greater with handwritten words than with printed words (Experiments 1 and 3). This finding is consistent with the idea of greater reliance on top-down effects with handwritten words and it replicates earlier research (Barnhart & Goldinger, 2010, 2013; Manso De Zuniga et al., 1991). However, when the handwritten words are easy to read, there is a reading cost (i.e., an advantage of printed over handwritten words), but the effects of script and word-frequency are additive (Experiments 1 and 3).

The overall differences in processing between handwritten and printed words can be readily explained in terms of a "normalization process" that would operate at the feature-to-letter levels (see Manso De Zuniga et al., 1991). When the handwritten words are difficult to process (e.g., when reading a handwritten word like ), such "normalization process" also entails an extra processing cost during the course of lexical access. As can be seen in Figures 1 and 3, the advantage of the printed vs. difficult-to-read handwritten words increases dramatically in the higher quantiles.

Furthermore, this was also accompanied by more errors for difficult-to-read words. That is, difficult-to-read handwritten words produce substantially lesser quality of information than printed words during the decision process in a lexical decision task, and this magnifies the magnitude of the word-frequency—note that the effect of script is magnified for nonwords as these stimuli do not benefit from top-down lexical feedback. As Barnhart and Goldinger (2013) claimed, “in perception, as a general rule, when bottom-up cues become less reliable, top-down processing tends to increase (Becker & Killion, 1977).” (p. 1320) This interpretation is consistent with the fMRI data from Qiao et al. (2010), who reported that there is extra activation in a bilateral frontoparietal network (i.e., an area related to attentional processing) in difficult-to-read handwritten words as compared to easy-to-read handwritten words.

Unsurprisingly, easy-to-read handwritten words also reflected an overall reading cost relative to printed words (Experiments 2 and 3). In a masked priming lexical decision experiment, Gil-López et al. (2011) reported that easy-to-read handwritten primes do not activate the target words to the same degree as printed primes. Similarly, Qiao et al. (2010) found that easy-to-read handwritten words produce extra activation in the right fusiform area when compared to printed words. More importantly, for the easy-to-read handwritten words, the effects of script and word-frequency were noticeably additive (see Tables 2 and 3; see Figures 2 and 3).

How can we explain that difficult-to-read handwritten words produce a script x word-frequency interaction, whereas easy-to-read handwritten words produce additive effects of script and word-frequency? The additivity of the effects of script and word-frequency for easy-to-read handwritten words can be readily interpreted in terms of two-staged models of word recognition (i.e., script would affect an early encoding stage and word-frequency would affect a later stage). However, these models would need to add extra assumptions to explain the script x word-frequency interaction with difficult-to-read handwritten words. Instead, the most parsimonious explanation is through the balance of bottom-up and top-down activity in a fully interactive model of visual word recognition (e.g., in an adaptive resonance framework; see Stone & Van Orden, 1994). When the handwriting is close to pristine (i.e., easy-to-read handwritten words), the bottom-up signal is strong, thus necessitating less top-down activation. When the handwriting is scruffy, the bottom-up signal is weak, and consequently top-down processes can exert a greater influence—this increases the effect of word-frequency and it also increases the effect of script for nonwords. Indeed, Barnhart and Goldinger (2010) had already anticipated that easy-to-read handwritten words could produce a pattern of data “equivalent to the computer print condition” (p. 908). This explanation is perfectly compatible with the absence of a blocking effect (i.e., pure vs. mixed lists of handwritten and printed stimuli) in Experiments 1 and 2. That is, as Manso De Zuniga et al. (1991) anticipated, the differences found when reading printed words and handwritten words can be parsimoniously explained on the basis of the greater vs. lesser “top-down” demands required by each script rather than by the existence of two fundamental different procedures.

In sum, the present experiments demonstrated that the quality of handwritten words moderates the recruitment of top-down mechanisms of perception, as reflected in word frequency effects. While the inherent physical variability of handwritten words produces a reading cost relative to the printed words (e.g., longer response times, more skewed response time distributions, decrease in accuracy), it does not necessarily lead to a magnification of lexical effects. Instead, the magnification of lexical effects is better explained by the unfamiliar characteristics of the handwritten words’ constituent letters (i.e., noisy and ambiguous forms such as  [this]). Further research is needed to clarify how (and when) the brain responds to easy-to-read and difficult-to-read handwritten words.

References

Balota, D. A., Aschenbrenner, A. J., & Yap, M. J. (2013). Additive effects of word frequency and stimulus quality: The influence of trial history and data transformations. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39*, 1563-1571. DOI: 10.1037/a0032186

Balota, D., Yap, M. J., & Cortese, M. J. (2006). Visual word recognition: The journey from features to meaning (A travel update). In M. Traxler and M. A. Gernsbacher (Eds.), *Handbook of Psycholinguistics* (2nd edition) (pp. 285-375). Amsterdam: Academic Press.

Barnhart, A. S., & Goldinger, S. D. (2010). Interpreting chicken-scratch: Lexical access for handwritten words. *Journal of Experimental Psychology. Human Perception and Performance*, *36*, 906-923. DOI: 10.1037/a0019258

Barnhart, A. S., & Goldinger, S. D. (2013). Rotation reveals the importance of configural cues in handwritten word perception. *Psychonomic Bulletin and Review*, *20*, 1319-1326. DOI 10.3758/s13423-013-0435-y

Becker, C. A., & Killion, T. H. (1977). Interaction of visual and cognitive effects in word recognition. *Journal of Experimental Psychology: Human Perception and Performance, 3,* 389-401. DOI:10.1037/0096-1523.3.3.389

Carreiras, M., Armstrong, B. C., Perea, M., & Frost, R. (2014). The what, when, where, and how of visual word recognition. *Trends in Cognitive Sciences*, *18,* 90-98. DOI: 10.1016/j.tics.2013.11.005

Coltheart, M., Davelaar, E., Jonasson, J. F., & Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Ed.), *Attention and Performance VI* (pp. 535-555). Hillsdale, NJ: Erlbaum.

Corcoran, D. W., & Rouse, R. O. (1970). An aspect of perceptual organization involved in reading typed and handwritten words. *Quarterly Journal of Experimental Psychology*, *22*, 526-530. DOI: 10.1080/14640747008401930

Davis, C. J. (2010). The spatial coding model of visual word identification. *Psychological Review, 117*, 713-758. DOI: 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. DOI: 10.3758/bf03192738

Forster, K. I. (1998). The pros and cons of masked priming. *Journal of Psycholinguistic Research, 27*, 203-233. DOI: 10.1023/A:1023202116609

Forster, K. I., & Forster, J. C. (2003). DMDX: A Windows display program with millisecond accuracy. *Behavior Research Methods, Instruments, and Computers, 35*, 116-124. DOI: 10.3758/BF03195503

Gauthier, I., Wong, A. C., Hayward, W. G., & Cheung, O. S. (2006). Font tuning associated with expertise in letter perception. *Perception, 35*, 541-559. DOI: 10.1068/p5313

Gil-López, C., Perea, M., Moret-Tatay, C., & Carreiras, M. (2011). Can masked priming effects be obtained with words? *Attention, Perception, and Psychophysics, 73*, 1643-1649. DOI: 10.3758/s13414-011-0174-y

Gomez, P. (2012). Mathematical models of the lexical decision task. In J. Adelman (Ed.), *Visual word recognition (Volume 1): Models and methods, orthography and phonology* (pp. 70-89). Hove, England: Psychology Press.

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

Gomez, P., Perea, M., & Ratcliff, R. (2013). A diffusion model account of masked vs. unmasked priming: Are they qualitatively different? *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 1731-1740. DOI: 10.1037/a0032333

Hellige, J. B., & Adamson, M. M. (2007). Hemispheric differences in processing handwritten cursive. *Brain and Language, 102*, 215-227. DOI: 10.1016/j.bandl.2006.11.003

Keuleers, E., & Brysbaert, M. (2010). Wuggy: A multilingual pseudoword generator. *Behavior Research Methods, 4*, 627-633. DOI: 10.3758/BRM.42.3.627

Manso De Zuniga, C., Humphreys, G. W., & Evett, L. J. (1991). Additive and interactive effects of repetition, degradation, and word frequency in the reading of handwriting. In D. Besner and G. W. Humphreys (Eds.), *Basic processes in reading: Visual word recognition* (pp. 10-33). Hillsdale, NJ: Erlbaum.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: I. An account of basic findings. *Psychological Review, 88*, 375-407. doi:10.1037/0033-295x.88.5.375

Perea, M., & Gomez, P. (2012). Increasing interletter spacing facilitates encoding of words. *Psychonomic Bulletin and Review, 19*, 332-338. DOI: 10.3758/s13423-011-0214-6

Perea, M., Abu Mallouh, & Carreiras, M. (2014). Are root letters compulsory for lexical access in Semitic languages? The case of masked form-priming in Arabic. *Cognition, 132*, 491-500. DOI: 10.1016/j.cognition.2014.05.008

Perea, M., Carreiras, M., & Grainger, J. (2004). Blocking by word frequency and neighborhood density in visual word recognition: A task-specific response criteria account. *Memory and Cognition, 32*, 1090-1102. DOI: 10.3758/BF03196884

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. DOI: 10.1016/j.cognition.2015.05.007

Plaut, D. C., & Booth, J. R. (2006). More modeling but still no stages: Reply to Borowsky and Besner. *Psychological Review, 113,* 196-200. DOI:10.1037/0033-295X.113.1.196

Pollatsek, A., & Well, A. D. (1995). On the use of counterbalanced designs in cognitive research: a suggestion for a better and more powerful analysis. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21*, 785-794. DOI: 10.1037/0278-7393.21.3.785

Qiao, E., Vinckier, F., Szwed, M., Naccache, L., Valabrègue, R., Dehaene, S., et al. (2010). Unconsciously deciphering handwriting: Subliminal invariance for handwritten words in the visual word form area. *NeuroImage*, *49*, 1786-1799. DOI: 10.1016/j.neuroimage.2009.09.034

Ratcliff, R., Gomez, P., & McKoon, G. (2004). A diffusion model account of the lexical decision task. *Psychological Review, 111,* 159-182. DOI:10.1037/0033-295X.111.1.15

Rumelhart, D. E., & Sipple, P. (1974). Process of recognizing tachistoscopically presented words. *Psychological Review, 87,* 99-118. DOI: 10.1037/h0036117

Schomaker, L., & Segers, E. (1999). Finding features used in the human reading of cursive hand-writing. *International Journal on Document Analysis and Recognition*, *2*, 13-18.

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*, 1248-1288. DOI: 10.1037/0096-1523.20.6.1248

Wing, A. M. (1979). Variability in handwritten characters. *Visible Language, 13*, 283-298.

Table 1. Mean response times (RT, in ms) and percentages of error (ER, in %) for words and nonwords in Experiment 1 (difficult-to-read handwritten stimuli). Standard errors (SEs) are presented between brackets.

	Type of stimulus			
Stimuli	Handwritten		Printed	
	RT	ER	RT	ER
Words				
High-Frequency	617 (12)	4.0 (0.5)	576 (12)	1.6 (0.3)
Low-Frequency	690 (13)	10.8 (0.8)	630 (12)	5.5 (0.5)
Word-frequency effect	73	6.8	54	3.9
Nonwords	787 (17)	6.8 (1.2)	710 (14)	5.4 (0.9)

Table 2. Mean response times (RT, in ms) and percentages of error (ER, in %) for words and nonwords in Experiment 2 (easy-to-read handwritten stimuli). Standard errors (SEs) are presented between brackets.

	Type of stimulus			
Stimuli	Handwritten		Printed	
	RT	ER	RT	ER
Words				
High-Frequency	517 (16)	1.4 (0.2)	493 (16)	0.9 (0.2)
Low-Frequency	576 (19)	5.8 (0.6)	552 (18)	4.2 (0.7)
Word-frequency effect	59	7.9	59	5.7
Nonwords	657 (24)	5.2 (0.7)	625 (24)	4.8 (1.0)

Table 3. Mean response times (TR, in ms) and percentages of error (ER, in %) for words and nonwords in Experiment 3. Standard errors (SEs) are presented between brackets.

	Type of stimulus					
Stimuli	Handwritten (Difficult)		Handwritten (Easy)		Printed	
	RT	ER	RT	ER	RT	ER
Words						
High-Frequency	588 (19)	5.3 (1.3)	564 (20)	2.2 (0.3)	552 (19)	1.7 (0.5)
Low-Frequency	651 (21)	13.2 (2.5)	610 (22)	7.6 (1.3)	594 (22)	6.7 (1.2)
Word-frequency effect	63	7.9	46	5.7	42	5.0
Nonwords	701 (25)	5.4 (0.9)	677 (23)	7.1 (1.4)	653 (23)	5.4 (1.7)

-

Footnotes

Footnote 1. As a reviewer indicated, perhaps the easy-to-read writer produced nonwords more dysfluently than words, and these cues might have facilitated lexical decision responses, and artificially reduced the word frequency effect in Experiment 1. These cues were presumably smaller for the hard-to-read writer (Experiment 2), as all stimuli were highly dysfluent. Therefore, designing an experiment with both easy-to-read and difficult-to-read handwritten stimuli would minimize the impact of these dysfluencies in lexical decision.

Figure Legends

Figure 1. Group RT distributions for correct responses to word and nonword stimuli in Experiment 1. The circles represent the .1, .3, .5, .7, and .9 quantiles for each condition.

Figure 2. Group RT distributions for correct responses to word and nonword stimuli in Experiment 2. The circles represent the .1, .3, .5, .7, and .9 quantiles for each condition.

Figure 2. Group RT distributions for correct responses to word and nonword stimuli in Experiment 3. The circles represent the .1, .3, .5, .7, and .9 quantiles for each condition.

Appendix

List of words and nonwords in the experiments

High-frequency words: juego; norte; texto; color; largo; negro; golpe; vivir; grave; línea; frase; tarde; autor; suelo; gente; pared; orden; noche; calle; dolor; humano; precio; esposa; abuelo; escena; sector; estilo; puerta; dinero; tiempo; ciudad; juicio; tierra; cocina; fuerte; piedra; música; riesgo; asunto; animal; poner; joven; padre; miedo; siglo; causa; fuego; fondo; clase; feliz; único; libre; nivel; coche; final; grupo; brazo; etapa; viaje; resto; acción; semana; doctor; señora; médico; sombra; verano; pasado; motivo; estado; efecto; normal; crisis; teatro; novela; origen; social; futuro; centro; verdad; mente; lucha; éxito; sitio; libro; mundo; capaz; gesto; ayuda; mujer; fácil; pobre; época; serie; cielo; moral; papel; bueno; razón; viejo; prueba; número; equipo; último; objeto; pareja; blanco; grande; hombre; modelo; fútbol; cambio; placer; espejo; fuerza; cuello; suerte; camino; diario; pueblo; forma; nuevo; deseo; campo; carne; sueño; plaza; claro; radio; salud; vacío; punto; tarea; carta; valor; verde; común; abajo; total; amigo; guerra; figura; medida; viento; sangre; cuerpo; marido; simple; visión; lengua; prensa; barrio; mirada; cabeza; salida; nombre; rostro; altura; imagen; arriba

Low-frequency words: viudo; recto; tarta; garra; miope; palco; limón; rubor; naval; flojo; lente; valla; mango; senda; hongo; limbo; hacha; larva; cisne; ayuno; cadera; cabaña; sultán; refrán; lineal; óptico; arruga; tanque; flecha; marfil; juerga; arroyo; desván; conejo; gestor; jarrón; sonoro; granja; paella; plasma; soplo; sonda; boina; melón; oliva; barca; gramo; mural; puñal; zorro; tutor; tigre; pauta; álbum; tango; esquí; letal; oveja; tacón; musgo; torero; dragón; pésimo; muñeco; gancho; grieta; cheque; parche; buitre; trofeo; faraón; fábula; liebre; azufre; dilema; sermón; pasivo; rebaño; legado; pijama; espía; bambú; peine; roble; opaco; faena; lápiz; timón; momia; asado; nasal; acero; vagón; tallo; boxeo; toldo; copla; gripe; abeja; fresa; matriz; ración; búfalo; canela; escaño; sequía; cuerno; filtro; violín; flauta; rebote; mártir; dorsal; furgón; cínico; mantel; laguna; meseta; fértil; corcho; oasis; dócil; bingo; obeso; dogma; resta; cesta; vocal; secta; clavo; gorro; mixto; buzón; celta; dólar; sello; molde; tecla; coral; torta; masaje; bañera; carril; fianza; látigo; astuto; cebada; jungla; pirata; cohete; gusano; resaca; volcán; latino; collar; trueno; resina; tocino; sondeo; delfín

Nonwords: oreal; fendú; madir; mecle; bripo; hauca; lucao; ebraz; lirge; titiz; rogma; vidra; orevo; arral; rurón; garir; gorón; droco; romir; teslo; iratí; uraza; fende; tuleá; jirgo; ágoto; durde; novaz; cucra; aroto; nerre; astex; urgol; satel; ansis; éxila; brupe; urave; sigur; sumbi; tobelo; suecho; ulcaza; romodo; torida; sonche; cistra; reucer; beltar; hongal; furazo; atolid; aldadí; brueso; resedo; dulesa; cuerpe; aciopo; landir; fienta; cecala; urrite; rafado; rontra; urbine; punchu; reidal; hansus; colsor; predaz; grosta; licide; trachu; sasini; adusar; cigile; potepe; toalce; mintor; metrel; nemel; heldo; sumel; núbel; hogón; paujo; nocor; gulba; ciras; tiser; ojida; edión; turde; ileto; jirro; esnol; nogón; daclo; óbole; nemán; pobia; cabol; crivo; vilfo; radel; jirto; etajo; votis; fulba; genca; erred; cegui; volpa; rabir; himbú; denit; búbol; vátem; purón; ileba; aridea; rimate; runder; abunco; pridos; baruna; pilesa; sulleo; ayacín; sendiz; rardiz; mogora; borter; aficir; dorzas; muledo; persor; cigueo; pagota; lícula; zaruna; foltre; redido; ardiga; bradro; satero; tarzas; ufanco; aduche; urruro; ocudor; cerata; trevar; domple; cenosi; datuar; rantal; cañide; subrea; rulate; óxile; riste; látel; disón; mejín; julga; curce; sigal; hille; aupuz; osure; mecel; ovión; melir; derza; relgo; laror; digui; siejo; prias; numbi; bimal; mirce; inger; nerel; rurto; pucre; ultad; civán; glape; ópeno; ambro; jorea; ponje; bamea; uratí; ralir; yarar; dotre; naito; concar; goluda; luerpo; boñido;

cloniz; preced; valepe; trusca; dopuda; combio; pabato; talmar; miliza; astido; pavino; matuna; dramba; caluta; lisano; fongir; tovile; vedana; dicava; repear; hilana; empuna; resiva; hocina; mureal; armite; popade; nacuro; sanodo; apucer; ibedua; luctor; mulede; hígana; espate; iguadi; darge; orgón; girse; vildo; erapo; taine; pugre; dueve; grajú; ronil; gulca; altad; vocón; furné; rurva; tulvo; piate; nailo; firla; timno; fentú; gruel; vodón; rivio; fuleo; colpo; sagir; irabe; jergo; iluel; eneja; dinda; nafre; gabol; sagio; cilpe; huase; atrot; tolir; cleca; cublar; dierne; tuntio; fonuta; idonés; acogua; córcil; lepial; biscia; sucear; ovisor; frusey; malcar; reunda; iberdo; crutar; vetera; cinear; metufo; crurpa; amarir; eludor; cajoro; mucteo; vindar; leptir; bunema; dracho; clisco; lítaca; bucena; aulabe; brusta; orniar; prulto; caturo; eviser; acenal; mitiza; grenta