Pre-final version

Does location uncertainty in letter position coding emerge because of literacy training?

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Abstract

In the quest to unveil the nature of the orthographic code, a useful strategy is to examine the transposed-letter effect (e.g., JUGDE is more confusable with its base word, JUDGE, than the replacement-letter nonword JUPTE). A leading explanation of this phenomenon, which is line with models of visual attention, is that there is perceptual uncertainty at assigning letters ("objects") to positions. This mechanism would be at work not only with skilled readers but also with preliterate children. An alternative explanation is that the transposed-letter effect emerges at an orthographic level of processing as a direct consequence of literacy training. To test these accounts, we conducted a same-different matching experiment with preliterate four-year old children using same vs. different trials (created by letter transposition or replacement). Results showed a significantly larger number of false positives (i.e., "same" responses) to transposed-letter strings than to one/two-replacement-letter strings. Therefore, the present data favor the view that the visual processing of location information is inherently noisy and rule out an interpretation of confusability in letter position coding as emerging from literacy training.

Key words: letter position; word recognition; orthographic code

In the past years, much attention in the areas of visual-word recognition and reading has been devoted to cracking the roles of letter *identity* vs. *position* in the orthographic code (Lupker, Zhang, Perry, & Davis, 2015). An important phenomenon that may help unveil the intricacies of how the orthographic code is attained is the transposed-letter effect: a transposed-letter nonword (e.g., JUGDE, CHOLOCATE) can be confused with its base word to a larger degree than a replacement-letter nonword (e.g., JUPTE, CHOTONATE; see Blythe, Johnson, Liversedge, & Rayner, 2014; Forster & Guerrera, 2008; Grainger, 2008; Perea & Lupker, 2004).

One of the leading explanations of the transposed-letter effect has its origins in a basic assumption of models of visual attention (e.g., see Ashby, Prinzmetal, Ivry, & Maddox, 1996; Logan, 1996): there is uncertainty at assigning positions to objects (i.e., letters). For instance, the letters G and D in JUGDE would activate not only their respective letter positions, but also neighboring positions. As Logan (1996) indicated, "locations are not points but distributions in l-D, 2-D, and 3-D space" (p. 606). Hence, the transposed-letter nonword JUGDE is perceptually more confusable with JUDGE than the replaced-letter nonword JUPTE. Indeed, most current models of visual word recognition include a parameter of position uncertainty in letter position coding (e.g., LTRS model, Adelman, 2011; spatial coding model: Davis, 2010; overlap model: Gomez, Perea, & Ratcliff, 2008; overlap open bigram model, Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006; noisy-slot Bayesian reader model: Norris, Kinoshita, & van Casteren, 2010).

Because the principle of position uncertainty during letter position coding has its foundation in models of visual attention (see Gomez et al., 2008; Norris et al., 2010, for discussion), one would expect this mechanism to be at work not only with beginning and skilled readers, but also with preliterate children (i.e., letters are just objects that

acquire a special status for readers). That is, the transposed-letter effect should occur in preliterate children—at least if they are given enough time to process the constituent objects (i.e., letters) of the string.

Crucially, another leading explanation of the transposed-letter effect offers a very different prediction. In the family of open bigram models (e.g., open bigram model: Grainger & van Heuven, 2003; SERIOL model: Whitney, 2001), letter position coding is attained on the basis of the relative ordering of pairs of letters that co-occur within the string (i.e., the "open bigrams") at an orthographic level of processing. For instance, the transposed-letter nonword JUGDE would activate more "open bigrams" in common with JUDGE (JU, JG, JD, JE, UG, UD, UE, GE, DE) than the replaced-letter nonword JUPTE (JU, JE, UE). The higher the number of open bigrams that are shared by two letter strings, the higher the perceptual similarity; hence JUGDE-JUGDE are more confusable than JUPTE-JUDGE. The key point here is that preliterate children have not yet acquired orthographic representations of the letters, let alone open bigrams. As a result, open bigram models would predict that, for preliterate children, the degree of similarity/confusability of JUGDE-JUDGE is comparable to that of JUPTE- JUDGE.

Thus, the examination of whether or not transposed-letter effects occur with preliterate children is a perfect scenario to test the predictions of perceptual uncertainty models and open bigram models (i.e., *an experimentum crucis*). To our knowledge, only one published experiment has examined whether transposed-letter effects can occur with preliterate (four-year old) children (Duñabeitia, Lallier, Paz-Alonso, & Carreiras, 2015). In the Duñabeitia et al. (2015) same-different experiment, a four-consonant referent was presented in lowercase for 1000 ms. This was replaced by a pattern mask (####) for 500 m and was followed by a four-consonant target string in lowercase that could be the same (e.g., rzsk-rzsk) or different (transposed-letter condition: rzsk-rszk or

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replaced-letter condition: rzsk-rhck). Participants ranged from four-year olds (i.e., children that have not yet acquired orthographic representations) to six-year olds (i.e., children that have already acquired orthographic representations). There were 80 trials (40 "same" trials, 20 "different" pairs in which two internal consonants were transposed, and 20 "different" pairs in which two internal consonants were replaced). Participants had to press a key for "same" trials and another key for "different" trials. Only error data were reported. Results from the four-year olds revealed similar proportions of "same" (incorrect) in the transposed- and replaced-letter conditions (.594 and .559, respectively) (i.e., a null transposed-letter effect). Two years later, after these children had acquired basic reading skills, results revealed a sizable transposed-letter effect: the proportions of "same" (incorrect) responses were .429 and .306 in the transposed-letter and the replaced-letter conditions, respectively.

Clearly, a lack of a transposed-letter effect with preliterate children would be more consistent with open bigram models than with perceptual uncertainty models. Duñabeitia et al. (2015) report what seems to be lack of a transposed letter effect; however, closer examination of their data reveals that their participants had poor performance in all conditions, which renders the comparison between the replaced-letter and the transposed letter condition difficult to interpret as participants seem to respond in a similar way to identical, replacement and transposed-letter items. For trials in which the referent and the target were identical, the proportion of "same" (correct) responses was .607, whereas for trials in which the referent and the target were different, the proportions of "same" (incorrect) responses were .559 and .594 in the transposed-letter and replaced-letter conditions, respectively. That is, preliterate children responded "same" about 60% of the time regardless of the identity of the items (i.e., there was just a bias for "same" responses). Consistent with this, the reported *d'* values for the

preliterate, four-year olds in the Duñabeitia et al. experiment did not differ from zero for either the transposed or the replaced letter conditions. {FOOTNOTE 1}

In the present same-different experiment, we examined whether or not letter transposed-letter effects occur when preliterate, four-year-old children process letter strings (i.e., same trials vs. different trials [via transposition/replacement). Pilot testing corroborated that, indeed, four-year olds could not satisfactorily be above chance level when we used the Duñabeitia et al. (2015) experimental setup with four-letter strings. Therefore, one basic issue is how to optimize the design to testing preliterate children in a same-different task. The capacity of visual short term memory is widely held to be four objects in adults, and this capacity is even smaller in children (see Riggs, McTaggart, Simpson, & Freeman, 2006, for developmental evidence), and to make sure that children could adequately perform the experiment with reasonable accuracy, and hence, obtain meaningful data, we employed a simplified version of the same-different task. First, we used two-letter strings instead of four-letter string. We should note here that while transposition effects are usually greater for internal than for external letter positions, they have also been reported in strings of two letters (e.g., ON-NO; Kinoshita & Norris, 2013) or two digits (e.g., 74-47; García-Orza & Perea, 2011). Second, to reduce working memory resources, we opted for a simultaneous same-different task (e.g., Chambers & Forster, 1975; Eichelman, 1970) rather than a sequential same-different task. Third, to minimize the memory load required to remember which key to respond, we collected the participants' verbal responses: children were instructed to say "*igual*" (same) or "*diferente*" (different) (see Laxon, Coltheart, & Keating, 1988, for a similar procedure). Fourth, to reduce fatigue, the number of trials was not markedly long (64 experimental trials that were preceded by 10 practice trials). Fifth, we employed uppercase consonant letters rather than lowercase consonant letters, the

reason being that uppercase letters have greater visual simplicity and distinctiveness than lowercase letters (see Worden & Boettcher, 1990). Finally, we should note the present research is predicated on the participants being pre-literate; we verified that none of the preschoolers in the experiment knew the name or sound of the consonant letters (i.e., they can be characterized as "pre-literate"; see Participants section for details).

The predictions of the experiment are straightforward. If, as proposed in the overlap and noisy-slot Bayesian reader models, the visual processing of location information in the processing of letter strings (i.e., objects) is inherently noisy, one would expect more "same" responses (i.e., more false positives) to transposed-letter strings (e.g. FK-KF) than to replaced-letter strings (e.g., RW-KF) in preliterate children. Alternatively, if, as proposed in open bigram models, confusability in letter position coding emerges at an orthographic level of processing as a consequence of literacy training, one would expect that preliterate children show a similar proportion of "same" responses to transposed-letter strings and replaced-letter strings (FK-KF and RW-KF; i.e., a null transposed-letter effect). To better understand the underlying processes, for "different" trials, we employed not only a transposed-letter condition (FK-KF) and the appropriate control condition (i.e., a two-replacement-letter condition, RW-KF), but also a one-replacement-letter condition (KW-KF; WK-KF), as this latter condition would inform us on how letter identities are processed when letter position is accurate and may be used to constraint models of letter position coding.

In the present report, we perform the statistical inference using Bayes factors. Bayes factors offer an estimate of the support for a model relative to another model. In this case, the models being compared are paired sample t-tests. Model 0 is the null hypothesis that there is no difference between conditions: $\mu_d=0$, and Model 1 is the alternative hypothesis that there is an effect; the exact size of this effect under the alternative hypothesis is unknown, but it is assumed

to come from a (prior) Cauchy distribution with parameters $x_0 = 0$ (i.e., as the distribution is centered on 0) and $\delta = 0.707$ (i.e., the scale parameter of the Cauchy distribution is 0.707 which is the default value): $\mu_d \sim \text{Cauchy}(\delta)$. We use the notation BF_{01} to express the probability of the data given a the null hypothesis (Model 0) relative to the probability of the data given the alternate hypothesis (Model 1): $p(\text{Model 1|Data}) / p(\text{Model 0|Data})$. The notation BF_{10} would express the inverse relationship: $p(\text{Model 0|Data}) / p(\text{Model 1|Data})$ (Rouder, Speckman, Sun, Morey, & Iverson, 2012). Thus, Bayes factors may offer valuable information to express our degree of certainty that location-noise in letter position coding emerges as a consequence of literacy training. There are guidelines in the literature to interpret the relevancy of BF values; notably, Jeffrey's (1961, page 432) guideline is often cited: 0 to 3: "evidence […], but not worth more than a bare mention"; 3 -10: "substantial"; 10-32: "strong", 32-100: "very strong", >100 "decisive".

Method

Participants

The participants were twenty preschoolers (M age= 54.5 months [4.54 years]; SD = 3.6; 7 girls) from a private school in the province of Valencia. All of them were native speakers of Spanish. None of them had any learning developmental problems. In the PLON test (*Prueba de Lenguaje Oral de Navarra* [Navarra Oral Language Test]; Aguinaga, Armentia, Fraile, Olangua, & Útiz, 2004), which was conducted when these children were three-year old, the average was 79.4 (SD=15.0; 15 participants in the "very high" category, 3 participants in the "high" category and 2 participants in the "medium" category). Informed consent from their parents was obtained before running the experiment. While all these children were exposed to letters (in words) on a regular basis, they had not received any specific, formal training on the name or sound of the consonant letters. At the time of testing, they were starting learning the vowels. After

the experiment was conducted, we assessed the knowledge of name and sound of letters in the alphabet using the standardized BIL 3-6 battery (Sellés, Martínez, Vidal-Abarca, & Gilabert, 2008). Results confirmed that the children did not know the name or sound of the consonant letters—as an anecdotal note, during the instructions and/or the practice phase of the experiment, some of them were able to distinguish their name's initial.

Materials

The stimuli were 64 pairs of consonant strings made of two consonants. In 16 trials, the letter strings were identical ("same" condition; e.g., SP – SP). In the remaining 48 trials, the letter strings were "different". For the "different" trials, the pairs were: 1) the same letters but switched (transposed-letter condition; e.g., TZ – ZT); 2) one of the letters was the same, but the other was different (one-replacement-letter condition; e.g., GC – GX or BD – HD); 3) created from different letters (two-replacement-letter condition; e.g., DL – PH). Four counterbalanced lists were created in a Latin square manner, so that each stimulus was rotated across the different conditions. Therefore, there were 16 trials in each of the four conditions. This produced more "different" trials (i.e., the trials that tested the transposed-letter effect) than "same" trials—note that there is no a priori reason why this would affect the sensitivity of the task. The presentation of the items was randomized for each participant.

Procedure

The experiment took place individually in a quiet room within the school premises. DMDX software (Forster & Forster, 2003) was employed for stimulus presentation and recording of the responses. In each trial, first, a fixation point (+ +) appeared in the center of the screen for 500 ms. This was followed by the presentation of the target for 1000 ms. Next, the screen remained blank during 5000 ms. Participants were instructed

to say "*igual*" [same] when the two consonant strings were identical or "*diferente*" [different] when the two consonant strings were different. Their response was recorded. Accuracy was stressed in the instructions. Ten practice trials preceded the 64 experimental trials. The whole session lasted for around 10 minutes.

Results

CheckVocal (Protopapas, 2007) was employed to obtain the participants' responses. For simplicity, only the accuracy data is analyzed, but the latency data follows the same pattern as the accuracy data (see Appendix).

In order to interpret the data, we made sure that the participant's performance was above chance (i.e., $d' > 0$). To calculate d' per participant, we used the hit rate for "same" trials (mean = .82) and the false alarm rate for two-replacement-letter trials (mean = .12). The average d' was 2.30, which supports the hypothesis of d' not being zero with $t(19) = 12.04$; $BF_{10} = 4e+7$ (For this and all other BF calculations we used Morey's BayesFactor R Package, Version 0.9.2+).

For the "different" trials, the accuracy ranges from .88 for the two-replacement-letter trial, .68 for the one-replacement-letter trials, and .33 for the transposed-letter trials (i.e., the proportion of false positives was substantially higher for transposed-letter pairs than for replacement-letter trials). All these differences revealed strong evidence supporting the alternate hypothesis: TL vs. 1L: $t(19) = 6.98$; $BF_{10} = 1.5e+4$, TL vs. 2L: $t(19) = 11.3$; $BF_{10} = 1.5e+7$; 1L vs. 2L: $t(19) = 5.56$; $BF_{10} = 1e+3$. Unsurprisingly, all p values for the three comparisons were smaller than .001.

Discussion

The main aim of the current same-different transposed-letter experiment with preliterate children was to test the predictions of perceptual uncertainty models and open bigram models. While perceptual uncertainty models predicted more errors to transposed-letter pairs than to replacement-letter pairs (i.e., letters are just a special type of "object"), open bigram models predicted a null transposed-letter effect (i.e., the letter/bigram level responsible for the transposed-letter effect had not been acquired yet). Preschoolers faced a same-different task that allowed them to have a reasonable level of accuracy ($d' = 2.3$; $BF_{10} = 4e+7$)—note that in the Duñabeitia et al. (2015) same-different experiment, four-year olds performed at chance level (i.e., comparing same to double replacement, $d' = 0.03$; $BF_{01} = 5.4$). Data showed the number of false positives (i.e., "same" responses) was substantially higher to transposed-letter strings than to one/two-replacement-letter strings. Bayesian analyses corroborated these differences. The response times were in the same direction (see Appendix).

This outcome is entirely consistent with the perceptual uncertainty models proposed by Gomez et al. (2008) and Norris et al. (2010), and also with the other models of letter position coding that include perceptual uncertainty as a parameter (LTRS model: Adelman, 2011; spatial coding model: Davis, 2010). Importantly, the finding of a robust transposed-letter effect here with external letters is even stronger evidence than if the transposed letters were string-internal—note that transposed-letter effects are typically greater for internal than for external transpositions. Furthermore, the present data rule out those open bigram accounts that assume that letter position coding is obtained on the basis of "open bigrams" emerging, as a consequence of literacy training, at an orthographic level of processing (e.g., open bigram model: Grainger & van Heuven, 2003; SERIOL model: Whitney, 2001). Nonetheless, the

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present findings are consistent with those open bigram models that include a

"perceptual uncertainty" parameter, as in the overlap open-bigram model described by

Grainger et al. (2006).

Therefore, the data favor the view that the transposed letter effects arise because

of noisy perception of location of objects. Converging evidence supporting our

conclusions comes from experiments that have reported transposed-letter effects with

non-human primates (baboons; see Ziegler et al., 2013), and from experiments on music

reading, in which the transposition of two musical notes produces a transposition effect

in a same-different matching task with non-musicians (Perea, García-Chamorro,

Centelles, & Jiménez, 2014). Additional evidence that a source of letter position coding

comes from perceptual uncertainty at the visual level comes from experiments in a

tactile modality with braille readers. These participants show a dramatic reduction of

letter transposition effects in word recognition and reading (see Perea, García-

Chamorro, Martín-Suesta, & Gomez, 2012; Perea, Jiménez, Martín-Suesta, & Gomez,

2014).

To sum up, the present data demonstrated the usual confusability of transposed

letter stimuli in preliterate children {Footnote 2}. This finding favors perceptual

uncertainty over open bigram models of letter position coding. The current experiment

also revealed a methodological take-home message: It is fundamental to adapt the

experimental settings to the characteristics of the individuals being tested (i.e., when

running experiments with special populations; e.g., children, neurological patients, etc.)

so that participants are adequately performing the tasks.

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Footnotes

Footnote 1. In signal detection theory, chance-level performance (i.e., $d'= 0$ or no

sensitivity) occurs when the correct rate (hit rate) for the identical items is the equal

to the error rate (false alarm rate) for the different items.}

Footnote 2. Duñabeitia, Orihuela, and Carreiras (2014) also reported a null letter

transposition effect in a same-different matching task with illiterate adults.

However, as discussed by Perea, Winskel, Abu Mallouh, Barnes, and Gomez

(2015), illiterate adults in their experiment did not show d' values different than

zero, and thereby these data were not interpretable.

Figure Captions

Figure 1. The Figure shows the accuracy rates for all conditions in the experiment. Note

that for the two-replacement-letter, one-replacement-letter, and transposed-letter

conditions, the correct response was "different".

The table shows the mean response times (RTs, in ms) and standard errors (between parentheses) in each of the conditions of the experiment

Condition	Error RT	Correct RT
Same	3851 (482)	1833 (72)
Two-replacement-letter	5038 (779)	1955 (64)
One-replacement-letter	3028 (285)	2133 (61)
Transposed-letter	2596 (208)	2336 (110)