Is there a cost at encoding words with joined letters during visual word recognition?

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For simplicity, models of visual-word recognition have focused on printed words composed of separated letters, thus overlooking the processing of cursive words. Manso de Zuniga, Humphreys, and Evett (1991) claimed that there is an early "cursive normalization" encoding stage when processing written words with joined letters. To test this claim, we conducted a lexical decision experiment in which words were presented either with separated or joined letters. To examine if the cost of letter segmentation occurs early in processing, we also manipulated a factor (i.e., word-frequency) that is posited to affect subsequent lexical processing. Results showed faster response times for the words composed of separated letters than for the words composed of joined letters. This effect occurred similarly for low- and high-frequency words. Thus, the present data offer some empirical support to Manso de Zuniga et al.'s (1991) idea of an early "cursive normalization" stage when processing joined-letters words. This pattern of data can be used to constrain the mapping of the visual input into letter and word units in future versions of models of visual word recognition.

Reading is a mental activity that distinguishes us from the rest of the living creatures. It has allowed us to develop our intellectual system, our modern civilization, and it is essential for the educational process. An important goal in reading research is to elucidate how we recognize individual words. Leaving aside that some reading deficits can be detected when reading isolated words (e.g., dyslexia), the literature on visual word recognition and reading has already implemented a number of computational models that simulate a large number of empirical phenomena (see Rayner,

Pollatsek, Ashby & Clifton, 2012, for a recent review). For simplicity, most of these studies have focused on printed words. However, in the past years, there has a growing interest in the processes underlying word recognition in the first mode of writing: handwritten words (e.g., see Barnhart & Goldinger, 2010, 2015; Perea, Gil-López, Beléndez, & Carreiras, 2016; Perea, Marcet, Uixera, & Vergara-Martínez, 2018; Qiao et al., 2010). There are two basic features that distinguish the processing of handwritten words (see Manso de Zuniga, Humphreys, & Evett, 1991): i) the shape of the letters that constitute the words differs among individuals and even in the same individual at different times; and ii) handwritten words are typically composed of joined letters, which may require a previous additional stage dedicated to segmenting the letters from the visual input.

Unsurprisingly, as first demonstrated by Manso de Zuniga et al. (1991), word identification times are longer for handwritten than for printed words (see also Barnhart & Goldinger, 2010, 2015; Perea et al., 2016). Manso de Zuniga et al. (1991) claimed that this cost was due to an early "cursive normalization" stage that occurs before the word identification stage. Furthermore, the effects of lexical-semantic variables (e.g., word-frequency, imageability, among others) are magnified in handwritten words when compared to printed words (Barnhart & Goldinger, 2010, 2015). To explain this pattern, Barnhart and Goldinger (2010) suggested that when processing handwritten words the human perceptual system is more dependent on top-down processes than when processing prototypical, printed words forms. It is important to take into account that the interaction between format (handwritten vs. printed words) and lexical factors (e.g., word-frequency) occurs mainly for difficult-to-read handwritten words. This was exemplified in the experiments conducted by Perea et al. (2016) with printed words and two types of handwritten words (easy vs. difficult to read). They found longer word identification times for difficult-to-read handwritten words than for easy-to-read handwritten words, which in turn produced longer word identification times than for printed words. Critically, Perea et al. (2016) found a magnification of the word-frequency effect for difficult-to-read handwritten words, but not for easy-to-read handwritten words (see also Barnhart & Goldinger, 2010, for a similar pattern). To explain this additive pattern of word-frequency and format (printed vs. easy-to-read handwritten), Perea et al. (2016) suggested that when the handwritten words are easy-to-read, there would be an early effect when encoding the letters (i.e., "cursive normalization" stage; see Manso de Zuniga et al., 1991), but that the word identification process was not affected. This pattern of effects with printed vs. easy/difficult handwritten words is not restricted to laboratory word

recognition tasks, but it has also been found in sentence reading when the participants' eye movements are registered (see Perea et al., 2018).

Thus, previous research has shown that reading handwritten words involves some processing cost when compared to reading printed words. This cost may be due to two elements: the lack of uniformity of the letters that constitute the words and the lack of segmentation across letters. The main goal of the present experiment was to isolate the effect of letter segmentation during word recognition.

To our knowledge, the only published study on this topic was conducted by Hellige and Adamson (2007). They employed a visual-field lexical decision paradigm in which the words were briefly presented in the left or right visual field. The format of the words could be printed or handwritten (with joined letters or with separated letters; e.g. *doa* vs. *doa*). Hellige and Adamson (2007) found a reading cost for handwritten when compared to printed words, but failed to find differences between the two types of handwritten words (i.e., with joined vs. separated letters). However, there were several methodological problems in the Hellige and Adamson (2007) experiment that make it difficult to extract firm conclusions: 1) format (printed vs. joined handwritten vs. separated handwritten) was manipulated between-subjects, thus diminishing statistical power relative to the usual within-subject manipulation; 2) the stimuli were all very short (three-letter long); 3) there was no a priori criterion to separate the letters in the handwritten words; and 4) accuracy was the single reported variable (i.e., response times could have been more sensitive measure to the impact of letter segmentation).

Figure 1. Depiction of the word *ciencia* (science) with joined and separated letters in the Number Five (top) and Memima (bottom) fonts.

In the present experiment, we examined if there is a processing cost due to letter segmentation when reading words with joined letters. We employed the lexical decision task (i.e., "does the letter string form a word?") because this is the most common word identification task (see Balota et al., 2007) and, furthermore, it is the one employed in most research on the processing of handwritten words. Each word was presented with joined or separated letters while occupying the same horizontal space. As there is little experimental control on where each joined letter begins or ends in handwritten words, we employed two typographical fonts that allowed to present words with joined or isolated letters: Number Five and Memima (see Figure 1, for examples)— Number Five was designed to be written with both joined and separated letters, whereas Memima was originally designed to be written with joined letters. As the expected effect size of letter segmentation is assumed to be small—note that the reading cost of easy-to-read handwritten words relative to printed words is around 14-24 ms (Perea et al., 2016), we employed a large number of words per condition (80 words with joined letters; 80 words with separated letters) and a moderately high number of participants (N = 44). As we were also interested in examining if the effect of segmentation was affected by a lexical factor such as word-frequency, we selected a set of high-frequency words and a set of low-frequency words.

The predictions are as follows. If there was an early "cursive normalization" stage during word recognition—as proposed by Manso de Zuniga et al. (1991), one would expect an effect of letter segmentation (longer response times for words with joined letters) that would be additive with the word-frequency effect. Alternatively, if the effect of letter segmentation also modulates subsequent lexical/post-lexical stages, one would expect a greater effect of letter segmentation for low frequency than for high frequency words. Finally, if the effect of letter segmentation were negligible—as might be inferred from the null findings reported by Hellige and Adamson (2007)— one would only expect an effect of word-frequency.

METHOD

Participants. The sample was composed of forty-four psychology students (25 females) from the University of Valencia. All participants were native Spanish speakers with normal/corrected vision and reported no history of reading problems. Prior to the experiment, all participants signed a consent form..

Materials. We selected 160 Spanish words of six and seven letters from the subtitled-based EsPal database (Duchon, Perea, Sebastián-Gallés,

Martí & Carreiras, 2003). Half of the words were of high frequency (M = 112 per million; range: 20.8 – 1287.7) and the other half were of low frequency (M = 2.8 per million; range: 1.0 – 5.0). The number of letters was the same for the two sets (M = 6.5). To act as foils in the lexical decision task, we created 160 orthographically legal pseudowords matched with the words in length and syllabic structure using Wuggy (Keuleers & Brysbaert, 2010). The stimuli are presented in the Appendix. None of the words/pseudowords contained the letters "r", "s" or "z" because their allographs differed in the joined and separated formats in the Number Five font—we made a small modification in this font so that all the remaining allographs were visually the same when presented in joined and separated letters (e.g., in the original Number Five font with joined letters, there is a dot inside some of the letters). We created two lists of materials so that each word/pseudoword appeared once in each list, but each time in a different format condition (joined vs. separated). The assignment of the participants to each list was random. Twenty-two participants received the stimuli with 20-pt Number Five font, and the remaining twenty-two participants received the stimuli with 20-pt Memima font.

Materials. We employed an Asus laptop equipped with DmDX (Forster & Forster, 2003) to present the stimuli and record the responses. Participants, who were tested individually, were instructed to press one of two buttons on the keyboard to indicate, as quickly and accurately as possible, whether the letter string was a Spanish word or not (M—yes and Z—no). The sequence in each trial was the following: 1) a fixation point (the "+" sign) appeared in the center of the screen for 500 ms; and 2) the stimulus item was presented in the same location until the participant responded or 2000 ms had passed. Each participant received a different order of trials. The session lasted around 15-17 min.

RESULTS

Error responses (5.5% for words; 4.9% for non-words) and lexical decision times shorter than 250 ms (less than 0.01%) were removed from the RT analyses. Table 1 displays the mean lexical decision time and the error percentage for each condition. To analyze the latency and error data, we conducted analyses of variance (ANOVAs) based on the subject (F_1) and item (F_2) means per condition. For the word trials, the fixed factors were Word-Frequency (high vs. low frequency), Format (joined vs. separated letters), Font (Number Five vs. Memima), and List (list 1, list 2)—List was a dummy factor to extract the variance due to the lists (Pollatsek & Well, 1995).

The ANOVAs on pseudoword stimuli were analogous to those on word stimuli, except for the lack of the factor Word-frequency.

Table 1. Mean lexical decision times (in milliseconds) and percent error rates (in parenthesis) in each of the conditions in the experiment

	Number Five font		Memima Font	
	Joined	Separated	Joined	Separated
Word Trials				
High-Frequency	567 (2.3)	564 (1.9)	616 (4.0)	606 (4.8)
Low-Frequency	619 (8.6)	614 (8.3)	664 (6.6)	659 (7.6)
Pseudoword trials	660 (4.3)	652 (3.6)	694 (5.9)	695 (5.9)

Word data. Lexical decision times were faster on high-frequency words than on low-frequency words (588 vs. 639 ms, respectively), $F_1(1,40) = 88.40$, $MSE = 120.19$, $\eta^2 = .69$, $p < .001$; $F_2(1,156) = 81.59$, $MSE = 5454.92$, $\eta^2 = .34$, $p < .001$, and for words with separated letters than for words with joined letters (611 vs. 617 ms, respectively), $F_1(1,40) = 9.24$, $MSE = 171.85$, $\eta^2 = .19$, $p = .004$; $F_2(1,156) = 5.36$, $MSE = 1542.89$, $\eta^2 = .33$, $p = .022$. The main effect of the font approached significance in the by-subject analysis, $F_1(1,40) = 3.25$, $MSE = 27777.48$, $\eta^2 = .075$, $p = .079$; $F_2(1,156) = 160.45$, $MSE = 1804.97$, $\eta^2 = .51$, $p < .001$. None of the interactions approached significance, all *F*s < 1.15 and all *p*s > .28[1].

The ANOVA on the error rates showed that participants committed fewer errors to high-frequency words than to low-frequency words (3.1 vs. 3.4 %, respectively), $F_1(1,40) = 50.08$, $MSE = 18.15$, $\eta^2 = .56$, $p < .001$; $F_2(1,156) = 20.28$, $MSE = 163.04$, $\eta^2 = .12$, $p < .001$. The interaction word

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[1] For completeness, we also conducted the inferential analyses using linear mixed effects models. Response times were inverse-transformed (-1000/RT) for normality and the levels of each factor were centered on zero (e.g., -0.5 vs. 0.5 for high- and low-frequency words, respectively). The results of these analyses mimicked those of the ANOVAs. Specifically, we found showed additive effects of word-frequency, $t = 9.69$, $SE = 0.013$, $p < .001$, and format, $t = 2.01$, $SE = 0.006$, $p = .045$ (the interaction between these two factors did not approach significance, $t < 1$, $p > .38$). Finally, the main effect of font approached significance, $t = 1.99$, $SE = 0.047$, $p = .053$.

frequency x font was significant, $F_1(1,40) = 8.01$, $MSE = 18.15$, $\eta^2 = .17$, $p = .007$; $F_2(1,156) = 10.28$, $MSE = 51.46$, $\eta^2 = .002$, $p = .002$: the word-frequency effect was greater in the Number Five font than in the Memima font. None of the other effects or interactions approached significance (all Fs < 1.25; all ps > .29).

Pseudoword data. In the latency data, neither the main effects of Font or Format showed significant values in the by-subjects analyses (Fs < 1)—nonetheless, responses were faster with the Number Five font than with the Memima font in the by-item analyses, $F_2(1,158) = 51.71$, $MSE = 2295.70$, $\eta^2 = .25$, $p < .001$. The interaction between the two factors did not approach significance (all Fs < 2.27, all ps > .134).

In the analyses of the error rates, none of the effects approached significance in the by-subjects analyses, all Fs < 1.78 and all ps > .19—in the by-items analyses, we found a higher percentage of errors in the Memima font than in the Number Five font (5.9 vs. 3.9 %, respectively), $F_2(1,158) = 12.71$, $MSE = 48.38$, $\eta^2 = .07$, $p < .001$.

DISCUSSION

One reason why handwritten words are identified more slowly than printed words is that they require an early "cursive normalization" stage that separates the joined letters (see Manso de Zuniga et al., 1991). We conducted a lexical decision experiment to examine if there is a cost due to reading words with joined letters when compared to words with separated letters, and whether this effect was modulated by a lexical factor (word-frequency). To control for letter uniformity, we employed two typographical fonts (Number Five and Memima) that allowed us presenting the words with joined or separated letters (see Figure 1). Results showed a small, but significant advantage in response times for those words composed of separated letters than for those composed of connected letters. This advantage was approximately similar in size in the latency data for the two typographical fonts, as well as for high- and low-frequency words.

Thus, the present data confirmed Manso de Zuniga et al.'s (1991) claim that there is an early segmentation cost for those words with joined letters. This cost is likely to occur very early during word processing because lexical processes were not affected by letter segmentation: we found additive effects of word frequency (i.e., a lexical effect) and format (joined vs. separated letters). How can we reconcile these findings with the Hellige and Adamson (2007) findings? The lack of an effect of letter segmentation in the Hellige and Adamson (2007) experiment was probably due to lack of power:

the manipulation of format in their experiment was between-subjects, the length of their stimuli was very short (i.e., three letter stimuli), and the number of items/condition was substantially smaller than in the current experiment.

The pattern of data in our experiment resembles that observed by Gomez and Perea (2014) in a lexical decision task that compared words presented horizontally or rotated 45°: word identification times were longer in rotated words than in horizontal words, and the cost was similar for high- and low-frequency words. To explain this pattern, Gomez and Perea (2014) claimed that there was an initial processing cost with rotated words at an encoding letter stage that—once the letters were normalized to their prototypical form—disappeared in the core processed underlying word identification. Indeed, Gomez and Perea (2014) conducted fits with Ratcliff's (1975) diffusion model (see also Gomez, 2012; Ratcliff, Gómez & McKoon, 2004) and showed that the effect of rotation mainly affected the "non-decisional encoding time" parameter while the word-frequency effect mainly affected the "quality of information" parameter during the decision process. Similarly, Perea et al. (2016) indicated that when the handwritten words are easy to read, the effects of format (handwritten vs. printed) and word-frequency are additive. Perea et al. (2016) interpreted this result as the product of an early effect when encoding the letters, but this effect did not hinder the core word recognition processes. Indeed, only difficult-to-read handwritten words showed a greater word-frequency effect (i.e., a marker of recruitment of lexical feedback; see also Barnhart & Goldinger, 2010, for a similar pattern). Thus, lexical feedback does not seem to play a role in the early segmentation processes of easy-to-read handwritten letters or printed words with joined letters. Taken together, and following Sternberg's idea of additive factors (1969), the present data suggest that the effect of segmentation (joined vs. separated letters) would affect the initial processing phases (letter encoding), while the word-frequency effect would affect later phases of processing (word identification)[2].

Therefore, the processing cost for words composed of connected letters relative to those with unconnected letters strongly suggests that there

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[2] One might argue that an early cursive normalization process would also slow down the processing of the pseudowords with joined letters. However, we found no signs on such an effect on "no" responses to pseudowords. An explanation of this null effect relies on the characteristics of the lexical decision task. While "yes" responses occur when a lexical unit reaches a threshold, "no" responses occur after a flexible deadline. The present findings suggests that cursive normalization does not affect this deadline (see Dufau, Ziegler, & Grainger, 2012, for a computational model of "yes" and "no" responses in lexical decision).

is an extra segmentation cost at a letter encoding stage during lexical access, as anticipated by Manso de Zuniga et al. (1991). However, the small size of the letter segmentation effect suggests that the cost of processing handwritten words is not just due to lack of letter segmentation, but it may also involve normalizing the visual input due to the lack of uniformity across letters. One way to systematically study this latter component is by comparing words using a single font (i.e., the usual setting when reading words) vs. words composed of letters composed of several typographical fonts (e.g., house vs. house). As reviewed by Sanocki and Dyson (2012), letter uniformity plays a role during word recognition (the so-called "font tuning"). That is, the processing cost that occurs when reading handwritten words would be due to a combination of two elements: lack of segmentation and lack of uniformity across letters. Clearly, future implementations of models of visual word recognition should offer a more developed account of the initial moments of letter processing. Keep in mind that the current versions of computational models of word recognition employ a rather rudimentary encoding of letter units (see Marcet & Perea, 2017, 2018, for discussion). Furthermore, from a general standpoint, the lack of uniformity/segmentation that characterizes handwritten words is closer to that encountered when perceiving objects in everyday life.

Along with theoretical implications, the current findings also have practical consequences. In Spain and other countries, most of the books aimed at teaching children how to read employ fonts using joined letters. However, the present data suggests that there may be a processing cost when reading words with joined letters in skilled adult readers, and perhaps, this cost would be even greater in an immature word recognition system. Further research should examine whether there is also a cost for reading words with joined letters in primary school children—if so, publishers should modify the typographical fonts used in stories/texts aimed at young children. Likewise, it is important to examine whether the same phenomenon occurs at the writing production level (see Afonso, Álvarez, & Kandel, 2014, for a review of handwriting production). Bear in mind that one of the first reasons why letters in words were joined together was because of the fragility of the quills when handwriting, but this does not apply to pens or pencils. Indeed, in some countries (e.g. Finland), children currently learn to write not on cursive (joined-up) handwriting but on print (separated) handwriting.

In sum, the present experiment has shown additive effects of letter segmentation and word frequency: letter segmentation would presumably affect a cursive normalization encoding stage, whereas word-frequency would affect a subsequent word identification stage. These findings have not only theoretical implications (the role of cursive normalization in models of

visual word recognition) but they also have practical repercussions for future research (i.e., whether books for children that are learning to read should employ words with joined or separated letters).

RESUMEN

¿Hay un coste a la hora de codificar las palabras con letras conectadas durante el reconocimiento visual de palabras?

Por simplicidad, los modelos computacionales de reconocimiento visual de palabras se han centrado en cómo procesamos las palabras impresas con letras separadas, omitiendo el procesamiento de las palabras con letras conectadas. Manso de Zuniga, Humphreys y Evett (1991) plantearon la existencia de un estadio temprano que segmenta las letras conectadas en las palabras. Para examinar esta hipótesis, se realizó un experimento de decisión léxica en el que las palabras se presentaban con letras separadas o conectadas. Para conocer si este estadio de segmentación ocurría tempranamente, se manipuló otro factor, la frecuencia de uso de las palabras, que influye en el procesamiento léxico. Los resultados mostraron tiempos de respuesta más rápidos para las palabras con letras separadas que conectadas. La magnitud de dicho efecto fue similar para las palabras de alta y baja frecuencia. Estos resultados ofrecen apoyo empírico a la hipótesis de un estadio temprano de segmentación de letras. Además, estos hallazgos permiten delimitar la codificación de las letras a partir de los rasgos visuales en futuras versiones en los modelos de reconocimiento visual de palabras.

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APPENDIX

Word and Pseudowords in the experiment

High-Frequency Words: colega; cuidado; planeta; campeón; equipo; lluvia; momento; puente; ventaja; cocina; policía; pelota; cadena; máquina; público; examen; modelo; maleta; médico; llamada; cuello; ciudad; canción; camión; colegio; enemigo; fuente; opinión; pueblo; leyenda; negocio; helado; clínica; vecino; opción; planta; cliente; viento; detalle; talento; demonio; aceite; ventana; abogado; océano; noticia; motivo; abuelo; ciencia; bebida; familia; imagen; palacio; fútbol; camino; botella; cuento; lección; tienda; montaña; oficina; capitán; batalla; página; empleo; combate; lengua; anuncio; mañana; actitud; agencia; alcohol; comida; paquete; caballo; víctima; animal; anillo; minuto; tiempo

Low-Frequency Words: maniquí; plancha; papilla; nativo; vegetal; olfato; colmena; calcio; empatía; canela; palillo; ingenio; jabalí; anguila; capucha; ámbito; maceta; empujón; gaviota; folleto; chalet; dictado; teclado; cuenco; mueble; vajilla; búfalo; plátano; patata; pechuga; nómina; cavidad; almeja; capote; albañil; pupila; fatiga; laguna; flauta; pocilga; higiene; banana; antojo; fábula; bufanda; lechuga; ombligo; cálculo; bocina; chivato; cuneta; maqueta; chuleta; afición; cafeína; adivino; latido; diploma; boletín; cúpula; delfín; atleta; fachada; módulo; fluido; índice; manteca; mantel; llanto; abdomen; túnica; bobina; empate; abanico; paleta; pincel; lavanda; galope; empeño; peluche

Pseudowords: cielco; lablida; mavalla; deinto; demnín; mávana; clacena; cacedo; tevetad; tovana; cacián; cónvulo; admatía; fagieta; benlido; pentiña; tocedo; alpohul; tiembo; múflaco; nacula; vatada; cluelle; plalto; búmaca; fauche; véltiga; nelido; fenano; egnepo; glucena; flipito; amijada; taciblo; paduena; claudo; melluja; toletún; mandol; navatán; fevocia; acallo; blatida; návuta; ágnato; balanto; onflago; oglaón; pafina; mafiote; tavena; japilú; tatena; chalit; hotana; colmite; altivil; olbito; nollela; gatalia; denteta; omicián; cacalo; tévito; avoile; plieta; teculle; oméaca; afelián; actinid; pafiota; vacilla; pocegma; caupido; colemia; eduefo; hatapo; plolta; apebico;

fengud; nueche; cabtena; alviola; vuencia; naloñe; agnojen; cacillo; cacullo; caldia; ojenica; tultado; exhajin; potanto; empudal; amacina; allica; ticulo; ciecho; mubala; canule; cucica; aciodo; vabenda; tifloda; potapo; momilio; fentima; tocudo; fintina; infetia; vadina; maufle; tuvenda; anvema; caveto; calmaón; cocepo; petcel; tavita; lildión; blítaca; catpeán; felluma; tedada; tianda; detotia; íntate; fuolol; veualda; tavalla; mueglo; patebui; tonane; egnite; focamo; atondio; bluvio; itimen; clacino; enllea; atadal; temona; tújilo; dlantla; tocella; tacena; apancio; nivione; melucle; cidcad; bilicia; ecidipo; paulle; cavadod; nocacio; capoíco; covito; ancopa; cucudo; hacado