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Can letter position encoding be modified by visual perceptual elements?

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Abstract

A plethora of studies has revealed that letter position coding is relatively flexible during word recognition (e.g., the transposed-letter [TL] pseudoword CHOLOCATE is frequently misread as CHOCOLATE). A plausible explanation of this phenomenon is that letter identity and location are not perfectly bound as a consequence of the limitations of the visual system. Thus, a complete characterization of letter position coding requires an examination of how letter position coding can be modulated by visual perceptual elements. Here we conducted three lexical decision experiments with TL and replacement-letter pseudowords that manipulated the visual characteristics of the stimuli. In Experiment 1, each syllable was presented either in a different colour or monochromatically (e.g., CHOLOCATE vs. CHOLOCATE) with the transposition occurring across syllables. In Experiment 2, the critical letters had a consistent contrast or not (e.g., CHOLOCATE vs. CHOLOCATE). In Experiment 3, the stimuli were presented either simultaneously or serially, letter by letter (i.e., as occurs in braille reading). Results showed that whereas colouring differently each syllable only produced a small nonsignificant reduction of the TL effect, the other two manipulations—presenting the two critical letters with an altered contrast and presenting the letters one at a time—reduced, but did not eliminate, the magnitude of the TL effect relative to the regular format. Although these findings are consistent with models that postulate an early perceptual locus of the TL effect, the robustness of the TL effect suggests that letter position coding also has an orthographic abstract component.

Keywords

Word recognition; letter position coding; lexical decision

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The effortless way that readers go from a written word to the activation of a lexical unit is an intriguing and widely studied phenomenon. In spite of the automatic character of this process, there are multiple factors that enable its existence. The present study focuses on the perceptual and representational aspects of letter position coding by exploring the interplay of visual information with orthographic-lexical representations.

In all writing systems, the location of components (e.g., letters in the case of alphabetic systems) conveys relevant information. For example, the Spanish words *ALERGIA* (*allergy*) and *ALEGRIA* (*happiness*) share all letters in almost all positions, even if they are semantically unrelated. Given this feature of alphabetic systems, perhaps the simplest account of letter position coding is that the identity of the letters and their location are strictly bound to each other. In fact, seminal theories of visual word recognition (e.g., the Interactive Activation Model [IAM], McClelland & Rumelhart, 1981) assumed positions-specific orthographic representations (also known as "slot coding"). Importantly, the aim of the IAM was not to explain letter position coding; hence, the position specific representation was a simplification rather than a theoretical claim. The same can be said about the IAM's descendants (dual-route cascaded model: Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; multiple read-out model: Grainger & Jacobs, 1996; Connectionist Dual Process (CDP+) model: Perry, Ziegler, & Zorzi, 2007).

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The evidence against letter identity and letter position being rigidly bound is robust and pervasive. As Chambers (1979) and O'Connor and Forster (1981) originally showed, pseudowords created by transposing two letters from a word (e.g., *JUGDE, CHOLOCATE*) can be easily misread as the base word. Since then, a large number of experiments have consistently reported that lexical decisions to transposed-letter (TL) pseudowords (e.g., *JUGDE*) are substantially longer and more error-prone than the lexical decisions to replacement-letter pseudowords (e.g., *JUPTE*; see Perea & Lupker, 2004). Likewise, for the target word *JUDGE*, the masked TL prime *jugde* is more effective than the masked replacement-letter (RL) prime *jupte* (Perea & Lupker, 2004); indeed, *jugde* is nearly as effective as the identity prime *judge* (Forster, Davis, Schoknecht, & Carter, 1987) and it provides with nearly as much parafoveal preview advantage during sentence reading (Johnson, Perea, & Rayner, 2007; see also Pagán, Paterson, Blythe, & Liversedge, 2015, for further evidence of TL effects during reading). This pattern is not restricted to the Roman alphabet: letter/character transposition effects have been reported in other writing systems (e.g., Chinese: Gu & Li, 2015; Hebrew: Velan & Frost, 2011; Arabic: Perea, Abu Mallouh, & Carreiras, 2010; Japanese Kana: Perea & Pérez, 2009; Korean Hangul: Lee & Taft, 2009; Thai: Perea, Winskel, & Ratitamkul, 2012). Furthermore, these effects are pervasive not only in adult skilled readers but also in developing readers (e.g., see Paterson, Read, McGowan, & Jordan, 2014).

The plethora of evidence for the so-called transposed-letter (TL) similarity effects has motivated theorists to develop an explanation for their prevalence. Two explanations for these effects are plausible; we refer to them as (1) perceptual system based and (2) orthographic representation based.

Perceptual system–based accounts. An explanation of why letter position coding is so flexible is based on models of visual attention (e.g., Logan, 1996, Contour Detector [CODE] model of visual attention). The basic assumption is that letters in words are objects subject to position uncertainty as a result of the limitations of the visual system (LTRS model: Adelman, 2011; spatial coding model: Davis, 2010; overlap model: Gomez, Ratcliff, & Perea, 2008; overlap open bigram model: Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006; Bayesian Reader model: Norris, Kinoshita, & van Casteren, 2010). For example, the letters *G* and *D* in *JUGDE* activate not only their own letter positions but also nearby letter positions. As a result, the TL pseudoword *JUGDE* would activate its base word (*JUDGE*) to a greater degree than the replacement-letter pseudoword *JUPTE*.

Orthographic representation–based accounts. An alternative account of letter transposition effects, which is specific to letter strings, assumes the existence of a "relative position map" level composed by open bigrams (i.e., pairs of ordered letters not necessarily adjacent) situated between the level of abstract letter units and the level of whole-word units in an interactive activation framework (open bigram model: Grainger & van Heuven, 2003; see also SERIOL model, Whitney, 2001). In open bigram models, the TL *JUGDE* would activate *J-U-G-D-E* at the level of letter units and *JU-JG-JD-JE-UG-UD-UE-GD-GE-DE* at the level of relative position map. As open bigrams have excitatory connections to the level of whole-word units, the TL pseudoword JUGDE would activate its base word *JUDGE* (they share all bigrams but one, *GD*/*DG*) to a larger degree than the replacement-letter pseudoword *JUPTE* (they only share three open bigrams, *JU-JE-UE*).

The two accounts described above are not mutually exclusive (e.g., see Adelman, 2011; Grainger et al., 2006, for hybrid models of visual word recognition that include both location uncertainty and open bigrams). While there might be abstract representations of orthographic features that contribute to TL effects, these effects might also be affected by visual perceptual processes. Therefore, we believe that a comprehensive characterization of letter position coding requires a careful examination of whether (and if so, how) this process can be modulated by visual perceptual elements. Importantly, previous research has reported an interaction between visual and orthographic-lexical factors when encoding letter identity. Grainger, O'Regan, Jacobs, and Segui (1992) found that the neighbourhood frequency effect (e.g., the identification of *spice*—which has the higher frequency neighbour *space*—being slower than that of a word with no higher frequency neighbours like *sauce*) was substantially reduced when participants fixated on the disambiguating letter (i.e., *i* in spice) than when they fixated on other letters. Thus, the effect of neighbourhood frequency (i.e., a phenomenon that involves the encoding of letter identities) is modulated by a visual attention element: whether the reader fixates the disambiguating letter or not. A remaining question is whether the TL effect (i.e., a phenomenon that involves the encoding of letter order) can be modulated by visual perceptual elements.

The main goal of the present series of experiments was to examine the role of three visual elements in the process of letter position coding during word recognition. As in the classic letter transposition experiments of Chambers (1979) and O'Connor and Forster (1981), we employed a single-presentation lexical decision task. The key comparison was between the TL pseudowords and their corresponding replacement-letter pseudowords. Specifically, the TL effect was computed as the difference in mean latency and in response accuracy between TL pseudowords (e.g., *CHOLOCATE*) and replacement-letter pseudowords (e.g., *CHOTONATE*). The idea is that the greater the similarity between the TL pseudoword and its base word, the greater the magnitude of the TL effect. In all cases, the transposition/replacement involved two non-adjacent internal consonants from different syllables (e.g., *CHOLOCATE* [TL pseudoword], *CHORONATE* [RL pseudoword]; in Spanish *CHOCOLATE* is composed of four syllables [*cho-co-la-te*]).

In Experiment 1, the whole stimulus was presented in the same colour—as is usually the case in word recognition and reading experiments—or with each syllable in a different colour (e.g., *CHOLOCATE* vs. *CHOLOCATE*). The rationale behind this manipulation is that colour is a useful perceptive cue that helps to distinguish the parts of a whole (see Goldfarb & Treisman, 2011, for a review). Indeed, colour produces a different grouping of the elements that constitute the words (see Chetail & Mathey, 2009; Häikiö, Hyönä, & Bertram, 2015; Perea, Tejero, & Winskel, 2015; Pinna & Deiana, 2014; Prinzmetal, Hoffman, & Vest, 1991; Prinzmetal, Treiman, & Rho, 1986). In a series of influential experiments conducted by Prinzmetal et al. (1991) and Prinzmetal et al. (1986) participants were briefly presented a word or a pseudoword in which the first two/three letters were in one colour and the others in another colour. When asked to indicate the colour of a target letter, participants were more accurate when the letter had the same colour as its syllabic unit than when not (e.g., more accurate responses for the colour of *T* in *AZTEC* than in *AZTEC*). Similarly, Chetail and Mathey (2009) and Häikiö et al. (2015) showed that alternate colouring is a useful cue to emphasise the syllabic boundaries in lexical decision and sentence reading, respectively. In the context of a perceptual account of letter position coding, one might argue that using different colours across syllables in TL pseudowords (e.g., *CHOLOCATE*) would induce the segmentation of the letter string into four objects (*CHO-LO-CA-TE*). As the critical letters *L* and *C* in the TL pseudoword *CHOLOCATE* would belong to different perceptual groups, this would diminish their location uncertainty relative to the case in which the critical letters belong to the same perceptual group (e.g., the monochromatic TL pseudoword *CHOLOCATE*). Therefore, if colour is an effective segmentation cue when processing syllables in letter strings, the magnitude of the TL effect would be smaller for *CHOLOCATE* than for *CHOLOCATE*.

In Experiment 2, the materials were the same as in Experiment 1, but the manipulation involved stimuli with a consistent contrast for all letters (*CHOLOCATE, CHORONATE*) versus stimuli in which the transposed/replaced letters have an altered contrast (*CHOLOCATE, CHORONATE*). Previous research has shown that this manipulation facilitates the perceptual grouping of letters in words (e.g., see Perea & Acha, 2009, for evidence during sentence reading). The idea is that the altered contrast of the letters *L* and *C* in *CHOLOCATE* would enjoy a special status during processing relative to the letters *L* and *C* in a consistent contrast (*CHOLOCATE*). As the sequence *L_C* from the TL pseudoword *CHOLOCATE* is not shared with the base word, *CHOLOCATE* would be less similar to its base word than the TL pseudoword *CHOLOCATE*, thus resulting in a smaller TL effect.

In Experiment 3, we examined whether a letter-by-letter presentation of the stimuli would reduce the TL effect. The idea was to keep conditions somewhat similar to braille reading. At an abstract level of processing, recent research has shown similarities between braille and sighted readers. Fischer-Baum and Englebretson (2016) showed that braille readers are sensitive to sublexical structures when identifying written words and these effects "extend beyond the serial recognition of a single cell at a time" (p. 170). That is, the sublexical orthographic processes in braille readers are comparable with their sighted peers when reading an alphabetic script—indeed, braille readers also activate the "visual word form area" when reading (see Reich, Szwed, Cohen, & Amedi, 2011). But the critical point here is that, unlike visual presentations, in which all letters from a word are available at the same time, braille reading proceeds serially, on a letter-by-letter basis (see Marcet, Jiménez, & Perea, 2016, for a recent review on braille reading). Thus, in braille reading, letter position could be directly encoded from the serial (along the temporal dimension) way in which letters are attained. If so, letter position coding should be much less flexible in the tactile than in the visual modality. In a lexical decision experiment, Perea, García-Chamorro, Martín-Suesta, and Gomez (2012) compared the magnitude of letter transposition effects (TL pseudowords [*CHOLOCATE*] vs. replacement-letter pseudowords [*CHOTONATE*]) in the visual modality (sighted readers) and the tactile modality (braille readers). Whereas sighted readers showed a large letter transposition effect (i.e., substantially longer response times and more errors to *CHOLOCATE* than to *CHOTONATE*), braille readers only showed a small nonsignificant trend in the error rates (see also Perea, Jiménez, Martín-Suesta, & Gomez, 2015, for evidence in a sentence reading task). In Experiment 3, the stimulus' constituent letters were presented simultaneously or serially one letter at a time. If readers encode with less perceptual uncertainty the order of the letters when they are presented serially one-by-one, the magnitude of the TL effect should be smaller in the serial format than in the simultaneous format.

In sum, the present lexical decision experiments were designed to study the interaction between visual and orthographic-lexical factors when encoding letter position coding in a word recognition task. Although we acknowledge that the results from these experiments cannot be a final arbiter on the relative contribution of the perceptual versus representational components to TL similarity effects, there are some patterns of data that would rule out some versions of the accounts described above: If the visual perceptual manipulations fail to modulate the TL effect, an explanation of such effect that relies solely on the

Table 1. Mean lexical decision times (in ms) and percent error on pseudowords in Experiment 1.

	Transposed-letter pseudoword		Replacement-letter pseudoword		Transposed-letter effect	
	RT	ER	RT	ER	RT	ER
Monocolour	957	29.7	872	8.3	85	21.4
Multicolour	946	25.5	857	7.1	89	18.4

ER: error rate; RT: Response Time. The mean RTs and ERs for the monocolour and multicolour words were 765 versus 790 ms, and 6.5% versus 4.8%, respectively.

characteristics of the visual system would be difficult to defend. According to such accounts, perceptual highlighting or serial reading should improve location coding. Alternatively, if the visual perceptual manipulations completely erase the TL effect, the idea of an encapsulated module of abstract representation (e.g., a layer of open bigrams between the letter and whole-word levels) would be untenable. Finally, from an applied perspective, if the uncertainty at letter position coding is modified by visual factors, this may help design the appropriate remediation strategies for those individuals with letter position dyslexia (see Kezilas, Kohnen, McKague, & Castles, 2014).

Experiment 1: changing the colours across syllables

Method

Participants. Twenty-eight participants from the Complutense and the Polytechnic University of Madrid, all of them native speakers of Spanish and with normal (corrected-to-normal) vision, took part voluntarily in the experiment. In this and subsequent experiments, participants signed a consent form before the experiment.

Materials. The set of stimuli was composed of 240 words and 240 pseudowords—they were extracted from the Carreiras, Vergara, and Perea (2007) experiment. The 240 pseudowords had been created by transposing/replacing two non-adjacent consonants from different syllables of a base word (e.g., *CHOLOCATE* and *CHOTONATE* from the base word *CHOCOLATE*). (In the Carreiras et al., 2007, experiment, they included pseudowords created by transposing/replacing two non-adjacent consonants vs. vowels—here we only included consonant transpositions/replacements.) The letter transposition/replacements did not occur in the initial syllable. The mean frequency of the base words was 23 per million (range: 1-147), the mean number of orthographic neighbours was 0.5 (range: 0-5) and the mean length was 8.9 letters (range: 7-11) in the B-Pal Spanish database (Davis & Perea, 2005). The 240 words had a mean frequency of 31 per million (range: 4-251) and the mean length was 8.9 (range 7-11). The colours of the multicoloured words and pseudowords were first syllable RGB: 171-41-51 (red); second syllable RGB: 75-160-52 (green); third syllable RGB: 166-106-46 (brown); fourth syllable RGB (blue): 58-92-154; and (when applicable) fifth syllable RGB: 192-20-192 (violet). Half of the items (words and pseudowords) were presented with different colours across syllables and the other half were presented in the same colour across all letters—each of the four colours used for the multicoloured condition was utilised in an equal number of the monochromatic strings. To rotate the stimuli across the four conditions, we created four counterbalanced lists in a Latin square manner.

Procedure. The session took place individually in a sound-attenuated room. We employed the DMDX software (Forster & Forster, 2003) to present the stimuli and register the participants' responses. The sequence of a given trial was as follows: (1) A fixation point (+) was presented at the centre of the CRT screen for 500 ms and (2) a target stimulus (always in uppercase) was presented on the screen until the participant responded—or until 2,100 ms had passed. Participants were asked to decide as quickly as possible if the letter string was a Spanish word by pressing the M key for words or the Z key for nonwords while trying to keep a low error rate. Each participant received a different random ordering of stimuli. Sixteen practice trials preceded the 240 experimental trials. The whole experimental session lasted approximately 20 min.

Results and discussion

We excluded from the correct response times (RT) analyses those latencies beyond the 250-2,000 ms cutoffs (0.04% for words and 0.19% for pseudowords). The average mean correct RTs and error rates per condition are presented in Table 1. The RT and accuracy data were analysed using linear mixed effects and generalised linear mixed effects (*lme4* package in R; Bates, Maechler, Bolker, & Walker, 2015). For the RTs, we employed the −1,000/RT transformation so that the resulting data distribution would be closer to the Gaussian distribution. For the pseudoword data, the fixed factors were Type of pseudoword (letter transposition/replacement) and Colour (monochromatic/multicolour), whereas for the word data, the only fixed factor was Colour (monochromatic/multicolour). For each model, we employed the maximal random structure model that successfully converged—each fixed factor was zero-centred in the models.

Table 2. Mean lexical decision times (in ms) and percent error on pseudowords in Experiment 2.

	Transposed-letter pseudoword		Replacement-letter pseudoword		Transposed-letter effect	
	RT	ER	RT	ER	RT	ER
Regular	949	28.9	829	5.8	120	23.2
Highlighted	930	19.2	821	4.6	109	14.6

ER: error rate; RT: Response Time. The mean RTs and ERs for regular and highlighted words were 751 versus 798 ms, and 3.9% versus 4.5%, respectively.

Pseudoword data. The analyses of the latency data showed that, on average, lexical decision responses were faster to replacement-letter pseudowords than to TL pseudowords, $t=13.81$, $p<.001$. Neither the difference between multicolour and monochromatic pseudowords nor the interaction between the two factors approached significance, both ps$>.25$.

The analyses of the accuracy data showed that participants responded more accurately to replacement-letter pseudowords than to TL pseudowords, $z=-21.71$, $p<.001$. In addition, participants responded more accurately to multicolour pseudowords than to monochromatic pseudowords, $z=2.71$, $p=.007$. The size of the TL effect was similar for monochromatic and multicolour pseudowords (0.214 vs. 0.184, respectively), as deduced by the lack of interaction between the two factors, $z<1$, $p>.40$.

Word data. The analyses of the RT data showed that monochromatic words were responded to, on average, 25 ms faster than multicolour words, $t=4.29$, $p<.001$. The analyses on the accuracy data showed that participants were more accurate with monochromatic words than with multicolour words (0.952 vs. 0.935), $z=-2.97$, $p=.003$.

This experiment showed a sizable TL effect in both response times and accuracy (i.e., slower and less accurate responses to TL pseudowords than to replacement-letter pseudowords), thus replicating earlier research (e.g., Carreiras et al., 2007; Lupker, Perea, & Davis, 2008; Perea & Lupker, 2004). But the critical question was whether perceptual grouping—using syllables of different colour—modulated this effect. Although results showed an effect of the perceptual manipulation on word stimuli (e.g., responses to words were faster for monochromatic than for multicolour words), there were no clear hints of a modulating effect of the perceptual grouping manipulation on the size of the TL effect in the accuracy rates: the effect was only 3% smaller for the multicolour pseudowords than for the monochromatic pseudowords (see Table 1). This null effect of colour on the magnitude of TL effects is consistent with the Friedmann and Rahamim (2014) study—they measured the number of letter migration errors (e.g., slat being misread as salt) with multicolour (colouring each letter in a different colour; e.g., slat) versus black monochromatic words in a small sample ($N=5$) of individuals with letter position dyslexia.

In Experiment 2, we employed a manipulation of perceptual grouping that was potentially more powerful than in Experiment 1. Instead of changing the colour across syllables, the manipulation focused exclusively on the critical letters that were transposed/replaced in the pseudoword stimuli, thus making those letters more salient: these letters were presented in altered contrast or not (e.g., *CHOLOCATE* vs. *CHOLOCATE*). For control purposes, we employed a parallel manipulation for the word stimuli (e.g., *DOCUMENTO* vs. *DOCUMENTO*).

Experiment 2: altered contrast of the critical letters

Method

Participants. Twenty-eight students from the University of Valencia, all of them native speakers of Spanish and with normal (corrected-to-normal) vision, took part voluntarily in the experiment.

Materials. The set of 240 words and 240 pseudowords was the same as in Experiment 1. The difference was that either all letters were presented with the same contrast or two internal consonant letters—the ones that were transposed/replaced in the pseudoword stimuli—had an altered contrast (e.g., *CHOLOCATE* vs. *CHOLOCATE*). For the word stimuli, we also applied the contrast manipulation to two internal consonant letters (e.g., *DOCUMENTO* vs. *DOCUMENTO*).

Procedure. The structure of the trials and the experimental sessions was the same as in Experiment 1.

Results and discussion

As in Experiment 1, correct RTs beyond the 250-2,000 ms cutoff (0.06% for words and 0.16% for pseudowords) were omitted from the latency analyses. The mean correct lexical decision times and error rates per condition are displayed in Table 2. The statistical analyses paralleled those in Experiment 1 except that Colour was replaced with Contrast (altered vs. consistent stimuli) as a fixed factor.

Pseudoword data. The latency data showed that, on average, responses were faster to replacement-letter pseudowords

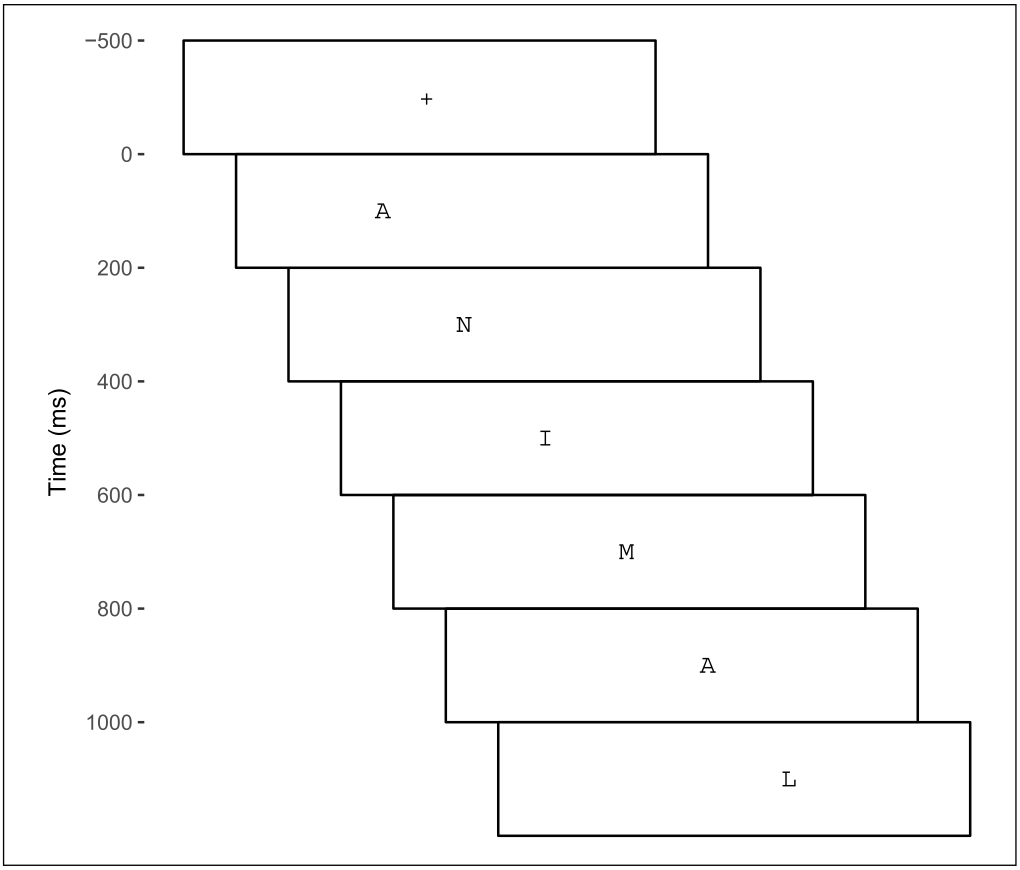

Figure 1. Schematic depiction of the procedure in Experiment 3.

than to TL pseudowords, $t=–21.33$, $p<.001$, and that pseudowords with altered contrast were responded to, on average, 13.5 ms more rapidly than the pseudowords with consistent contrast, $t=2.61$, $p<.009$. The interaction between the two factors was not significant, $t=–1.45$, $p>.14$.

The accuracy data revealed that participants were more accurate with replacement-letter pseudowords than with TL pseudowords, $z=21.41$, $p<.001$. Participants were also more accurate with the pseudowords with altered contrast than with the pseudowords with consistent contrast, $z=–5.25$, $p=.007$. But the most important finding was that the magnitude of the TL effect was smaller for those pseudowords with altered contrast than for the pseudowords with consistent contrast (0.146 vs. 0.231, respectively), as deduced from the significant interaction between the two factors, $z=2.42$, $p=.015$.

Word data. The latency data showed that participants responded more quickly to regular words than to words with consistent contrast, $t=–9.42$, $p<.001$. The analyses on the accuracy data did not show any differences between the words with altered versus consistent contrast (0.961 vs. 0.955, respectively), $z<1$, $p=.71$.

As in Experiment 1, the processing of the word stimuli was affected by the perceptual manipulation (i.e., word response times were slower for words with altered contrast than for regular words). As measured by response latencies, the TL effect was not significantly modulated by the contrast manipulation; however, the key finding is that, as measured by error rate, the TL similarity effect was substantially reduced for the pseudowords with altered contrast (14.6% in the altered-contrast format vs. 23.2% in the consistent-contrast format, respectively)—note that the magnitude of the effect for the regular format was very similar to that of monochromatic stimuli in Experiment 1 (i.e., 21.4%).

Therefore, we found that a visual perceptual element such as altering the contrast of the critical letters (e.g., *CHOLOCATE* vs. *CHOLOCATE*) can modulate letter position coding. However, the magnitude of the TL effect was still reasonably large in the altered-contrast condition. To examine whether the TL effect could be erased by visual perceptual factors, we conducted yet another experiment with a potentially more extreme manipulation: the word/pseudoword's constituent letters were presented simultaneously (i.e., as in the typical word recognition experiments) or were presented serially one-by-one as

Table 3. Mean lexical decision times (in ms) and percent error on pseudowords in Experiment 3.

	Transposed-letter pseudoword		Replacement-letter pseudoword		Transposed-letter effect	
	RT	ER	RT	ER	RT	ER
Immediate	1,183	31.8	1,000	9.6	183	22.1
Serial	2,115	44.7	2,040	16.8	75	27.9

ER: error rate; RT: Response Time. The mean RTs and ERs for the words in the immediate and serial formats were 804 versus 1,874 ms, and 1.9% versus 17.2%, respectively.

occurs when reading in braille—note that although braille readers do not show TL similarity effects in lexical decision (Perea, García-Chamorro, et al., 2012), they are sensitive to the sublexical structure of words (Fischer-Baum & Englebretson, 2016).

Experiment 3: letter-by-letter (serial) reading

Methods

Participants. Fifty-six undergraduate students from the DePaul University, all of them native speakers of English and with normal (corrected-to-normal) vision, took part in the experiment.

Materials. The set of stimuli was extracted from the Lupker et al. (2008) experiments and was composed of 80 words and 80 pseudowords. As in Experiments 1 and 2, these pseudowords had been created by transposing/replacing two non-adjacent consonants from different syllables of a base word (e.g., *CHOLOCATE* and *CHOTONATE* from the base word *CHOCOLATE*). (Lupker et al., 2008, also created pseudowords with transposed/replaced vowels—here we only employed those stimuli based on consonant transpositions/replacements.) The mean frequency of the base words was 14.30 per million (range: 1-101.96), the mean number of orthographic neighbours was 0.338 (range: 0-2), and the mean length was 7.3 letters (range: 6-8) in the English Lexicon Project subtitle database (Balota et al., 2007). The 80 words had a mean frequency of 61.97 per million (range: 3.96-625.14) and the mean length was 7.3 (range 6-9). Half of the items (words and pseudowords) were presented with all the letters simultaneously (immediate format [i.e., the standard format]) and the other half were presented one successive letter at a time (serial format [i.e., to simulate braille reading conditions]). The stimuli were rotated across the four conditions to create four counterbalanced lists following a Latin square method.

Procedure. The instructions and general organisation of the experimental sessions was parallel to that employed in Experiments 1 and 2. The trial structure (see Figure 1) was somewhat different to the previous two experiments, as the letters from the printed stimuli were presented either simultaneously (immediate format) or letter by letter one at a time for 200 ms in its relative position (serial format). The deadline to make a response was increased to 3,500 ms because of the slow rate of presentation in the serial format.

Results and discussion

Correct RTs beyond the 250-3,500 ms cutoff (less than 0.01% for words and pseudowords) were omitted from the RT analyses. The mean correct RTs and error rates per condition are presented in Table 3. The statistical analyses were analogous to those in Experiment 1, except that Colour was replaced with presentation format (Immediate vs. Serial) as a fixed factor.

Pseudoword data. The analyses of the RT data showed that responses were faster to replacement-letter pseudowords than to TL pseudowords, $t=-8.43$, $p<.001$, and that responses were faster in the immediate format than in the serial format, $t=18.65$, $p<.001$. Critically, the interaction between the two factors was significant, $t=-7.34$, $p<.001$: the TL effect was smaller in the serial format, $t=-3.10$, $p=.003$, than in the immediate format (75 vs. 183 ms, respectively), $t=-9.24$, $p<.001$.

The analyses on the accuracy data showed more accurate responses with replacement-letter pseudowords than with TL pseudowords, $z=13.77$, $p<.001$, and more accurate responses in the immediate format than in the serial format, $z=-6.23$, $p<.001$. There were no signs of an interaction between the two factors, $z=-0.54$, $p=.59$.

Word data. The RT data showed that participants responded faster when all the letters were presented simultaneously than when presented serially one at a time, $t=-32.96$, $p<.001$. The analyses on the accuracy data also showed an advantage of the immediate over the serial format, $z=-7.61$, $p<.001$.

The present experiment showed that magnitude of the TL effect in the RT data was reduced in the serial letter-by-letter format than in the standard, immediate format (75 vs. 183 ms, respectively)—note that this was so despite the fact that the overall latencies were much greater in the serial format, hence this is not a scaling effect. That is, readers encode more precisely letter order when the constituent letters of the stimuli are presented serially than when presented simultaneously. However, unlike braille reading (Perea, García-Chamorro, et al., 2012), the TL effect was sizable in the serial letter-by-letter format. A reason for this discrepancy is that whereas in braille reading, participants have control on how long the fingers sense each letter (e.g., low-frequency words receive longer scanning times than high-frequency words), in the visual modality, each letter is presented for a limited (and constant) exposure duration. We acknowledge that, to make to two tasks more equivalent, the braille experiment would have to present the letters also at a fixed rate.

General discussion

The present work examined whether visual elements could modify the process of letter position coding during visual word recognition. We conducted three experiments that manipulated three visual perceptual elements in a single-presentation lexical decision task with TL and replacement-letter pseudowords: using different colours for each syllable (Experiment 1), using a different contrast for the critical letters (Experiment 2), and simultaneous versus letter-by-letter presentation (Experiment 3). Experiment 1 showed that colouring differently each syllable only produced a negligible reduction of the TL effect relative to the regular format. In addition, Experiments 2 and 3 revealed that using a different contrast for the two critical letters (e.g., L and C in the TL pseudoword CHOLOCATE) and presenting the letters serially one at a time (e.g., C, then H, then O, then L . . .) reduced substantially the magnitude of the TL effect relative to the standard presentation. Therefore, visual elements can modify how letter order is encoded during lexical access.

Perhaps the first-order result is that the TL effect in the lexical decision task is quite robust and seemingly impossible to eliminate. A more nuanced examination of our results indicate that, consistent with those models that assume a perceptual locus of letter position coding, TL effects can be modulated by visual perceptual elements. This is consistent with prior evidence showing that location uncertainty of objects in space is not restricted to letters: they have been found for strings of digits (García-Orza, Perea, & Muñoz, 2010), strings of symbols (García-Orza et al., 2010), strings of non-alphanumeric objects (García-Orza, Perea, & Estudillo, 2011), and also for musical notes in a staff (Perea, García-Chamorro, Centelles, & Jiménez, 2013). Likewise, TL effects have also been found with preliterate children (Perea, Jiménez, & Gomez, 2016) and with non-human species (baboons: Ziegler et al., 2013). A further demonstration of the importance of visual elements in TL effects is that they do not arise in the tactile modality: lexical decision times and error rates to *CHOLOCATE* and *CHOTONATE* are remarkably similar in braille reading (see Perea, García-Chamorro, et al., 2012).

As mentioned in the Introduction, some patterns of results would be inconsistent with particular versions of the accounts of letter position coding. The modulation of the TL effect in Experiments 2 and 3 is consistent with the view that letter transposition effects have an early visual perceptual locus. Hence, the "strong" version of the orthographic coding theory (i.e., transposition effects are purely based on an abstract code via "open bigrams") can be ruled out. Conversely, the robustness of the TL effect when the critical pair of letters had an altered contrast or when letters were presented serially one at a time suggests that an important component of letter position coding is at an abstract orthographic level, thus ruling out the "strong" version of the perceptual account of letter transposition effects.

Therefore, as occurs with other factors in orthographic-lexical processing, it may be more accurate to talk about the various loci of letter position coding rather than a unique locus (e.g., see Knobel, Finkbeiner, & Caramazza, 2008, for evidence of several loci of the word-frequency effect). Indeed, several accounts of letter position coding assume both an early perceptual effect common to other visual objects and a late letter-specific effect due to the activation of abstract representations—typically in the form of open bigrams (Adelman, 2011; Grainger et al., 2006; Grainger & Ziegler, 2011). An obvious advantage of hybrid accounts of letter position coding is that they can simultaneously accommodate the presence of letter transposition effects for non-letter strings—which a "strong" open bigram model cannot capture—and the existence of greater transposition effects for letter strings than for other types of alphanumeric objects (e.g., digits, symbols)—which a "strong" perceptual account cannot capture. Indeed, using a same-different perceptual matching task, Massol, Duñabeitia, Carreiras, and Grainger (2013) found transposition effects for strings of letters, digits, and symbols, but the magnitude of the effect was greater for the strings of letters than for digits or symbols. Massol et al. (2013) suggested that this pattern reflected both "generic positional noise" which applies to all types of objects and "letter-specific position-coding mechanism" which applies exclusively to letter strings. The present experiments provide converging evidence to this hybrid account of letter position coding, with the advantage that we employed a lexically based task (i.e., a lexical decision task rather than a same-different task) with letter strings—keep in mind that strings of letters follow different neural paths than strings of symbols or digits (see Schubert, 2017, for review).

In summary, we have demonstrated that visual perceptual elements (i.e., altering the contrast of the critical letters [e.g., CHOLOCATE] and presenting the letters serially one at a time) may diminish the TL effect in lexical decision. This finding is consistent with those models of word recognition that postulate a perceptual locus of letter position coding. Nonetheless, the reduced but substantial TL effect even with the altered-contrast format or with serial presentations suggests that another major component of the TL effect is at an abstract orthographic level. Characterising these abstract orthographic representations is far beyond the scope of the present study, and our data cannot shed light on this issue.

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The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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