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The effects of length and transposed-letter similarity in lexical decision: Evidence with beginning, intermediate, and adult readers

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Do length and transposed-letter effects reflect developmental changes on reading acquisition in a transparent orthography? Can computational models of visual word recognition accommodate these changes? To answer these questions, we carried out a masked priming lexical decision experiment with Spanish beginning, intermediate, and adult readers ($N = 36$, 44, and 39; average age: 7, 11, and 22 years, respectively). Target words were either short or long (6.5 vs. 8.5 letters), and transposed-letter primes were formed by the transposition of two letters (e.g. *aminal–ANIMAL*) or by the substitution of two letters (orthographic control: *arisal–ANIMAL*). Children showed a robust length effect (i.e. long words were read slower than short words) that vanished in adults. In addition, both children and young adults showed a transposed-letter priming effect relative to the control condition. A robust transposed-letter priming effect was also observed in non-word reading, which strongly suggests that this effect occurs at an early prelexical level. Taken together, the results reveal that children evolve from a letter-by-letter reading to a direct lexical access and that the lexical decision task successfully captures the changing strategies used by beginning, intermediate, and adult readers. We examine the implications of these findings for the recent models of visual word recognition.

The development of the visual word recognition system involves changes on the processes used by children and adults to encode printed words in the mental lexicon. There is little doubt that reading proficiency results from a transition from serial letter-by-letter processing strategies to a more efficient, parallel, and direct process of lexical access (e.g. Bowey & Muller, 2005; Duncan, Seymour, & Hill, 1997; see also Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001). In this light, the process of word recognition is likely to be more difficult for words with more letters, and this difficulty may increase for beginning/intermediate readers of transparent orthographies. In other words, print-to-sound mapping seems to be much more useful for lexical access in transparent orthographies than in opaque orthographies (see Jimenez & Guzmán, 2003).

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Thus, exploring how the coding of letters is attained for short and long words by beginning, intermediate, and adult readers can be critical to understand how lexical access is achieved in a transparent orthography like Spanish. This is the main goal of the present study.

Models on reading development assume that the strategies used to recognize printed words change when automatic access to the mental lexicon is achieved. Children begin to be aware of graphic features of print when they start learning to read. This implies an evolution from a visual logographic (or prephonetic) stage to a phonetic–alphabetic reading stage (Ehri, 1995; Mason, 1980). During this latter stage, children must acquire domain about specific letter identities and their corresponding sounds. As proposed by Frith (1985), the process of reading establishes the link between orthographic knowledge and spelling. That is, the reading experience triggers letter–sound relations, being the spelling ability the direct consequence of this process. Thus, the acquisition of reading skill is developed on a continuum, from print awareness to accurate phonemic mapping in the alphabetic code. Indeed, there is evidence of a progression from relying on word's small units, like letters or graphemes, to word's larger units (see Duncan, Seymour, & Hill, 2000; Ziegler & Goswami, 2005). Not surprisingly, in a transparent and regular orthography like Spanish, children reach the ceiling of competent reading faster than in an opaque and irregular orthography (e.g. English; see Aro & Wimmer, 2003). This is because children in a regular orthography become easily aware of the spelling regularities of their language.

Developmental studies on the length effect (i.e. the difference in time processing between short and long words) are, therefore, important to capture the evolution of these strategies. However, there are very few previous studies that have examined the length effect for beginning, intermediate, and adult readers. Using a reading aloud task with third graders, fifth graders, and adult readers, Bijeljac-Babic, Millogo, Farioli, and Grainger (2004) found that the effect of length for words (in French) diminished with age, indicating a transition from a serial grapheme–phoneme mapping to a greater reliance on lexical knowledge. Bijeljac-Babic *et al.* (2004) also employed a speeded identification task, and they found a strong length effect for words in third grade children who diminished with increasing age (see Aghababian & Nazir, 2000, for a similar pattern). Likewise, Samuels, Laberge, and Bremer (1978) found that response times in a word categorization task in English were affected by the word length, and that this effect diminished with age. To our knowledge, there are no prior studies examining the length effect from beginning and intermediate to adult readers in Spanish with the lexical decision task – the most popular (and modelled) paradigm in visual word recognition (Coltheart, Rastle, Conrad, Langdon, & Ziegler, 2001; Grainger & Jacobs, 1996; Ratcliff, Gomez, & McKoon, 2004; Wagenmakers *et al.*, 2004). Unlike the above-cited developmental studies, which only used word stimuli, we tested the effect of length for both word and non-word stimuli.

The lexical decision task has provided mixed evidence with respect to the length effect with adult readers. Hudson and Bergman (1985), O'Regan and Jacobs (1992), and Balota *et al.* (2004) found a length effect for words (i.e. slower response times to longer words), whereas Frederiksen and Kroll (1976) failed to find such effect. A recent study based on a complete set of simulations with the word pool of the English Lexicon Project conducted by New, Ferrand, Pallier, and Brysbaert (2006) concluded that the mixed evidence was probably due to several uncontrolled factors (e.g. language, number of 'orthographic neighbours' and different lengths used) among the different studies. More important for the present purposes, and as indicated above, there is no published evidence on the length effect for words with children population, or on how the length effect varies among beginning, intermediate, and adult readers in a lexical decision task – in Spanish or in other languages. Needless to say, it is critical to gather these data to know 'what is there to simulate' by the computational models of visual word recognition. Finally, it has been argued that the lexical decision task may amplify lexical effects, particularly the word frequency effect (see Balota & Chumbley, 1984). Nonetheless, word frequency was tightly controlled in the present experiment. Clearly, response times are always measured within the distorting lenses of the particular task used, and we should note that the lexical decision task decreases the potential effect of the inherent phonological component which occurs in a naming task (Pollatsek, Perea, & Carreiras, 2005; see also Carreiras, Perea, & Grainger, 1997, for a cross-task comparison Spanish, including lexical decision and naming).

Another factor that is critical to understand the processes underlying reading development in children is how the ordering of letters in a printed word is encoded within that word's specific representation (Perea & Lupker, 2004). How can readers discriminate the words *causal* and *casual*? Robust empirical evidence, obtained with adult readers, strongly suggests that letter identity and letter position are not integral perceptual dimensions (Perea & Lupker, 2004; Johnson, Perea, & Rayner, 2007). For instance, transposed-letter pseudowords (e.g. *RELOVUTION*) are perceptually similar to their base words and they are easily confusable with their base word (see O'Connor & Forster, 1981; Perea & Fraga, 2006; Perea, Rosa, & Gómez, 2005). Furthermore, there is evidence of transposed-letter priming effect using the masked paradigm (Forster & Davis, 1984) with adult participants. In this technique, the priming stimulus is presented briefly just prior to the target. A forward pattern mask precedes the prime and, under these conditions, the trace of the prime is relatively inaccessible to conscious report, so that it minimizes the impact of strategic effects. Prior research has found that masked transposed-letter pseudoword primes produce form-priming effects relative to the appropriate orthographic control in the lexical decision task (e.g. *jugde–JUDGE* vs. *jupte–JUDGE*; Perea & Lupker, 2003, 2004; see also Andrews, 1996; Forster, Davis, Schoknecht, & Carter, 1987; Schoonbaert & Grainger, 2004). Furthermore, these priming effects also occur when two non-adjacent internal letters are transposed (*caniso–CASINO* vs. *caviro–CANISO*; Perea & Lupker, 2004).

Interestingly, the letter coding process may be subject to developmental changes. The idea is that the process of assigning locations to objects (in our case, letters) may not be straightforward, and this difficulty could increase for beginning readers. In a recent study, Castles, Davis, Cavalot, and Forster (2007) reported a lexical decision experiment that tested the magnitude of masked transposed-letter priming effects in third grade children and adults. They found that the magnitude of the priming effects diminished with age. Castles *et al.* suggested that the visual recognition system stores knowledge about words through a discrimination mechanism; during reading exposure, this knowledge about words allows this discrimination mechanism become more 'fine tuned'. That is, in the initial stages of reading acquisition, the word recognition system may be more flexible when coding letter positions into the string. In addition, Perea and Estévez (2008) found that, when reading aloud transposed-letter pseudowords (e.g. *CHOLOCATE*; the base word is *CHOCOLATE*), beginning readers of Spanish made more errors – usually lexicalizations (e.g. *CHOCOLATE*) – than intermediate and adult readers. Likewise, Friedmann and Gvion (2005) reported that some children may develop a selective deficit in letter position encoding that result in errors of letter position within words: developmental letter position dyslexia. Hence, the transposed-letter effect is a reliable phenomenon that may be used to reflect the evolution of the discrimination mechanism of the visual recognition system in Spanish (see Castles, Davis, & Forster, 2003).

An important implication of the effects of length and transposed-letter similarity is that they pose a problem for current computational models of visual word recognition. On the one hand, models which assume that a letter is coded only in a certain position in the word (i.e. 'position specific' coding models such as the DRC model of Coltheart *et al.*, 2001; or the DCP + model of Perry, Ziegler, & Zorzi, 2007) cannot capture the presence of transposed-letter effects, although the DCP + model can account for developmental data. More specifically, Perry *et al.* developed a connectionist model by modifying the (static) DRC model of Coltheart *et al.* with the learning procedure of the PDP model of Seidenberg and McClelland (1989). Although the DCP + model may account for the intricacies of the length effect in developmental data, it has two handicaps: (a) it is a model of reading aloud (i.e. other experimental tasks – e.g. lexical decision – are beyond the scope of the model) and (b) it is based on an absolute position coding in which letter slots are coded into an onset-vowel-coda scheme (i.e. the model cannot capture transposed-letter effects).

Alternatively, several recently proposed models that employ a more flexible input coding scheme (e.g. SOLAR model; Davis, 1999; SERIOL model, Whitney, 2001; open-bigram model Grainger & van Heuven, 2003) can readily accommodate the presence of transposed-letter effects but – at least in their present implementation – cannot account for developmental data. In the SOLAR model (Davis, 1999; see also Davis, 2006), letters are activated serially and coded across a spatial activation gradient: the first letter of the word has the greater activation and activation decreases across the letter string. The effect of length would be due to this serial process. In this model, orthotactic (lexical) input rules are not taken into account, so that it predicts an effect of length of similar magnitude for words and non-words. In addition, because of the relative position coding in the activation gradient, the items *AMINAL* and *ANIMAL* would be perceptually very similar, so that the model can readily capture transposed-letter effects. An interesting feature of this model to the understanding of reading development is that it can learn new encountered orthographic representations when inputs are not found in the model's lexicon (see Castles & Nation, 2006, for discussion). In addition, in the SERIOL model (Whitney, 2001), the identity of all letters is first coded in parallel. Then, a temporal coding of letters takes place. Letters are fired serially following their order in the word, forming bigrams. Bigrams created by adjacent letters have more weight than those formed by non-adjacent letters. (In the open-bigram model of Grainger and van Heuven, the similarity between two words is also calculated by the shared number of bigrams, but the activation of the bigrams is not determined by the position of the letters across the string as in the SERIOL model). Whitney and Cornelissen (2008) modified the original SERIOL model by a normalization of weights (weights to shorter words are larger than weights to longer words) to capture the presence of length effects. In addition, the activation of bigram nodes determines the grade of similarity between two words (the prime *aminal* is composed of the open bigrams *AM*,*AI*,*MI*,*MN*,*IN*,*IA*, *NA*,*NL*,*AL* and the target *ANIMAL* is composed of the open bigrams *AN*,*AI*,*NI*,*NM*, *IM*,*IA*,*MA*,*ML*,*AL*). Hence, this procedure allows the model to account for transposed-letter effects relative to an orthographic control (e.g. the prime *arrival*, which only shares a few open bigrams with *ANIMAL*). As described by Whitney and Cornelissen (2005), some aspects of the model are innate (the temporal representation and the ordering of letters in bigrams) and some others must be learned (reading direction and association of orthographic representations with the corresponding lexical representations). Whitney and Cornelissen listed several types of dyslexia in terms of the lack of efficiency of the learned aspects of the model and they proposed solutions for children who show these deficits. However, the current version of the SERIOL model is not able to learn.

In sum, there exist computational models that can fit developmental data, but cannot accommodate the presence of the transposed-letter effects. Other models can accommodate transposed-letter effects, but cannot account for developmental data (i.e. they are not able to learn). Clearly, both length and transposed-letter similarity are two critical factors that reflect orthographic processing during reading, and they may be sensitive to developmental changes across reading development. The conjoint examination of length and transposed-letter effects across reading experience is necessary to constrain the parameters in the computational models of visual word recognition.

The present experiment is intended to provide behavioural evidence of reading development in Spanish – a transparent and very regular orthography – using the most popular task in the field of visual word recognition, lexical decision. Specifically, we conducted a masked priming experiment with beginning (third grade), intermediate (sixth grade), and adult readers in which word length and prime-target relatedness (via transposed-letter similarity) were manipulated. We selected a set of short (mean 6.5 letters) and long (mean 8.5 letters) words that could be preceded by a transposed-letter pseudoword prime or an orthographic control prime (e.g. *aminal–ANIMAL* vs. the orthographic control *arisal–ANIMAL*; and *cholocate–CHOCOLATE* vs. the orthographic control *chotosate–CHOCOLATE*). If the process of assigning locations to objects (letters) is sensitive to reading skill, then beginning readers should show a greater transposed-letter priming effect than adult readers (see Perea & Estévez, 2008, for evidence with a naming task). Furthermore, if reading acquisition involves a transition from a serial grapheme–phoneme mapping to a greater reliance on lexical knowledge (Bijeljac-Babic *et al.*, 2004) then the effect of length should diminish with reading skill for word (but not for non-word) stimuli. This pattern may well be detected soon after children start beginning to read in comparison with other languages, due to the regularity of Spanish.

EXPERIMENT

Method

Participants

The participants were 36 third grade children in Experiment 1a (beginning readers; 19 female, 17 male; mean age = 7 years), 44 sixth grade children in Experiment 1b (intermediate readers; 24 female, 20 male; mean age = 11 years), and 39 college students from the University of the Basque Country in Experiment 1c (adult readers; 21 female, 18 male; mean age = 22 years). The children came from average socio-economic backgrounds and from two different public schools in urban areas of Guipuzcoa (Spain). For third and sixth graders, the test took place at the beginning of the academic year. All of them had normal or corrected-to-normal vision and were native speakers of Spanish – all of them were also speakers of Basque (another transparent orthography). The children had been taught to read using a phonics-based approach, in which teachers focus on teaching the rules of correspondence between graphemes and phonemes. Participants were excluded if they had sensory, acquired neurological, or other problems traditionally used as exclusionary criteria for learning disabilities.

Materials

The word targets were 128 words of six to nine letters. These words were divided into two groups as a function of length: 'short words' (mean number of letters: 6.5; range 6–7 letters), and 'long words' (mean number of letters: 8.5; range: 8–9 letters). Word frequency was controlled for short and long words: the mean word frequency per 1 million was 18 (range 1–352) for short words and 19 (1–210) for long words, respectively, in the Spanish database (Davis & Perea, 2005). (All these words were familiar to beginning readers, as they appeared in the Spanish word frequency count for first grade children of Corral, Goikoetxea, & Laseka, 2004). The mean number of 'orthographic neighbours' was quite low: 1.2 for short words and 1.7 for long words. The targets were presented in uppercase and preceded by primes in lowercase that were: (a) the same as the target except for a transposition of two internal non-adjacent consonants (*aminal–ANIMAL*, transposed-letter condition) or (b) the same as the target except for the substitution of the two internal non-adjacent consonants (*arisal–ANIMAL*, orthographic control – double-substitution – condition). The letter transpositions occurred, on average, around positions 3.8 and 4.0 for short and long words, respectively. The primes were always non-words and their syllabic structure was always the same as that of their corresponding base words. Bigram frequencies for transposed-letter and double-substitution primes did not differ significantly ($p > .50$). An additional set of 128 non-words was created for the lexical decision task (64 'short' non-words and 64 'long' non-words). Non-words were created by changing the first syllable and the following consonants of the target words, so that both length and orthographic structure was the same as in the target words (e.g. the non-word *degero* was formed from the word *babero*, and the non-word *cresotale* was formed from the word *chocolate*). The prime manipulation for the non-word trials was the same as that for the word trials. Two lists of materials were constructed so that each target appeared once in each list. In one list, half of the targets were primed by transposed-letter primes and half were primed by double-substitution primes. In the other list, the targets were assigned to the opposite prime condition. Half of the participants were presented with each list.

Procedure

Participants were tested individually in a quiet room. The experiment was run using DMDX (Forster & Forster, 2003). Reaction times were measured form target onset until the participant's response. On each trial, a forward mask consisting of a row of hash marks (#s) was presented for 500 ms in the centre of the screen. Next, a centred lowercase prime was presented for 50 ms (three cycles of 16.66 ms). Primes were immediately replaced by an uppercase target item, which remained on the screen until the response. (Note that a stimulus-onset asynchrony – SOA – of around 50 ms has become the standard in most current lexical decision experiments – as it is long enough to show early orthographic effects, and short enough to avoid any potential confound derived from conscious processing of the primes). Participants were instructed to press one of two buttons on the keyboard to indicate whether the uppercase letter string was a legitimate Spanish word or not ('m' for yes and 'z' for no). Participants were instructed to make this decision as quickly and as accurately as possible. Participants were not informed of the presence of lowercase items. Each participant received a different order of trials. Each participant received a total of 22 practice trials (with the same manipulation as in the experimental trials) prior to the 256 experimental trials. None of the participants reported having seen the lowercase words when asked after the session. The whole session lasted approximately 15 minutes.

Results

Incorrect responses were excluded from the latency analysis. For each grade (third grade, sixth grade, and college), analyses of variance (ANOVAs) based on the subject's median correct response latencies and error rates were conducted based on a 2 (length: long, short) × 2 (relatedness: transposition, double-substitution) × 2 (List: list 1, list 2) design. List was included as a dummy variable in the ANOVAs to extract the variance due to the error associated with the lists (Pollatsek & Well, 1995). The mean latencies for correct responses and the percentage error are presented in Table 1. As usual, separate analyses were conducted for word and non-word targets. All significant effects had p values less than the .05 level.

Table 1. Mean lexical decision times (in ms) and percentage of errors (in parentheses) for word and non-word targets in beginning, intermediate, and skilled readers

	Type of target			
	Words		Non-words	
	Short	Long	Short	Long
Beginning				
TL	1,438 (21.8)	1,546 (26.9)	1,634 (39.5)	1,745 (46.6)
DS	1,485 (23.6)	1,604 (28.0)	1,728 (43.2)	1,771 (50.7)
TL effect	47 (1.8)	59 (1.1)	94 (3.7)	26 (4.1)
Intermediate				
TL	946 (8.0)	1,026 (6.9)	1,255 (11.4)	1,407 (11.3)
DS	955 (6.7)	1,036 (6.5)	1,362 (11.6)	1,452 (11.9)
TL effect	9 (−1.3)	10 (−0.4)	107 (0.2)	45 (0.6)
Skilled				
TL	640 (3.8)	653 (2.2)	820 (5.6)	897 (5.1)
DS	650 (3.1)	664 (1.7)	846 (4.4)	942 (3.8)
TL effect	10 (−0.7)	11 (−0.5)	26 (−1.2)	45 (−1.3)

Note: TL, transposed-letter prime; DS, double-substitution prime; TL effect, difference between the double-substitution and the transposed-letter prime.

Experiment 1a (beginning readers)

Word data

Short words were responded to 114 ms faster than long words, $F(1, 34) = 3.86$, $MSE = 48,068.7$, and words preceded by a transposed-letter prime were responded to

53 ms faster than the words preceded by a double-substitution prime, $F(1, 34) = 5.35$, $MSE = 5,587.6$. The interaction between the two factors was not significant.

The ANOVA on the error data only revealed a significant length effect (22.7 and 27.5% of errors for short and long words, respectively), $F(1, 34) = 17.29$, $MSE = 94.9$.

Non-word data

Short non-words were responded significantly faster (77 ms) than long non-words, $F(1, 34) = 10.39$, $MSE = 22,324.8$, and non-words preceded by a transposed-letter prime were responded to 60 ms faster than the non-words preceded by a double-substitution prime, $F(1, 34) = 11.78$, $MSE = 9,713.1$. The interaction between the two factors was not significant.

The ANOVA on the error data showed that participants committed fewer errors for short than for long non-words (41.4 vs. 48.7% of errors, respectively), $F(1, 34) = 21.19$, $MSE = 90.3$, and that the error rate for non-words preceded by a transposed-letter prime was lower than that for the non-words preceded by a double-substitution prime (43.1 vs. 47.0%, respectively, $F(1, 34) = 7.60$, $MSE = 72.25$). The interaction between the two factors was not significant.

The results with beginning readers showed robust effects of length and transposition-letter for words and non-words. Interestingly, while the length effect was numerically stronger for words than for non-words (probably as consequence of modest knowledge about orthographic representations in their own language, and the frequent use of sublexical processes), the transposed-letter effect was greater for non-words than for words (suggesting a prelexical locus of the effect). Finally, a combined analysis including lexicality in the ANOVA showed that words were read 201 ms faster than non-words, $F(1, 34) = 48.44$, $MSE = 61,292.4$.

Experiment 1b (intermediate readers)

Word data

Short words were read 80 ms faster than long words, $F(1, 42) = 51.61$, $MSE = 7,991.8$, and words preceded by a transposed-letter pseudoword were responded to 9 ms faster than the words preceded by a double-substitution pseudoword, $F(1, 42) = 4.55$, $MSE = 4,983.2$. The interaction between the two factors was not significant.

The ANOVA on the error data did not show any significant effect.

Non-word data

Short non-words were responded 121 ms faster than long non-words, $F(1, 42) = 79.82$, $MSE = 8,147.6$, and non-words preceded by a transposed-letter pseudoword were responded to 77 ms faster than the non-words preceded by a double-substitution pseudoword, $F(1, 42) = 37.13$, $MSE = 6,968.9$. There was also an interaction between relatedness and length, $F(1, 42) = 5.83$, $MSE = 7,252.7$: the transposed-letter effect was greater for short non-words (108 ms), $F(1, 42) = 36.74$, $MSE = 6,943.70$, than for long non-words (46 ms), $F(1, 42) = 6.30$, $MSE = 7,277.8$.

None of the effects on the error data was significant.

Not surprisingly, response times were faster – and error rates were fewer – for intermediate than for beginning readers (see Table 1). The effect of length on the latency data remained significant in both words and non-words. However, unlike beginning readers, intermediate readers did not show a length effect in the error data. Finally, as occurred with the beginning readers, there was a robust lexicality effect: intermediate readers responded to words 378 ms faster than to non-words, $F(1, 42) = 251.58$, $MSE = 50,080.9$.

Experiment 1c (adult readers)

Word data

Words preceded by a transposed-letter pseudoword were responded to 11 ms faster than the words preceded by a double-substitution pseudoword, $F(1, 37) = 6.76$, $MSE = 1,366.2$. Unlike the data with children, there was a non-significant (13 ms) advantage of short over long words $F(1, 37) < 1$, $MSE = 1,911.6$. The interaction between the two factors was not significant.

The ANOVA on the error data only showed that participants committed more errors for short than for long words (3.4 vs. 1.9%, respectively), $F(1, 37) = 13.09$, $MSE = 12.7$.

Non-word data

Short non-words were responded 86 ms faster than long non-words, $F(1, 37) = 56.71$, $MSE = 4,986.5$, and non-words preceded by a transposed-letter pseudoword were responded to 36 ms faster than the non-words preceded by a double-substitution pseudoword, $F(1, 37) = 15.93$, $MSE = 3,050.9$. The interaction between the two factors was not significant.

The ANOVA on the error data only revealed that non-words preceded by a transposed-letter pseudoword were responded to more accurately than the non-words preceded by a double-substitution pseudoword (4.1 vs. 5.3% of errors, respectively), $F(1, 37) = 5.24$, $MSE = 11.02$.

In summary, faster response times were found in young adults than in children. More important for the present purposes, the effect of length for words vanished in adult readers – indeed, it was inhibitory in the error data. At the same time, there was a robust length effect when reading non-words (86 ms). Taken together, these findings reveal a greater use of their orthographic knowledge for direct access to the lexicon in skilled readers with respect to children. It seems that only when achieving proficiency, Spanish readers start using different processes for word and non-word processing. In addition, adult readers also showed a significant masked transposed-letter priming effect for word and for non-word targets. Finally, as occurred with the children, there was a robust lexicality effect: words were responded to 224 ms faster than non-words, $F(1, 37) = 9.08$, $MSE = 33.9$.

Global analysis

To assess how the effects of length and transposed-letter similarity varied across grade, an ANOVA (on the latency data and on the error data) was conducted, based on a 2 (grade: third grade, sixth grade, and college) $\times$ 2 (length: long and short) $\times$ 2 (relatedness: transposition and double-substitution) $\times$ 2 (List: list 1 and list 2) design. List and grade were included as between subject factors.

Word data

The ANOVA on the latency data showed significant main effects of transposed-letter similarity, $F(1, 116) = 8.06$, $MSE = 5,562.9$, and word length, $F(1, 116) = 57.17$,

$MSE = 9,637.7$. The only significant interaction was that between length and grade, $F(1, 116) = 9.90$, $MSE = 6,789.2$: short words were read 114 ms faster than long words by beginning readers, 80 ms faster by intermediate and 13 ms faster by college students.

The ANOVA on the error data did not show any significant effect.

Non-word data

Non-words preceded by a transposed-letter prime were responded to 58 ms faster than the targets preceded by a double-substitution prime, $F(1, 116) = 56.71$, $MSE = 6,542.6$, and short non-words were also responded 95 ms faster than long non-words, $F(1, 116) = 94.5$, $MSE = 11,435.3$. There was a significant interaction between relatedness and length, $F(1, 116) = 4.85$, $MSE = 6,528.9$: the transposed-letter effect was greater for short non-words (76 ms), $F(1, 116) = 50.74$, $MSE = 6,105.2$, than for long non-words (39 ms), $F(1, 116) = 13.33$, $MSE = 6,966.4$. The other effects were not significant.

The ANOVA on the error data revealed less errors for short non-words (19.2%) than for long non-words (21.5%), $F(1, 116) = 12.13$, $MSE = 49.4$. There was also a significant interaction between relatedness and grade, $F(1, 116) = 14.40$, $MSE = 49.4$. This interaction reflected a lower error rate in the transposed-letter condition (43.1%) than in double-substitution condition (47.0%) in beginning readers; this effect disappeared in intermediate and skilled readers. In addition, a significant interaction was found between length and grade, $F(1, 116) = 6.44$, $MSE = 39.4$: there was a lower error rate for short words (41.4%) with respect to long words (48.7%) in beginning readers; this effect vanished in intermediate and skilled readers. The other effects/interactions did not approach significance.

Finally, when grade was included in the ANOVA on the latency data, there was a robust lexicality effect: words were read 268 ms faster than non-words $F(1, 112) = 319.01$, $MSE = 52,968.4$. Interestingly, this ANOVA revealed a significant three-way interaction of lexicality, length, and grade, $F(2, 112) = 4.54$, $MSE = 5,729.7$. This interaction reflected that the length effect varied significantly across grade for words, $F(2, 112) = 9.90$, $MSE = 6,789.2$, but not for non-words ($F < 1$).

In sum, the global analysis showed that the length effect for words was not constant in Spanish readers: the magnitude of the length effect for words (but not for non-words) decreased with age. Interestingly, the transposed-letter effect was greater for non-words than for words, and differed numerically across grade. Finally, we should also note that the transposed-letter priming effect obtained for words in intermediate and adult readers (9 and 11 ms, respectively), though significant, was slightly smaller than the transposed-letter effect obtained in previous with adult readers (around 18–20 ms; e.g. Perea & Lupker, 2004); nonetheless, Carreiras, Vergara, and Perea (2005), also found a (significant) transposed-letter priming effect of 11 ms.

Discussion

The main findings of the present lexical decision experiment can be summarized as follows: (i) there was a robust effect of length for words in beginning and intermediate readers, which vanished for adult readers, (ii) the effect of length for non-words was robust, and similar in magnitude, across grade, (iii) beginning, intermediate, and adult readers showed a significant masked transposed-letter priming effect from non-adjacent transposed-letter pseudowords relative to the appropriate orthographic control condition (e.g. *aminal–ANIMAL* vs. *arisal–ANIMAL*), which was especially large for beginning readers, and (iv) the effect of transposed-letter priming was robust (and relatively constant) for non-word targets. Taken together, these results have important implications for models of visual word recognition.

The effect of length in developing and adult readers

The present lexical decision data confirm and extend recent developmental studies about the effects of length in perceptual identification and naming tasks (e.g. see Bijeljac-Babic *et al.*, 2004). The robust length effect for words found with children in lexical decision vanishes when the readers achieve a fully developed lexical system, as was the case of young adults. What we should also note is that beginning readers showed a greater length effect for words than for non-words, while this pattern reverses for intermediate readers – and this trend increases with young adults (see Table 1). This result strongly suggests that beginning readers tend to use a letter-by-letter coding strategy to encode words and non-words. In contrast, a more direct process of lexical access starts to take over in early phases of reading acquisition: intermediate readers showed a greater effect of length for non-words than for words. This progress implies an increasing reliance on direct lexical processes: the start-to-end reading strategy used by beginning readers changes when (via reading experience) the children adjust to the salient orthographic representations of their written language (see Bowey & Muller, 2005; Castles & Nation, 2006).

As indicated above, the magnitude of the length effect for words decreased across grade reflecting a developmental pattern – interestingly, adults showed a greater error rate for short than for long words. It is also remarkable that the magnitude of the length effect for non-words was numerically similar across grade: short non-words were read 77 ms faster than long non-words by beginning readers, 80 ms faster by intermediate readers, and 86 ms faster by skilled readers. This pattern of data suggests that the mechanisms involved in reading words and non-words are somewhat different in children and in adult readers. There is empirical evidence that shows readers are able to attend to lexical or sublexical cues depending on the demands of orthography (see Brown & Deavers, 1999; Goswami, Ziegler, Dalton, & Schneider, 2003; Perry & Ziegler, 2000). When letter-by-letter coding is the only strategy operative (i.e. beginning readers), readers show robust length effects in word and non-word reading, but once knowledge about the orthographic representations of their language is more fully acquired, readers are able to choose the most suitable strategy depending on the lexical status of the stimulus item.

The ability to change from a letter-by-letter strategy to a direct process of lexical access would not be possible without an adjustment of the visual word recognition system to a given language, and this process starts at a very early age in Spanish readers (Sebastián-Gallés & Parreño-Vacchiano, 1995). As beginning readers are exposed to more vocabulary, they learn to extract relevant orthographic structures from words. Consequently, they can retain in memory lexical representations, make analogies and discriminate words with little effort: they achieve automatization (see Tindall-Ford, Chandler, & Sweller, 1997; for an explanation about schemes, cognitive load and automatization processes). As suggested by Bijeljac-Babic *et al.* (2004), this process can be the result of a tendency to read letter by letter when reading instruction begins (and, certainly, because in shallow orthographies the reading instruction *per se* emphasizes this process), groups of letters of different sizes when reading skills are being acquired, and whole words when reading has developed successfully.

Nonetheless, it is difficult to ascertain whether this evolution involves a change from serial letter by letter coding towards a direct parallel lexical access as assumed by Bijelac-Babic *et al.* (2004) or just a more rapid sweep through the letter string due to more efficient serial processes (see Whitney, 2007). This is probably determined by the nature of the language and by the teaching strategies (Goswami, 2004). For example, the teaching method more usual in Spanish emphasizes blending phonemes to graphemes. This is why Spanish children who start to read tend to rely basically on slow, grapheme–phoneme mapping strategies (Valle-Arroyo, 1996). Due to the orthographic consistency of Spanish, children begin to learn about phonemes via their corresponding letters, and quickly start to integrate the structural regularities in their mental lexicon. During reading experience, this process becomes more sensitive to word properties (i.e. sets of letters and salient word features), and accessing to words becomes more automatic (Sebastián-Gallés & Parreño-Vacchiano, 1995). Indeed, previous studies suggest that this progressive development results from a reciprocal interaction between the storage of orthographic properties of words (Castles & Coltheart, 1993) and the implicit associations of the stored segments with phonological information (Share, 1995; Wimmer, Mayringer, & Landerl, 2000). In this light, the interaction between lexical and sublexical processes may differ across transparent and deep orthographies (Arduino & Burani, 2004). For example, Spanish and English children who suffer from phonological impairments show different reading patterns. English children tend to commit more errors for long than for short words, when compared with Spanish children, but the striking point here is that the error rate of short words in English children is particularly high when the CVC structure implies an inconsistent vowel pronunciation (Davis & Bryant, 2006). Thus, orthographic inconsistency hinders the establishment of direct connections between orthography and phonology from early stages of reading acquisition, whereas these connections can be directly established in a transparent orthography (Landerl, Wimmer, & Frith, 1997). If this is the case, it would be difficult to deny the presence of serial processes in a shallow and regular orthography like Spanish, where orthography and phonology are highly interconnected. We must bear in mind that the processing of phonology is assumed to be serial in nature (Coltheart *et al.*, 2001; Whitney & Cornelissen, 2005).

Only the DCP+ model of Perry *et al.* (2007) can account for the observed pattern of length effects across the different grades in the present experiment. Indeed, this model can capture the presence of length effects in other shallow orthographies (e.g. German). The DCP+ model has a serial and a parallel route to account for phonological and orthographic processes. In addition, the spelling–sound mapping regularities of the language can be trained and learned so that both small and large units can be recognized. This leads to a decreasing length effect with age, as found with Spanish readers. Despite the fundamental importance of the DCP+ model, one potential limitation is that (at present) it has been only implemented with monosyllabic words/non-words in a reading aloud task. Another limitation is that the input Coding scheme of this model cannot account for transposed-letter effects.

Letter coding in developing and adult readers

The results of the experiment showed a masked transposed-letter priming effect for beginning, intermediate, and adult readers: words preceded by transposed-letter pseudowords were responded to faster than words preceded by double-substitution pseudowords (*aminal–ANIMAL* vs. *arisal–ANIMAL*). Thus, we have replicated and extended previous research with adult readers (Perea & Lupker, 2003, 2004; see also Christianson, Johnson, & Rayner, 2005; Perea & Carreiras, 2006). The tendency to misperceive non-words as their base words (e.g. *cholocate* being perceived as *chocolate*) may stem from the fact that, very early on processing, the visual recognition system allows some noisy on letter position (Gomez, Ratcliff, & Perea, 2007) or it may be due to a spatial/temporal flexible letter coding (Davis, 1999; Grainger & van Heuven, 2003; Whitney, 2001). As Castles *et al.* (2003) suggested, this process may be subject to developmental changes: for word targets, the transposed-letter priming effect decreased numerically with age: 53 ms for beginning readers, whereas intermediate and adult readers showed a small, but significant, effect of 9 and 11 ms effect, respectively. As an anonymous reviewer suggested, z scores may be an alternative way to assess the effect size when the overall response times differ across the different groups (e.g. children vs. young adults or young vs. older adults). To that end, z scores for each participant were calculated to test the reliability of the effects between groups (see Faust, Balota, Spieler, & Ferraro, 1999, for a similar procedure). All the effects found in the global analysis remained significant, and more important, the interaction between transposed-letter similarity and grade was significant, $F(2, 112) = 3.44$, $p = .03$. This interaction strengthens the idea that, as reading skill increases, the visual recognition system acquires a better, more accurate match procedure between the input and the mental representation.

What is the locus of the transposed-letter priming effect? Most researchers (and models) assume that it occurs very early in processing, probably at a prelexical orthographic stage (see Davis, 1999; Grainger & van Heuven 2003; Perea & Lupker, 2004; Whitney, 2001). Consistent with this idea, we found a strong masked transposed-letter priming effect with non-word targets in beginning, intermediate, and adult readers (60, 77, and 36 ms, respectively; see also Perea & Carreiras, 2008, for a significant effect of transposed-letter priming for non-words). We must bear in mind that if the effect were lexical, only word targets would have shown the transposed-letter priming effect – since non-words do not have lexical units. Indeed, the transposed-letter priming effect in the present experiment was greater for non-words than for words (58 vs. 24 ms, respectively). How can we explain the non-word priming effect? Presumably, participants are engaged in an active verification process of the target item on the basis of the orthographic/phonological information activated by the masked primes. As a result, the non-words preceded by transposed-letter primes would be discarded earlier than the non-words preceded by double-substitution primes (see Perea *et al.*, 2005, for further evidence on how 'no' decisions are made in lexical decision). Clearly, this finding stresses the idea that sublexical processes are critical for Spanish readers, since letter identification and grapheme–phoneme mapping are necessary for further successful word reading (see Ellis & Young, 1996).

As indicated in the introduction, the presence of transposed-letter priming effects can be readily accommodated by the SOLAR, SERIOL, and open-bigram models. To examine in detail, the predictions made by the SOLAR, open-bigram, and SERIOL models regarding the transposed-letter effect in long and short words, we computed the degree of match between primes and targets for the different conditions in the experiment (see Figure 1), as provided by the application MatchCalculator (Footnote 1). The SOLAR,

[1] *The application MatchCalculator can be obtained at the website of Colin Davis (http://www.pc.rhul.ac.uk/staff/c.davis/Utilities/MatchCalculator.exe)*

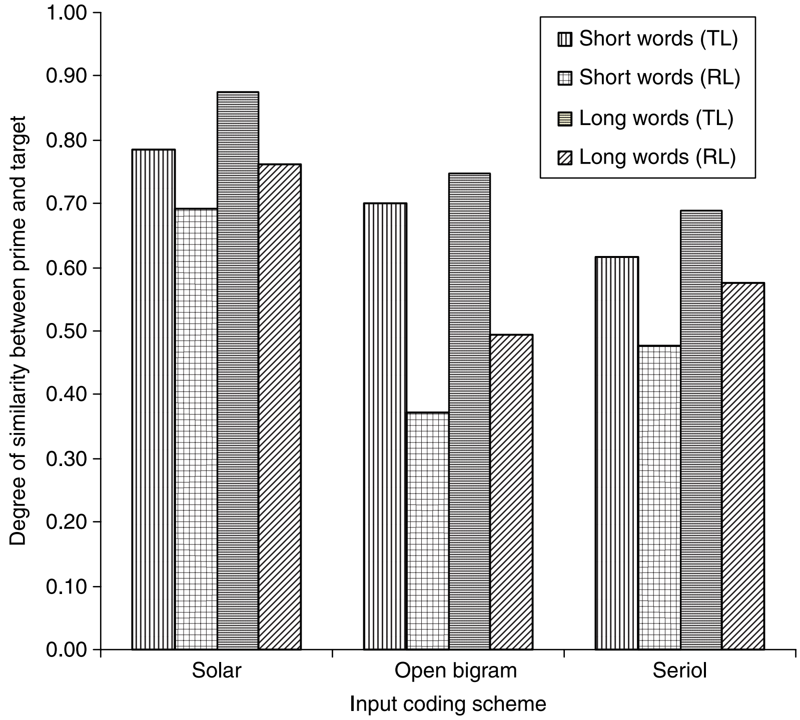

Figure 1. Degree of similarity between prime and target in the SOLAR, open-bigram, and SERIOL models.

open-bigram, and SERIOL models predict that transposing two letters in a long word makes this item more similar to its base word than transposing two letters in a short word. Nonetheless, if we take the transposed-letter priming effect as the difference between the transposed-letter condition and the double-substitution condition, both the SOLAR and SERIOL models predict an (approximate) additive relatedness by length interaction effect, whereas the open-bigram model predicts a somewhat larger transposed-letter effect for short words than for long words. The data for word targets actually showed an additive length by relatedness pattern, supporting the predictions of the SOLAR and SERIOL models. In any case, the predicted similarity values must be taken with caution: there is a lack of sensitivity to lexical constraints (or top-down processing, in general) in the similarity match values. The similarity match values just reflect the similarity between two letter strings, without taking into account that there are other factors involved when computing the degree in which two words are related.

Thus, the present experiment supports the assumption that the visual recognition system is sensitive to orthotactic constraints (i.e. features of words), as a result of a natural process of adaptation during reading experience. Furthermore, the course of this adjustment process does not only depend on the activation mechanisms inherent to the visual recognition system, but also on external factors like orthography, teaching method, or reading exposure (see Castles & Nation, 2006). Put another way, the visual recognition system does not work under constrains of static and fully specified representations (like the required parameters to implement a model), because it interacts with external factors. This interaction involves a complexity that computational models of word recognition, at present, cannot capture entirely. On the one hand, models that are based on a flexible letter coding are capable of explaining transposed-letter effects (like the SOLAR, SERIOL, and open-bigram models) and, on the other hand, models that have been capable to learn and capture developmental changes, like the DCP + model of Perry *et al.* (2007), employ an orthographic coding scheme that cannot capture the effects of transposed-letter priming. It would be desirable that these models would be able to explain the letter encoding process from a developmental perspective. Thus, one important issue for future research is to design appropriate coding schemes for representing the orthography/phonology of polysyllabic words and to assess which orthographic segments become relevant when a simple statistical learning mechanism (such as our phonological assembly network) tries to learn the mapping between spelling and sound. One possibility is that DCP + model employs an orthographic coding scheme other than a channel-specific one. For instance, Brunsdon, Coltheart, and Nickels (2005) successfully applied the coding scheme of the SOLAR model of Davis (1999) within the framework of the DRC model. Whether changes to the DCP + model within these limits (i.e. applying the orthographic coding scheme of the SOLAR/SERIOL models) would actually allow the model to predict the transposed-letter priming effect and whether these modifications would then harm the models' abilities to explain other results would be a question for future research.

In sum, this paper has provided empirical evidence of the effects of length and transposed-letter similarity in Spanish across beginning, intermediate, and adult readers in the most popular paradigm – with the reading aloud task – in visual word recognition: lexical decision. The results extend previous findings on how readers encode the order of letters, and they strongly suggest that letter position coding takes place at an early prelexical effect. In addition, the dissociation in the magnitude of the length effect for words and for non-words across beginning, intermediate, and adult readers clearly strengthens the hypothesis of a reliance on direct grapheme–phoneme associations in transparent orthographies. Taken together, these findings pose some problems for current computational models of visual word recognition. As Castles and Nation (2006) indicated, computational models of visual word recognition still have a way to go before they can capture the full complexities of orthographic learning. The development of these models remains a key issue for future research.

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Appendix: Primes and target words

The items are arranged in triplets in the following order: target word, transposed-letter prime, and double-substitution prime.

Short words: BABERO, barebo, banedo; CEREZO, cezero, cevemo; MINERO, mireno, micemo; PELUCA, pecula, peruta; PECERA, pereca, pemesa; SALERO, sarelo, saceto; PATOSO, pasoto, paroho; MIMOSO, misomo, micoro; NEVADO, nedavo, nebaro; BOBADA, bodaba, bolaha; PELUDO, pedulo, petudo; JOYERO, joreyo, jocego; ESTUFA, esfuta, esluba; GOTERA, goleta, gosela; ABEJAS, ajebas, apedas; TIRITA, titira, tiliba; RANITAS, ratinas, ralimas; BAÑADOR, badañor, babamor; CANICAS, cacinas, carimas; REGALIZ, relagiz, redapiz; TOBOGÁN, togobán, tojodán; AZAFATA, afazata, atasata; TIBURÓN, tirubón, tinudón; REGALAR, relagar, retajar; DIBUJAR, dijubar, digudar; DEBERES, derebes, decehes; EDUCADO, ecudado, erubado; OVEJITA, ojevita, opesita; AGOTADA, atogada, afopada; OCUPADO, opacado, ojusado; ABANICO, anabico, amalico; LEÑADOR, ledañor, lebasor; CABEZA, cazeba, casefa; MAÑANA, manaña, masara; DINERO, direno, divemo; CAMINO, canimo, caciro; SEMANA, senama, seraca; SEÑORA, seroña, secova; MÚSICA, múcisa, múniva; VERANO, venaro, vesavo; VECINO, venico, vemiso; ESPEJO, esjepo, esyego; MARIDO, madiro, mabiso; ESPADA, escapa, esbaya; AMIGOS, agimos, ajinos; ANIMAL, aminal, arisal; AZÚCAR, acúzar, arúsar; MÉDICO, mécido, mévibo; CORAZÓN, cozarón, cosanón; MINUTOS, mitunos, miluros; MAYORES, maroyes, masojes; CAPITÁN, catipán, caliján; COLORES, coroles, cosotes;VECINOS, venicos, vemisos; ZAPATOS, zatapos, zalagos; COMEDOR, codemor, cobenor; PÁJAROS, párajos,pánagos; ÁRBOLES, árlobes, ártodes; EMPEZAR, emzepar, emnejar; ACABADO, abacado, adarado; AGUJERO, ajugero, ayupero; OFICINA, ocifina, ositina; ENEMIGO, emenigo, erecigo; ABOGADO, agobado, ajodado

Long words: CAMAROTE, caramote, casanote; FAVORITO, farovito, fanocito; CARACOLA, cacarola, cavanola; PEGATINA, petagina, pelapina; LIMONADA, linomada, lisorada; ZAPATERO, zatapero, zalagero; MARINERO, manigero, mavimero; CARIÑOSO, cañiroso, cavisoso; COCINERO, conicero, comivero; SEMÁFORO, efámoro, setávoro; CAMISETA, casimeta, carineta; GASOLINA, galosina, gaborina; ENSALADA, enlasada, entarada; ESCOPETA, espoceta, esgoreta; AMAPOLAS, amalopas, amatogas; MECÁNICO, menácico, mesárico; NAVIDADES, nadivades, natimades; MARAVILLA, mavarilla, masacilla; PESADILLA, pedasilla, pebarilla; FELICITAR, fecilitar, fesititar; GOLOSINAS, gosolinas, gonotinas; CORAZONES, cozarones, cosanones; MAMÍFEROS, mafímeros, mabíneros; MARIPOSAS, mapirosas, maginosas; VEGETALES, vetegales, velepales; CUCURUCHO, curucucho, cusunucho; PANECILLO, pacenillo, paserillo; ZAPATILLA, zatapilla, zalagilla; VAGABUNDO, vabagundo, vadapundo; CHOCOLATE, cholocate, chotosate; JARDINERO, jarnidero, jarsibero; PASAJEROS, pajareros, pagaveros; PELÍCULA, pecílula, pevítula; TELÉFONO, tefélono, tebétono; DESAYUNO, deyasuno, deravuno; SEÑORITA, seroñita, secozita; CONOCIDO, coconido, coromido; ESCALERA, eslacera, estasera; ESTÓMAGO, esmótago, esnólago; UNIDADES, udinades, ubimades; REALIDAD, readilad, reatibad; RELACIÓN, recalión, resatión; ENEMIGOS, emenigos, everigos; ADELANTE, aledante, atebante; UNIVERSO, uvinerso, umicerso; AMARILLO, aramillo, acanillo; ALIMENTO, amilento, anitento; OLVIDADO, oldivado, oltirado; VELOCIDAD, vecolidad, vesotidad; RECONOCER, renococer, remosocer; VEHÍCULOS, vehílucos, vehítusos; TELEVISOR, tevelisor, teretisor; MUNICIPAL, mucinipal, murimipal; FELICIDAD, fecilidad, fesitidad; DIFERENTE, direfente, disetente; HORIZONTE, hozironte, hocisonte; OPERACIÓN, orepación, osegación; EDUCACIÓN, ecudación, esubación; PRIMAVERA, privamera, pricanera; ENAMORADO, enaromado, enasonado; ORDENADOR, ornedador, ormebador; PERSONAJE, pernosaje, permoraje; SOLITARIO, sotilario, sodibario; FENÓMENOS, femónenos, feróvenos.