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BRIEF REPORT

Letter position coding across modalities: Braille and sighted reading of sentences with jumbled words

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Abstract This article explores how letter position coding is attained during braille reading and its implications for models of word recognition. When text is presented visually, the reading process easily adjusts to the jumbling of some letters (*jugde–judge*), with a small cost in reading speed. Two explanations have been proposed: One relies on a general mechanism of perceptual uncertainty at the visual level, and the other focuses on the activation of an abstract level of representation (i.e., bigrams) that is shared by all orthographic codes. Thus, these explanations make differential predictions about reading in a tactile modality. In the present study, congenitally blind readers read sentences presented on a braille display that tracked the finger position. The sentences either were intact or involved letter transpositions. A parallel experiment was conducted in the visual modality. Results revealed a substantially greater reading cost for the sentences with transposed-letter words in braille readers. In contrast with the findings with sighted readers, in which there is a cost of transpositions in the external (initial and final) letters, the reading cost in braille readers occurs serially, with a large cost for initial letter transpositions. Thus, these data suggest that the letter-position-related effects in visual word recognition are due to the characteristics of the visual stream.

Keywords Letter position · Word recognition · Reading

A pervasive phenomenon in the literature on visual word recognition and reading is that a jumbled word like *jugde* can be easily confused with *judge* (Perea & Lupker, 2003, 2004). Indeed, the ERP waves of jumbled words like *jugde* closely resemble those of their base words (*judge*) in relatively late time windows (N400 component; Vergara-Martínez, Perea, Gómez, & Swaab, 2013). The robustness of this phenomenon across different orthographic systems (see Frost, 2012) demonstrates that character position encoding during visual word recognition is graded in some form: the string *ABCD* is more perceptually similar to *ACBD* than to *ADCB*, and even more than to *AXYD*.

In a sentence-reading experiment, Rayner, White, Johnson, and Liversedge (2006) found that readers were able to understand *setneces wirtten with jubmled lettres* relatively accurately. Rayner et al. also reported that there was a decrement in reading speed, relative to intact sentences. The reading cost (in terms of words per minute) with jumbled words was especially large when the letter transpositions occurred at external positions (a slowdown of 36% and 26% in initial and final transpositions), while it was substantially smaller when the letter transpositions occurred in internal positions (11%). This pattern is consistent with the commonly held view that external letters play a special role during visual word recognition (Tydgat & Grainger, 2009) and that letters in the visual modality are processed in parallel (Adelman, Marquis, & Sabatos-DeVito, 2010).

The results outlined above indicate that some form of graded representations of letter position coding is utilized during word recognition. The question is whether these graded representations are a consequence of the characteristics of the visual system or, instead, are an intrinsic property of all orthographic codes (i.e., they occur at an abstract level of representation). To answer this question, we examined how letter position coding is attained during sentence reading in a tactile modality: braille. The braille code is employed by

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people who are blind or have low vision. Braille characters are represented as raised dots in a 3 × 2 matrix that are read sequentially (e.g., JUDGE would be ⠚ ⠥ ⠙ ⠛ ⠑). Because of its letter-by-letter nature, braille has been characterized as "the most strictly serial mode of language input" (Bertelson, Mousty, & Radeau, 1992, p. 284). Comparing braille and sighted reading not only provides us with insights into modality-specific versus modality-independent processes in reading (Perea, García-Chamorro, Martín-Suesta, & Gómez, 2012), but also may be of particular relevance for improving the methods of braille teaching; among the visually impaired, fluency in braille is crucial to achieving employment and higher incomes (Ryles, 1996).

In the experiment, we included two types of sentences: (1) intact sentences and (2) sentences *wirtten with jubmled lettres* (at the beginning, in the middle, or at the end of the words; for illustrations, see Table 1). To present the sentences and to record the location/timing of the participant's reading position during sentence reading in braille, we employed a display that detects the position of the finger while reading (Active Braille 40-cell display, HandyTech). Thus, it was possible to obtain information about reading speed, which has some commonalities with (and important differences from as well) the data obtained from an eyetracker. For comparison purposes, we also presented the sentences on a computer screen to sighted readers, and their eye movements were monitored via an eyetracker.

In the eye-tracking literature, there are global and local ocular–motor measurements that have been accepted and validated (see Rayner et al., 2006). Studies on the motor component of braille reading have shown that there are some fundamental differences between the two reading modalities (see Hughes, McClelland, & Henare, 2014, for a discussion). While eyetrackers measure oculomotor activity, active braille displays measure the point of contact with the braille line. Nonetheless, both methods yield some measurements that can be thought of as indices of reading difficulty. Total reading time is analogous in sighted and braille reading: reading rate (words per minute); note, however, that reading times are around 3 times faster in the visual than in the tactile modality. Number of fixations in eye movement research is qualitatively different from any parallel measurement in braille: While saccades are ballistic and there is saccadic suppression, braille readers actually detect the dots during the movement. Furthermore, while visual information is obtained during a fixation, an interruption of motion for a braille reader implies loss in information gathering. Nonetheless, the number of *lingers* in braille (the reading finger slowing down and lingering on one character) may also be a good index for reading difficulties—as is the number of fixations in sighted readers. Another measurement that differs in sighted and braille readers, yet could reflect processes related to reading difficulty, is the percentage of regressions even if those regressions are different in the two modalities (e.g., eye regressions are ballistic, while finger regressions can stop at any time; eye regressions benefit from parafoveal preview of the intended target of the regression, while finger regressions have no analogous benefits).

The present experiment is intended to disentangle the possible loci of the effects of letter position coding in reading. If the high degree of flexibility of letter position coding during reading is mostly due to perceptual uncertainty at the visual level, as is claimed in a number of models (Davis 2010; Gómez, & Ratcliff, & Perea, 2008; Norris, Kinoshita, & van Casteren, 2010), the cost of reading sentences with jumbled words should be markedly large in the tactile modality—clearly, larger than in the visual modality. Alternatively, if the locus of the *jumbled word* phenomenon is a consequence

Table 1 Example sentences and results for each dependent measure (with means and standard errors in parentheses)

Condition	Example	Number of fixations/ lingers	Percentage of regressions	Words per minute	First-Pass Time on Target (ms)
Visual					
NOR	Fue el mejor momento de su vida	7.1_a (0.4)	23.5_a (1.9)	268_a (11.4)	245_a (11.8)
BEG	Fue el emjor ommento de su vida	8.2_c (0.4)	26.1_a (1.6)	208_c (9.8)	325_c (16.8)
INT	Fue el mjeor momneto de su vida	7.8_b (0.3)	25.4_a (1.7)	234_b (11.4)	279_b (15.8)
END	Fue el mejro momenot de su vida	8.8_d (0.4)	25.3_a (1.2)	208_c (9.7)	329_c (18.6)
Braille					
NOR	⠋⠥⠑ ⠑⠇ ⠍⠑⠚⠕⠗ ⠍⠕⠍⠑⠝⠞⠕ ⠙⠑ ⠎⠥ ⠧⠊⠙⠁	28.8_a (2.4)	10.2_a (9.5)	103_a (11.1)	$1,361_a$ (131.9)
BEG	⠋⠥⠑ ⠑⠇ ⠑⠍⠚⠕⠗ ⠕⠍⠍⠑⠝⠞⠕ ⠙⠑ ⠎⠥ ⠧⠊⠙⠁	50.2_d (5.7)	22.4_d (7.9)	55_d (7.8)	$2,517_d$ (325.9)
INT	⠋⠥⠑ ⠑⠇ ⠍⠚⠑⠕⠗ ⠍⠕⠍⠝⠑⠞⠕ ⠙⠑ ⠎⠥ ⠧⠊⠙⠁	38.6_c (3.6)	17.7_c (9.4)	72_c (8.3)	$1,869_c$ (225.2)
END	⠋⠥⠑ ⠑⠇ ⠍⠑⠚⠗⠕ ⠍⠕⠍⠑⠝⠕⠞ ⠙⠑ ⠎⠥ ⠧⠊⠙⠁	35.2_b (3.7)	14.7_b (12.7)	83_b (10.7)	$1,600_b$ (169.2)

Note. The English translation of the sentence is: "It was the best moment of her life". NOR = normally (intact) written text; BEG = transpositions of initial letters; INT = transpositions of internal letters; END = transpositions of final letters. The (global) dependent variables are (1) number of fixations, (2) percentage of regressions, and (3) number of words per minute, and the (local) dependent variable is first-pass time on the target word (in the example, the target word is "momento"). For each column of results in the visual/tactile modalities, entries not sharing the subscript differ at $p < .025$. The reading cost in the main text was computed averaging the reading cost across all participants, rather than on the average reading times; unsurprisingly, the two computations show the same pattern of an abstract (amodal) level of representations intrinsic to all orthographic systems (*open-bigram* accounts; Dehaene, Cohen, Sigman, & Vinckier, 2005; Whitney, 2001), reading with jumbled words in braille should not differ at a qualitative level from reading jumbled words in the visual modality. The alleged open-bigram detectors, according to this account, are located in a brain area (the *visual-word form* area) that shows similar patterns of activation during reading for sighted and congenitally blind braille readers (Reich, Szwed, Cohen, & Amedi, 2011). Finally, there are hybrid accounts that combine the ideas of perceptual uncertainty and bigram activation (Adelman, 2011; Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006).

To our knowledge, only one published experiment has examined the process of letter position coding during braille word recognition. Using a word/nonword discrimination task, Perea et al. (2012) found that the responses to pseudowords created by transposing/replacing two nonadjacent internal letters (e.g., *cholocate* vs. *chotonate*) were equally fast and accurate in braille readers. When presented in the visual modality with sighted readers, these transposed-letter pseudowords yielded much longer latencies and error rates than the replacement-letter pseudowords. Thus, at the level of isolated word recognition, letter position coding in the tactile modality is substantially less noisy (meaning that there is less letter position uncertainty) than in the visual modality. Nonetheless, as Perea et al. (2012) indicated, "with some effort, they [braille readers] were able to volitionally reconstruct the base word of a number of pseudowords" (p. 3). To examine in finer detail the intricacies of letter position coding in a more natural scenario, the present experiment examined the role of the different letter positions (initial, middle, final) during normal reading.

The experiment was conducted in Spanish. The most common braille code in Spanish (Grade 1) does not employ abbreviations, while the most common braille code in English (Grade 2) employs many contractions and abbreviations (e.g., the = ⠮, -ing = ⠬); thus, each sentence was composed of the same number of letters in the two modalities. The word transpositions in the jumbled word sentences involved adjacent letter positions, at the beginning of the word, in the middle, or at the end (see Table 1), with the constraint that only words with five or more letters had letter transpositions.

The predictions are straightforward. Because of the intrinsic seriality of braille reading, the cost of the sentences with jumbled words should be substantially larger for the initial letter position—the one that creates the initial access code—than for the other positions, following a monotonic function (see Bertelson et al., 1992, for evidence using word identification tasks). In contrast, we expect to find a nonmonotonic (quadratic) function in the visual modality (i.e., the smallest reading cost should be for middle transpositions), as in the Rayner et al. (2006) experiment. The experiment also has implications for the different models regarding the locus/loci of transposed-letter effects: perceptual uncertainty at the visual level versus abstract representation accounts of letter position coding. If the processes underlying letter position coding are (mostly) due to perceptual uncertainty at the visual level, reading jumbled words during sentence reading in the tactile modality should involve a much greater cost than in the visual modality. Alternatively, if the processes underlying letter position coding are modality independent (e.g., due to the activation of abstract open bigrams), reading jumbled words during sentence reading in the visual and tactile modalities should involve a similar cost. While the open-bigram account has not explicitly been expanded to braille reading, there is the claim that open bigrams provide us with a near optimal level of representation (Dandurand, Grainger, Duñabeitia, & Granier, 2011). If transposed-letter effects are a consequence of a representation intrinsic to all orthographic systems and if the bigram representation is such a representation open bigrams would be activated as the braille reader progresses in the finger movement. For example, if the word is *TRIAL*, the word identification process would begin with the detection of the letter *T*, followed by the letter *R*, which activates the bigram [*TR*]; detecting *I* activates the bigrams [*TR-TI-RI*]; detecting *A* activates the bigrams [*TR-TI-TA-RI-RA-RI-IA*]; and finally, detecting the final letter *L* activates the bigrams [*TR-TI-TA-TL-RI-RA-RL-IA-IL-AL*]. The idea is that while the manner of braille reading makes the activation of the bigram-level unit more serial, it is those bigrams that are the driving force of the word recognition process.

To summarize, given that there are differences between braille and sighted reading due to motor and sensory limitations that constrain each of the two modalities, is there a common abstract representation, and, if so, is that representation responsible for the transposed-letter effects described above?

Method

Participants

In the braille subexperiment, we recruited 20 congenitally blind participants (mean age 40 years, range = 24–60), all of them university undergraduates/graduates in Valencia or Málaga. They had learned braille when they were 5/6 years old and reported reading in braille on a daily basis. All of them had normal hearing. Most (77%) of the participants were daily braille display users; the rest employed a braille display occasionally. None of the participants reported any difficulties while reading in the braille display. In the sighted-reading subexperiment, we recruited 16 students from the University of Valencia with normal vision/hearing. All participants were native speakers of Spanish.

Stimuli

We created a set of 80 sentences in Spanish. Each sentence contained a high-frequency target word (mean = 123.6 per million, range = 30–545, in the EsPal database (Duchon, Perea, Sebastián-Gallés, Martí, & Carreiras, 2013); mean length = 7.4, range = 7–9). None of the sentences contained more than 40 characters, a length that could be displayed on a single line in the braille display and on the computer screen. As in the Rayner et al. (2006) experiment, we created four versions of each sentence: (1) The word was intact; (2) the initial letters of each word were transposed; (3) two internal letters were transposed; and (4) the two final letters were transposed. Words of four or fewer letters were not presented in jumbled form. The initial word in the sentence was always four letters or shorter (see Table 1). One quarter of the participants received each experiment list.

Procedure

The experiment took place individually in a quiet room. For the braille subexperiment, a HandyTech-Active Braille 40-cell display was employed to present the sentences and record the participant's reading position during reading; participants only used their preferred hand. This device detects the participant's tactile reading position of the finger with the strongest pressure approximately every 16 ms (i.e., it provides one data point 60 times per second: the braille cell in which there is the firmest contact). For the printed-reading subexperiment, participants were instructed to read the printed sentences; their eye movements were monitored with an Eyelink-II eyetracker (500 Hz) using Eyetrack (available at http://blogs.umass.edu/eyelab/software/). A chinrest was employed to reduce head movements, and calibrations/recalibrations were performed when necessary. In the two subexperiments, comprehension questions were asked after 50% of the trials.

Data analysis

We computed a number of global and local dependent variables. The global measures were number of words per minute, number of fixations (eye) or lingers (finger), and percentage of regressions (Rayner et al., 2006). The local measure was the first-pass time on the target word. For the eye-tracking subexperiment, fixation times beyond the 80- to 800-ms cutoffs were excluded from the analyses. For the braille subexperiment, when participants' reading finger lingered for more than 1 s on a given character, those pauses were excluded from the analyses.

Results

Most participants claimed to have understood all or to have trouble with no more than two sentences (94% and 95% in the visual and tactile modalities, respectively). None of the participants made more than two comprehension errors (mean = 1.5% and 3.5% errors in the visual and tactile modalities, respectively). The averages of the dependent measures are shown in Table 1.

Given the analogous yet dissimilar nature of eye- tracking and braille-tracking measurements, we did not directly perform any type of statistical inference comparing the two modalities, except for a global measure of reading cost. The average reading cost for participants (in terms of words per minute) from reading sentences with jumbled words (merged together), relative to the normally written condition, was dramatically larger in braille than in the visual modality (34.0% vs. 18.7%, respectively), $F(2, 68) = 40.28$, $\eta^2 = .54$, $p < .001$. Instead, we focused on the comparison of the distinct features of the data from sighted versus braille reading regarding letter position encoding. To examine in detail the cost of reading jumbled words on the dependent measures, position of transposition (initial, middle, final) was the factor in the by-participants (F_1) and by-items (F_2) ANOVAs.

Reading rate (words per minute)

The data in the tactile modality reflected more words per minute in the sentences involving transpositions in the initial letter position and less cost in the final letter position. This was reflected in a linear function, $F_1(1, 19) = 43.18$, $\eta^2 = .69$, $p < .001$; $F_2(1, 79) = 56.50$, $\eta^2 = .42$, $p < .001$; the quadratic function was not significant, $F_1 < 1$; $F_2(1, 79) = 2.26$, $\eta^2 = .03$, $p = .13$. In contrast, in the visual modality, the number of words per minute was larger in the external-letter transpositions and smaller in the internal-letter transpositions. This was reflected in a quadratic function, $F_1(1, 15) = 28.71$, $\eta^2 = .66$, $p < .001$; $F_2(1, 79) = 18.37$, $\eta^2 = .19$, $p < .001$; the linear function was negligible, both Fs < 1.

Number of fixations (visual) and lingers (braille)

The data in the visual modality reflected a larger number of fixations for those sentences involving transpositions in the external letters. Most of the variance was explained by a quadratic function, $F_1(1, 15) = 27.50$, $\eta^2 = .65$, $p < .001$; $F_2(1, 79) = 13.73$, $\eta^2 = .15$, $p < .001$, and there was also a small linear function, $F_1(1, 15) = 7.46$, $\eta^2 = .33$, $p = .015$; $F_2(1, 79) = 3.11$, $\eta^2 = .10$, $p = .08$. In the tactile modality, there is not a variable that directly compares with number of fixations, for the reasons mentioned in the introduction; however, as another measurement of reading difficulties, we computed the number of times in which the finger lingered on a braille cell for longer than a refresh cycle (16 ms). Note that this does not necessarily mean a pause in the finger movement but, rather, a slowdown in motion. The number of lingers was larger for those sentences involving transpositions at the initial letter position and fewer lingers when the sentences involved transposition at the final letter position. Most of the variance was explained by a linear function, $F_1(1, 19) = 33.17$, $\eta^2 = .64$, $p < .001$; $F_2(1, 79) = 65.40$, $\eta^2 = .45$, $p < .001$, and there was also a small quadratic component, $F_1(1, 19) = 5.85$, $\eta^2 = .02$, $p = .026$; $F_2(1, 79) = 9.84$, $\eta^2 = .11$, $p = .002$.

Percentage of regressions

The regression data in the tactile modality reflected a linear function (more regressions in the initial position and fewer regressions in the final position), $F_1(1, 19) = 43.71$, $\eta^2 = .70$, $p < .001$; $F_2(1, 79) = 53.50$, $\eta^2 = .40$, $p < .001$, while the quadratic component did not approach significance, $F_1(1, 19) = 1.37$, $\eta^2 = .06$, $p = .26$; $F_2(1, 79) = 2.53$, $\eta^2 = .03$, $p = .12$. The regression data in the visual modality failed to reveal any linear or quadratic trends, all *F*s < 1.

First-pass time (on target word)

In the tactile modality, the duration of the first-pass time on the target word reflected a linear function, $F_1(1, 19) = 25.23$, $\eta^2 = .57$, $p < .001$; $F_2(1, 79) = 64.10$, $\eta^2 = .34$, $p < .001$, and was accompanied by a smaller quadratic component, $F_1(1, 19) = 7.31$, $\eta^2 = .27$, $p = .014$; $F_2(1, 79) = 6.49$, $\eta^2 = .08$, $p = .013$. In contrast, the data in the visual modality reflected a quadratic function (i.e., there was a larger cost in the external letter positions), $F_1(1, 15) = 29.98$, $\eta^2 = .66$, $p < .001$; $F_2(1, 79) = 18.37$, $\eta^2 = .19$, $p < .001$, whereas the linear function was negligible, both *F*s < 1.

Discussion

As occurs with sighted readers in the visual modality, congenitally blind readers can accurately understand sentences with jumbled words in braille. The high level of comprehension of the sentences with jumbled words was accompanied by a reading cost. This cost was modulated by the position of the transposition (initial, internal, final) and the modality. In the visual modality, the cost reflected mostly a quadratic function (i.e., larger cost of the external letter transpositions, thus replicating Rayner et al., 2006), whereas in the tactile modality, the cost reflected a linear function (i.e., larger cost of the initial letter position). Thus, the nature of word processing is more parallel in the visual modality and more serial in the tactile modality. The reading cost of presenting jumbled words in braille was larger than that in the visual modality (in terms of words per minute: 34.0% vs. 18.7%, respectively), which favors those models that assume that perceptual uncertainty at the visual level is key in the high degree of flexibility of letter position coding.

Therefore, the characteristics of the sensory modality shape the process of letter position coding during sentence reading. While the perceptual system in the visual modality has to deal with the identity and position of several objects (e.g., letters while reading) in a single gaze, the process in the tactile modality is manifestly more serial. The larger reading cost in braille reading than in sighted reading fits entirely with models of letter position coding that assume that the jumbled word phenomenon is the results of perceptual uncertainty when the location of objects is processed in the visual modality (see Perea, García-Chamorro, Centelles, & Jiménez, 2013, for evidence when music is read).[1] In the case of visual reading, a feasible account of the present findings is based on the overlap model (Gómez et al., 2008). In this model, the position of a visual stimulus in a string is described as a field, rather than as a discrete point (e.g., the position of the letters *I* and *A* in *TRIAL* have some overlap in their encoded locations). When we present a sentence such as "FNACY LAYWER . . . ," these strings of letters will have a large overlap with the representations of their base words ("FANCY LAWYER . . ."), thus producing little cost relative to the intact sentence. The overlap model assumes that these fields can be described as normal distributions and that different letters can have smaller and larger standard deviations (σ) (i.e., perceptual noise). In the visual modality, the external letters would have smaller σs, and hence, there would be less overlap than in internal letters. Importantly, the present experiment poses some problems for those accounts that assume that the graded representation in letter position coding is intrinsic to reading in all orthographic codes (i.e., open-bigram models; Dehaene et al., 2005). These accounts assume an abstract level of representations of open bigrams shared by all orthographic codes; note that open-bigram detectors are allegedly activated in the *same* brain area for sighted and blind readers (Reich et al., 2011). Thus, open-bigram accounts would have predicted a similar reading cost in the two modalities.

How are letter identities and positions attained in braille? One might argue that the location of a given letter in a word is obtained earlier than its identity. This can readily explain the presence of a strong linear component in performance as a

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[1] We acknowledge, however, that at some level, there are processes that are specific to letter/word processing (e.g., word/nonword differences in letter position coding, as shown in Gómez et al., 2008). However, these "late" processes may not require a level of open bigram detectors that encode letter position. Additional research is necessary to determine whether bigrams (or some form of frequent orthographic/morphological chunks) play a relevant role during word recognition and reading, as proposed by hybrid models of letter position coding (Adelman, 2011; Grainger et al., 2006).

function of position of the letter transposition (see Bertelson et al., 1992, for evidence of a *uniqueness point* effect in braille word identification). The limitations of the motor and tactile systems make even the most expert braille readers slower than fluent sighted readers, as is clear from the reading times in our baseline (intact) condition. Note that this does not scale up the effects: The reading cost of the transposed-letter conditions was linear in the tactile modality (i.e., less reading cost for the final transpositions) and quadratic in the visual modality (i.e., less reading cost for the internal transpositions). Thus, braille reading is qualitatively different from sighted reading. Determining whether this difference occurs because of the slower pace, the sensory modality, or any other factor not explored here is beyond the scope of this article.

In sum, the present experiment demonstrates that comparing the data from parallel sighted versus braille reading experiments can give us insights into modality-specific versus modality-independent processes in sentence reading. In particular, the particularities of the visual and tactile sensory systems shape the way letter positions are encoded during sentence reading. Future research should focus on how sensory modality modulates higher-level processes during sentence reading.

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