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Suppression of mirror generalization for reversible letters: Evidence from masked priming

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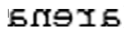
ABSTRACT

Readers of the Roman script must "unlearn" some forms of mirror generalization when processing printed stimuli (i.e., herb and herd are different words). Here we examine whether the suppression of mirror generalization is a process that affects all letters or whether it mostly affects reversible letters (i.e., b/d). Three masked priming lexical decision experiments were conducted to examine how the cognitive system processes mirror images of reversible vs. non-reversible letters embedded in Spanish words. Repetition priming effects relative to the mirror-letter condition were substantially greater when the critical letter was reversible (e.g., idea-IDEA vs. ibea-IDEA) than when the critical letter was not reversible (e.g., arena-ARENA vs. aɿena-ARENA). Furthermore, responses to target words were substantially slower when they were preceded by prime containing a reversible mirror-letter (e.g., ibea-IDEA) than when preceded by a control prime (ilea-IDEA). This inhibitory effect did not occur when the mirror image of the critical letter does not form a grapheme (i.e., aɿena-ARENA vs. aɔena-ARENA). Thus, the cognitive system suppresses mirror images of reversible letters – but not of non-reversible letters. We examine the implications of these findings for models of visual-word recognition.

Introduction

When we process visual information,  and  are taken as corresponding to the same image. The difficulty of discriminating between mirror images of an object occurs not only in primates (Logothetis & Pauls, 1995) but also in more distant relatives (e.g., octopi, Sutherland, 1957; pigeons, Mello, 1965). One common explanation for mirror generalization, whose origin goes back to Orton (1925), is that interhemispheric fiber systems (in particular, the corpus callosum), may "symmetrize" memory traces, thus preserving structural symmetry (e.g., see Corballis & Beale, 1970).

One important question is to ask how this phenomenon affects reading. In alphabetic languages, words are composed of objects (namely, letters) which are not invariant on rotation (e.g., compare arena with ). Furthermore, items composed of reversible letters (e.g., d and b) may produce different words: herd vs. herb (see Lachmann, 2002, for an exhaustive review of the literature on mirror generalization in reading). Given that the area which responds particularly to letters and printed words in the human brain "builds upon a pre-emption of object recognition skills" in which mirror generalization is a built-in property (see Pegado, Nakamura, Cohen, & Dehaene, 2011, p. 340), it is not surprising that normal-reading children who are learning to read/write sometimes employ mirror letters (or mirror words), and make reversal errors when reading (see Cubelli and Della Sala (2009), Schott (2008), for recent reviews).

Unlike ordinary objects, letters are not insensitive to mirror reversals (i.e., we do not process "b" and "d" as the same grapheme). As a result, children "may develop a special strategy for processing letters and words"

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(Lachmann & van Leeuwen, 2007, p. 63). More specifically, in the course of the functional tuning of the letter identification system, the cognitive system must unlearn some forms of mirror generalization when processing printed stimuli. This may involve "the active suppression of mirror images in mapping a phoneme to a grapheme" (Lachmann & van Leeuwen, 2007, p. 63; see also Dehaene, Cohen, Sigman, & Vinckier, 2005). Lack of suppression of mirror generalization beyond a certain age has been claimed to be a predictor of some types of dyslexia (e.g., see Brendler & Lachmann, 2001; Lachmann & Geyer, 2003; Lachmann & van Leeuwen, 2007).

In the Roman script, there are four reversible letters (all of them in lowercase): b vs. d and p vs. q. As Pederson (2003) noted, reversible characters in other scripts are either rare or non extant (e.g., Kana syllables in Japanese, Chinese ideograms, Hindi letters) and readers of Tamil – another script without reversible letters – with no knowledge of the Roman script tend to process reversible letters like b and d as the same stimulus. For readers of the Roman script, reversible letters such as d or b have two potential attractors during the process of letter processing (i.e., the letter nodes corresponding to d and b), whereas non-reversible letters such as r only have one potential attractor (the letter node corresponding to r). Thus, one relevant question to ask is to what degree the lack of mirror generalization in normal-reading individuals is a process that affects all letters in the Roman script, or whether it affects especially the reversible letters (i.e., b/d and p/q).

At present, none of the input coding schemes of the computational models of visual-word recognition (e.g., interactive activation model, McClelland & Rumelhart, 1981, multiple read-out model, Grainger & Jacobs, 1996, and dual-route cascaded model, Coltheart, Rastle, Perry, Ziegler, & Langdon, 2001; Spatial Coding model, Davis, 2010) can account for the effects of orientation specificity and/or mirror reversals. This is due to the fact that the featural analysis in all these models is based on the uppercase letter font defined by Rumelhart and Siple (1974) (e.g., the letters ABCD, etc., in a ⊠ matrix). As McClelland and Rumelhart (1981) acknowledged, this font "obviously skirts several fundamental issues about the lower levels of processing" (p. 383). Nevertheless, if they were equipped with a more flexible input coding scheme at the feature/letter level, the dynamics of letter recognition in the course of word processing would be expected to differ for reversible and non-reversible letters. The reason is that these computational models assume within-level inhibitory links. This implies that that the node corresponding to b would inhibit the node corresponding to the letter d (and vice versa), while this inhibition would be absent in the case of non-reversible letters (e.g., ɿ in aɿena).

The aim of the present study is to examine how the cognitive system processes mirror images of reversible and non-reversible letters (e.g., d or b vs. r or c, respectively) embedded in words during the course of visual-word recognition. To unveil the earliest stages of word processing, and to minimize the potential use of participants' strategies, one strategy is to use the masked priming technique (Forster & Davis, 1984; see Grainger, 2008, for a review). In the usual setup, an uppercase target word is preceded by a briefly presented lowercase masked prime (e.g., related condition: #####-houre-HOUSE vs. control condition: #####-drall-HOUSE). The difference in performance (e.g., in response times) between the control condition and the related condition is the so-called "priming" effect. For instance, response times for a target word like HOUSE are significantly shorter when it is preceded by a replaced-letter prime (e.g., houre) than when it is preceded by a control prime (e.g., drill) (form-priming effect; see Forster, Davis, Schoknecht, & Carter, 1987; Perea & Rosa, 2000). One common explanation for form-masked priming is that the brief presentation of an item like houre preactivates the lexical entry corresponding to HOUSE. Interestingly, masked priming effects for word stimuli can also be obtained with letter-like digits/symbols embedded within words. Perea, Duñabeitia, and Carreiras (2008; see also Perea, Duñabeitia, Pollatsek, & Carreiras, 2009) found that response times to a target word were only slightly faster when it was preceded by an identity prime (MATERIAL-MATERIAL) than when it was preceded by a prime with letter-like digits/symbols (e.g., M4T3R14L-MATERIAL), whereas targets preceded by an orthographic control (e.g., M9T8R98L-MATERIAL) produced substantially longer identification times. This finding implies that the lexical system in the brain is able to regularize the shape of letter-like stimuli embedded in words without much cost. The issue under consideration here is what happens if instead of using letter-like digits (e.g., 4 instead of A), we employ mirrored images from reversible letters (e.g. d or b) vs. non-reversible letters (c or r). Our hypothesis is that non-reversible letters such as r can be written in mirror-image form (i.e., ɿ) and still be recognized as having the same abstract letter representation, whereas reversible letters b and d (or p and q) produce quite different graphemes. In passing, we should note here that it is not uncommon to find brand names with mirror images of non-reversible letters, as in Deꙅigual©.[1]

As stated above, the process of mirror generalization must be somehow unlearned when processing written stimuli in the Roman script. The basic questions under scrutiny in the present study are: (i) whether the cognitive system is able to block mirror images of reversible letters embedded in words (e.g., b in ibea [idea]), and (ii) whether this process also applies to non-reversible letters (e.g., ɿ in aɿena [arena]). To that end, we examined the magnitude of masked priming effects using primes in which there was a rotated reversible letter (e.g., b in ibea; Experiment 1) and for words in which there was a rotated non-reversible letter (e.g., ɿ in aɿena; Experiment 2). More specifically, in Experiment 1, a target word (e.g., IDEA) was preceded by an identity prime (idea), by a pseudoword exactly the same as the identity prime except for an existing mirror letter (ibea), or by a control pseudoword in which the mirror letter was replaced by another letter (ilea). If the process of mirror generalization is suppressed for reversible letters, the grapheme b in ibea

[1] A similar same case occurs with transposed-letter stimuli (as in the acronym corresponding to French Connection at the UK; see Perea & Lupker, 2003) and with words without vowels (e.g. MNG; see Perea & Gomez, 2010).

would (presumably) inhibit the grapheme d in models in which there are inhibitory links at the letter level (e.g., interactive activation model, McClelland & Rumelhart, 1981, and its successors). In this case, there would be substantially faster response times for idea-IDEA than for ibea-IDEA – despite its apparent perceptual similarity. Furthermore, a pseudoword such as ibea could produce more interference on target processing than the orthographic control ilea – via the inhibitory links between b and d. The goal of Experiment 2 was to examine whether mirror generalization is also actively suppressed for non-reversible letters (e.g., c, r; as in aɹena-ARENA): A given target word (e.g., ARENA) was preceded by an identity prime (arena), by a pseudoword exactly the same as the identity prime except for a rotated non-reversible letter (aɹena), or by an orthographic control pseudoword in which the rotated letter was replaced by another non-reversible mirror letter (aɔena). Note that the letter ɹ does not directly active any grapheme, and therefore one would expect no inhibition to the node corresponding to the grapheme r at the letter level. If this is so, the repetition priming effect relative to the mirror-priming condition should be substantially smaller than in Experiment 1. Finally, Experiment 3 was designed to replicate the main findings of Experiments 1 and 2. To that end, we combined both the identity and mirror conditions from Experiments 1 and 2 in a single experiment (e.g. idea-IDEA vs. ibea-IDEA; arena-ARENA vs. aɹena-ARENA). The present series of experiments were conducted in Spanish; we should note here that prior work has shown that orthographic coding processes are remarkably similar in English and in Romance languages like French or Spanish (e.g., orthographic neighborhood effects: Davis, Perea, & Acha, 2009; consonant/vowel status and letter transposition effects: Lupker, Perea, & Davis, 2008; Perea & Lupker, 2004).

One additional issue under scrutiny in the present study is the role of reading development in the suppression of mirror generalization. Mirror writing/reading behavior is not too uncommon for beginning readers, but it (mostly) disappears by age 8 (e.g., see Cornell, 1985; Lachmann & Geyer, 2003). The question here is whether the suppression of mirror generalization for letters is modulated by reading skill. In the present experiments, participants were normal-reading children of Grade 4 (9 year olds) and skilled readers (college students). If fourth graders have already suppressed mirror generalization for letters (see above), the pattern of masked priming effects should be quite similar for children and adults. Alternatively, if the cognitive system in fourth graders is sensitive – to some degree – to mirror generalization, we would expect a different pattern of masked priming effects for children and adults.

To examine the effects of mirror reading in the masked priming paradigm, we employed the most popular task in the literature on visual-word recognition: the lexical decision task ("is the item a word?"; see Ratcliff, Gomez, & McKoon, 2004, for a model of the task). This task is highly sensitive to a wide variety of orthographic/phonological/lexical phenomena (see Balota et al., 2007). We employed a go/no-go lexical decision task, rather than the yes/no variant, because it produces less task demands and less errors than the standard yes/no lexical decision task (Perea, Rosa, & Gómez, 2002; see also Gómez, Ratcliff, & Perea, 2007, for a mathematical model of the go/no-go task). Finally, we preferred to use an orthographic control condition like ilea-IDEA or aɔena-ARENA rather than an unrelated priming condition (e.g., etoe-IDEA, oɔumo-ARENA) because the former is a more appropriate baseline for the effects under study – in the same way the appropriate control condition for relovution-REVOLUTION is retocution-REVOLUTION (see Perea & Lupker, 2004). Given the limitations at selecting the words in a developmental study (i.e., use of frequent, familiar words), including an unrelated priming condition would have decreased the number of items per condition, thus affecting experimental power.

Experiment 1

In the Roman alphabet, there are four reversible letters in lowercase: d/b on the one hand, and q/p on the other. We focused on the d/b contrast because the letter q always forms part of the grapheme qu.

Method

Participants

Twenty-four fourth grade children (average age: 9.7 years) and 24 undergraduate students from the University of Valencia took part voluntarily in the experiment. In this and subsequent experiments, the children came from above-average socioeconomic backgrounds in a private school in Valencia. The test took place at the end of the academic year. All participants had normal or corrected-to-normal vision and were native speakers of Castilian Spanish. Participants were excluded if they had sensory, neurological, or other problems traditionally used as exclusionary criteria for learning disabilities.

Materials

We selected a set of 144 Spanish words of 4–9 letters (mean: 5.4 letters, *SD* = 1.1) which contained either a d or a b. The mean word frequency per 1 million was 97 (range 1–1956, *SD* = 253) 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 graders of Corral, Goikoetxea, and Ferrero (2009) – the mean frequency in this word count was 29 (range 1–272, *SD* = 39). The average number of orthographic neighbors (Colheart's N) was 3.0 (range: 0–19, *SD* = 3.6). These words were presented in uppercase and preceded by primes that were: (1) the same stimuli in lowercase (identity condition; e.g., idea-IDEA), (2) the same except for the substitution of a d/b with its reversible letter – always creating a pseudoword (mirror-letter condition; e.g., ibea-IDEA), (3) the same except for the substitution of a d/b with another ascending letter – always creating a pseudoword (control condition; e.g., ilea-IDEA). The complete list of prime–target pairs is available at http://www.uv.es/mperea/irreversible.pdf. An additional set of 144 legal pseudowords in Spanish was created for the purposes of the lexical decision task by replacing several letters from Spanish words (e.g. gadati, rardu, orsubo). All these pseudowords always contained a d/b letter. The target nonwords were matched to the target words in length, and the average number of orthographic neighbors was .6 (range: 0–8; $SD = 1.4$). The manipulation of the nonword trials was the same as that for the word trials (i.e., identity prime, mirror-letter prime, control prime). Three sets of materials were constructed so that each target appeared once in each set, but each time in a different priming condition. Different groups of participants were used for each set.

Procedure

Participants were tested in a quiet room in groups of three or four. Presentation of the stimuli and recording of response times were controlled by Windows computers running DMDX (Forster & Forster, 2003). On each trial, a forward mask consisting of a row of hash marks (#'s) was presented for 500 ms in the center of the screen. Next, the prime was presented in lowercase and stayed on the computer screen for 50 ms (3 cycles at a refresh rate of 16.6 Hz). The prime was then followed by the presentation of the target stimulus in uppercase. Both prime and target were presented in the same screen location as the forward mask. The target stimulus remained on the screen until the participant's response – or until 2500 ms had elapsed. Participants were told that words and nonwords would be displayed on the monitor in front of them, and that they should press one button to indicate if the uppercase item was an existing Spanish word, and refrain from responding if the stimulus was not a word. They were instructed to respond as quickly as possible while trying not to make errors. Each participant received a different random order of stimuli. Each participant received a total of 20 practice trials prior to the experimental phase. The session lasted approximately 15 min.

Results and discussion

Incorrect responses (1.7% of the word trials) and response times less than 250 or greater than 1800 ms (4.1% and .4% for children and adults, respectively) were excluded from the RT data.[2]

The mean latencies for correct responses and error rates are presented in Table 1. Given that the overall RTs were not considerably different across each Grade, we did not perform any transformations on the RTs. Nonetheless, we additionally conduct ANOVAs on the *z*-scores-transformed latencies for each participant (as proposed by Faust, Balota, Spieler, & Ferraro, 1999, when dealing with group differences; see also Acha & Perea, 2008), and the pattern of results was exactly the same as that reported here. Subjects and items analyzes of variance (ANOVAs) based on the participant ($F1$) and item ($F2$) response latencies were conducted on the basis of a 3 (prime–target relationship: identity, mirror-letters, control) $\times$ 2 (grade: 4th grade, college students) $\times$ 3 (List: list 1, list 2, list 3) design. The factor List was included in the statistical analyses to separate out the variance due to the counterbalancing lists (Pollatsek & Well, 1995). Error rates in this and subsequent experiments were very low (see Tables 1–3) and were not further analyzed.

Table 1
Mean lexical decision times (in ms) and percentage of errors (in parentheses) for word and pseudoword targets in Experiment 1 (reversible letters).

	Type of prime		
	Identity	Mirror letter	Control
Fourth graders			
Words	848 (2.7)	892 (3.0)	870 (2.7)
Nonwords	– (4.6)	– (3.7)	– (3.8)
Adult readers			
Words	536 (.6)	565 (.9)	546 (.3)
Nonwords	– (2.9)	– (2.3)	– (2.2)

The ANOVA on the latency data showed that college students responded to faster to target words than fourth graders, $F1(1, 42) = 90.91$, $\underline{MSE} = 76637$, $\eta^2 = .70$, $p < .01$; $F2(1, 141) = 2542.15$, $\underline{MSE} = 8518.6$, $\eta^2 = .95$, $p < .01$. The effect of prime–target relationship was also significant, $F1(2, 84) = 23.60$, $\underline{MSE} = 1369$, $\eta^2 = .36$, $p < .01$; $F2(2, 282) = 21.77$, $\underline{MSE} = 5018$, $\eta^2 = .13$, $p < .01$. This indicates that, on average, target words were responded to 21 ms more rapidly when they were preceded by a control prime than when they were preceded by a mirror-letter prime ($F1(1, 42) = 17.36$, $\underline{MSE} = 1212$, $\eta^2 = .29$, $p < .01$; $F2(1, 141) = 8.46$, $\underline{MSE} = 6938$, $\eta^2 = .06$, $p < .01$); in addition, target words were responded to more rapidly when they were preceded by an identity prime than when they were preceded by a mirror-letter prime ($F1(1, 42) = 38.88$, $\underline{MSE} = 1608$, $\eta^2 = .48$, $p < .01$; $F2(1, 141) = 51.61$, $\underline{MSE} = 4232$, $\eta^2 = .27$, $p < .01$) or a control prime ($F1(1, 42) = 9.28$, $\underline{MSE} = 1187$, $\eta^2 = .18$, $p < .01$; $F2(1, 141) = 13.04$, $\underline{MSE} = 3885$, $\eta^2 = .09$, $p < .01$). The pattern of priming effects was similar for children and adults – the interaction between the two factors did not approach significance (both *ps* > .25).

The present experiments showed substantially faster response times in the identity condition than in the mirror-letter condition (37 ms; idea-IDEA vs. ibea-IDEA). More importantly pseudoword primes created by replacing a mirror letter (e.g., ibea-IDEA) produced longer response times on the target words than the control primes (ilea-IDEA): a 21-ms interference effect. This interference effect from mirror-letter primes strongly suggests that there is an active suppression of mirror generalization for letters embedded in words – as suggested by Lachmann and van Leeuwen (2007). Interestingly, this mirror suppression occurs to a similar degree for both college students and fourth graders.[3]

[2] The percentage of excluded data was remarkably similar across priming conditions, and the results were the same when other trimming procedures were applied (see Ratcliff, 1993). We chose a fixed-cutoff procedure (250–1800 ms) rather than the criterion based on 2 (or 2.5) standard deviations from the mean because the latter procedure has a bias dependent on sample size in RT distributions (see Miller, 1991).

[3] One may wonder whether phonology played some role in the obtained priming effects. However, phonological effects tend to be very small with the masked priming technique (see Rastle and Brysbaert (2006)). Furthermore, in a child population, Davis, Castles, and Iakovidis (1998) failed to find any evidence of masked phonological priming effects with fourth-grade children.

We now address whether or not the suppression of mirror generalization in a masked priming paradigm is restricted to reversible letters (e.g., d/b, q/p) or whether it also occurs for non-reversible letters. Note here that the reversal of non-reversible letter r produces the non-letter ɿ – which does not map to any extant grapheme. In Experiment 2, we examined the pattern of masked priming effects when the critical letter was not reversible (e.g., identity condition: arena-ARENA; mirror-letter condition: aɿena-ARENA; control condition: aɔena-ARENA). For the non-reversible letters, we chose as critical letters c, r, s, and z. Note that these letters do not have a symmetric appearance (unlike t, v, x, w, n, or m) and they are frequent in Spanish (e.g., the letter k in Spanish only occurs with loanwords, and the letter f is quite infrequent). In addition, we avoided using vowels as critical letters (e.g., the letter a), the reason being that vowels may not be processed in the same way as consonants during visual-word processing (e.g., see Perea & Lupker, 2004).

Experiment 2

Method

Participants

The participants were 36 fourth grade children (average age: 9.6 years) and 24 undergraduate students from the University of Valencia. The children came from the same school as in Experiment 1. None of the participants had taken part in Experiment 1.

Materials

We selected a set of 144 Spanish words of 4–7 letters (mean: 5.1 letters) which contained a c, an r, an s, or a z. The mean word frequency per 1 million was 76 (range 1–630; *SD* = 101) 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 graders of Corral et al. (2009) – the mean frequency in this dictionary was 59 (range 4–472; *SD* = 47). The average number of orthographic neighbors was 5.2 (range: 0–23, *SD* = 5.8). These words were presented in uppercase and preceded by primes that were: (1) the same stimuli in lowercase (identity condition; e.g., arena-ARENA), (2) the same except for the substitution of an r/c/s/z with its mirror image (mirror-letter condition; e.g., aɿena-ARENA), (3) the same except for the substitution of an r/c/s/z letter with the mirror image of another letter – always a pseudoword (control condition; e.g., aɔena-ARENA; note that acena is a pseudoword). The complete list of prime–target pairs is available at http://www.uv.es/mperea/irreversible.pdf. An additional set of 144 legal pseudowords in Spanish was created for the purposes of the lexical decision task by replacing several letters from Spanish words (e.g. prurano, gurí, hauco). All these pseudowords always contained an r/c/s/z letter. The target nonwords were matched to the target words in length, and the average number of orthographic neighbors was .75 (range: 0–3, *SD* = 1.0). The manipulation of the nonword trials was the same as that for the word trials (i.e., identity prime, mirror-letter prime, control prime). Three sets of materials were constructed so that each target appeared once in each set, but each time in a different priming condition. Different groups of participants were used for each set.

Table 2
Mean lexical decision times (in ms) and percentage of errors (in parentheses) for word and pseudoword targets in Experiment 2 (non-reversible letters).

	Type of prime		
	Identity	Mirror letter	Control
Fourth graders			
Words	787 (.9)	791 (.8)	798 (1.0)
Nonwords	– (4.9)	– (4.7)	– (4.3)
Adult readers			
Words	463 (.2)	473 (.1)	480 (.2)
Nonwords	– (2.2)	– (2.3)	– (1.9)

Procedure

This was the same as in Experiment 1.

Results and discussion

Incorrect responses (.5% of the data) and response times less than 250 or greater than 1800 ms (1.9% and .03% for children and than adults, respectively) were excluded from the RT data. The mean latencies for correct responses and error rates are presented in Table 2. The design was the same as in Experiment 1.

The ANOVA on the latency data showed that college students responded to faster to target words than fourth graders, $F1(1,54) = 112.38$, $MSE = 80015$, $\eta^2 = .68$, $p < .01$; $F2(1,141) = 5067.4$, $MSE = 4066.7$, $\eta^2 = .97$, $p < .01$. The effect of prime–target relationship was also significant, $F1(2,108) = 6.36$, $MSE = 1620$, $\eta^2 = .11$, $p < .01$; $F2(2,282) = 7.98$, $MSE = 1849$, $\eta^2 = .05$, $p < .01$, which reflected that target words were responded to more rapidly when they were preceded by an identity prime than when they were preceded by a control prime ($F1(1,54) = 14.18$, $MSE = 1453$, $\eta^2 = .21$, $p < .01$; $F2(1,141) = 22.84$, $MSE = 1261$, $\eta^2 = .14$, $p < .01$); the mirror-letter condition was somehow in between these two conditions (see Table 2): target words were responded to 7 ms faster in the identity condition than in the mirror-letter condition ($F1(1,54) = 3.59$, $MSE = 1529$, $\eta^2 = .06$, $p = .06$; $F2(1,141) = 5.66$, $MSE = 2048$, $\eta^2 = .04$, $p < .02$) and, on average, target words were responded to 7 ms faster in the mirror-letter condition than in the control condition ($F1(1,54) = 2.57$, $MSE = 1878$, $\eta^2 = .05$, $p = .11$; $F2(1,141) = 1.72$, $MSE = 2236$, $\eta^2 = .01$, $p = .19$). Again, the pattern of priming effects was similar for children and adults – the interaction between the two factors did not approach significance (both *F*s < 1).

Not surprisingly, we obtained a repetition priming effect relative to the orthographic control condition. But the critical finding here is that the mirror-letter priming condition with a non-reversible letter (e.g., aɿena-ARENA) was only 7 ms milliseconds slower than the identity condition (arena-ARENA) – this difference was around 36 ms when the primes contained a mirror image of a non-reversible letter (e.g., ibea-IDEA) in Experiment 1. That is, primes containing a mirror image of a non-reversible letter act nearly as identity primes. Note that a parallel "normalization" effect occurs when the masked primes are composed of letter-like digits/symbols (e.g., M4T3R14L-MATERIAL is processed as MATERIAL-MATERIAL; Perea et al., 2008).

The aim of Experiment 3 was to replicate Experiments 1 and 2 in a joint experiment. We expect to obtain a greater difference between the identity and mirror-letter priming conditions when the rotated letter has an reversible letter (idea-IDEA vs. ibea-IDEA) than when the rotated letter does not have a reversible letter (aꓤena-ARENA vs. aɔena-ARENA). One question to address here is which control baseline would be the most appropriate, since control primes like ilea are composed of legal letters while primes like aɔena contain a non-letter (i.e., the mirror image of c). As in the recent experiment of Vergara-Martínez, Perea, Marín, and Carreiras (in press), we opted to use the ░ character as a missing letter. The idea here is that the ░character as a missing letter. The idea is that the ░ character would presumably work similarly for both idea-type targets and arena-type targets.

Experiment 3

Method

Participants

The participants were 36 fourth grade children (average age: 9.7 years) and 24 undergraduate students from the University of Valencia. The children came from the same school as in Experiment 1–12 of them had taken part in Experiments 1 or 2 during the previous month.[4]

Materials

We selected two sets of word targets, the vast majority of which were taken from Experiments 1 and 2. For the first set we selected 75 Spanish words of 4–7 letters (mean: 5.3 letters; *SD* = .8) containing a d or a b in a middle letter position. The mean word frequency per 1 million was 98 (range 1–675; *SD* = 129) in the Spanish database (Davis & Perea, 2005). The mean frequency in the Spanish word frequency count for first grade children of Corral et al. (2009) was 49 (range 1–206, *SD* = 41). The average number of orthographic neighbors was 2.6 (range: 0–11; *SD* = 2.6). For the second set we selected 75 Spanish words of 4–7 letters (mean: 5.4 letters; *SD* = .8) containing a c or an r in a middle letter position. The mean word frequency per one million was 68 (range 1–689; *SD* = 103) in the Spanish database (Davis & Perea, 2005). The mean frequency in the Spanish word frequency count for first grade children of Corral et al. (2009) was 38 (range 10–142, *SD* = 23). The average number of orthographic neighbors was 2.5 (range: 0–11; *SD* = 2.7). These words were presented in uppercase and preceded by primes that were: (1) the same stimuli in lowercase (identity condition; e.g., idea-IDEA; arena-ARENA), (2) the same except for the substitution of a d/b or c/r with its mirror letter (mirror-letter condition; e.g., ibea-IDEA; aꓤena-ARENA), (3) the same except for the substitution of a d/b/c/r letter with a ░ character (control condition; e.g., i░ea-IDEA; a░ena-ARENA). We should indicate that, in the majority of cases, the target word was the only legal word that could be generated by filling in the missing letter; the average number of words in the i░ea set was 1.7 (*SD* = 1.2), and the average number of words in the a░ena set was 1.4 words (*SD* = 1.0). The complete list of prime–target pairs is available at http://www.uv.es/mperea/irreversible.pdf. An additional set of 150 legal pseudowords in Spanish was created for the purposes of the lexical decision task by replacing several letters from Spanish words. Half of these pseudowords contained a d/b letter and the other half contained a c/r letter in a middle position. The target nonwords were matched to the target words in length, and the average number of orthographic neighbors was .45 (range: 0–6). The manipulation of the nonword trials was the same as that for the word trials (i.e., identity prime, mirror-letter prime, control prime). Three sets of materials were constructed so that each target appeared once in each set, but each time with a different priming condition. Different groups of participants were used for each set.

Table 3
Mean lexical decision times (in ms) and percentage of errors (in parentheses) for word and pseudoword targets in Experiment 3.

	Type of prime		
	Identity	Mirror letter	Control
Fourth graders			
Words			
Reversible letter	749 (2.4)	772 (2.3)	766 (2.3)
Non-reversible letter	745 (1.7)	753 (2.1)	760 (1.8)
Nonwords			
Reversible letter	– (3.8)	– (3.4)	– (3.1)
Non-reversible letter	– (5.2)	– (4.0)	– (4.3)
Adult readers			
Words			
Reversible letter	486 (.5)	514 (.3)	502 (.8)
Non-reversible letter	487 (.2)	495 (.3)	499 (.2)
Nonwords			
Reversible letter	– (1.8)	– (2.2)	– (3.0)
Non-reversible letter	– (.8)	– (3.5)	– (3.0)

Procedure

This was the same as in Experiments 1 and 2.

Results and discussion

Incorrect responses (1.1% of the word trials) and response times less than 250 or greater than 1800 ms (2.8% and .2% for children and than adults, respectively) were excluded from the RT data. The mean latencies for correct responses and error rates are presented in Table 3. ANOVAs based on the participant and item response latencies were conducted based on a 3 (prime–target relationship: identity, mirror-letters, control) × 2 (grade: 4th grade, college students) × 2 (type or target: existing mirror letter [d/b],

[4] We found exactly the same pattern of data when excluding the data of the 12 children who had participated in Experiments 1 or 2 the previous month. As in other masked priming experiments with repeated sessions (e.g., Perea, Moret-Tatay, & Carreiras, in press), the basic difference is that the overall latencies tend to be shorter in the second session than in the first session.

non-existing mirror letter [c/ɾ]) × 3 (List: list 1, list 2, list 3) design.

The ANOVA on the latency data showed that college students responded to faster to target words than fourth graders, $F1(1, 54) = 71.93$, MSE = 86811, $\eta^2 = .57$, $p < .01$; $F2(1, 144) = 4008.0$, MSE = 3705, $\eta^2 = .97$, $p < .01$. On average, target words containing a *c/r* were responded to 8 ms faster than those targets containing a *d/b*, $F1(1, 54) = 4.12$, MSE = 3456, $\eta^2 = .07$, $p < .05$; $F2(1, 144) = 2.65$, MSE = 9981, $\eta^2 = .02$, $p = .106$. The effect of prime–target relationship was also significant, $F1(2, 108) = 7.96$, MSE = 1463, $\eta^2 = .13$, $p < .01$; $F2(2, 288) = 13.79$, MSE = 2104, $\eta^2 = .09$, $p < .01$.

More importantly, the interaction between type of target and prime–target relationship was significant, $F1(2, 108) = 3.23$, MSE = 1360, $\eta^2 = .06$, $p < .05$; $F2(2, 288)$=.84, MSE = 2104, $\eta^2 = .03$, $p < .01$. This reflected that, relative to the mirror-letter condition, the repetition priming effect was substantially greater when the prime had a mirror image of a non-reversible letter than when it had a mirror image of a reversible letter (25 vs. 8 ms; two-way interaction effect: $F1(1, 54) = 7.10$, MSE = 1225, $\eta^2 = .12$, $p < .01$; $F2(1, 144) = 10.03$, MSE = 2028, $\eta^2 = .07$, $p < .01$). Likewise, relative to the control condition, there was a differential effect for the mirror-letter condition depending on whether the critical letter was reversible or non-reversible (two-way interaction effect: $F1(1, 54) = 4.24$, MSE = 586, $\eta^2 = .07$, $p < .05$; $F2(1, 144) = 2.51$, MSE = 2263, $\eta^2 = .02$, $p = .11$). Finally, the identity priming effect relative to the control condition was similar in size for the two types of target (17 vs. 13 ms, respectively; priming effect: $F1(1, 54) = 11.99$, MSE = 1413, $\eta^2 = .18$, $p < .01$; $F2(1, 144) = 18.60$, MSE = 2023, $\eta^2 = .11$, $p < .01$; interaction effect: both *F*s < 1). As in Experiments 1 and 2, the pattern of masked priming effects was quite similar for children and adults – the interaction of grade with prime–target relationships and/or type of target did not approach significance (all *F*s < 1).

As in Experiments 1 and 2, masked pseudoword stimuli which are created by rotating a letter (e.g., ibea, aɾena) have a quite different impact on target processing depending on whether the critical letter is reversible or not. Again, the effect was similar for young readers and for adult readers. It is important to note here that the greater repetition priming effect for non-reversible than reversible letters, relative to the mirror-letter condition, was not due to potential confounds. As indicated in the "Method" section, the number of words that could be generated by filling a letter in the ░ space was very small and was similar for both types of target words (i.e., i░ea-IDEA and a░ena-ARENA). Furthermore, the repetition priming effect relative to the orthographic control condition was similar for the two types of target words (17 and 13 ms).

General discussion

The present masked priming experiments were designed to shed some light on how the cognitive system processes mirror letters embedded in words. The main findings of the present experiments can be summed up as follows: (i) repetition priming effects relative to the mirror-letter condition are substantially greater when the critical letter is reversible (e.g., idea-IDEA vs. ibea-IDEA: around 23–44 ms) than when the critical letter is not reversible (e.g., arena-ARENA vs. aɾena-ARENA; around 4–10 ms), (ii) responses to target words were slower (around 21 ms) when they were preceded by prime containing a reversible mirror-letter (e.g., ibea-IDEA) than when preceded by a control primes (ilea-IDEA), (iii) this inhibitory effect from the mirror-letter priming condition does not occur when the mirror image of the critical letter does not form a grapheme (i.e., aɾena-ARENA was, if anything, faster than the control aɔena-ARENA),[5] and (iv) the basic pattern of data is remarkably similar for normal-reading children from Grade 4 and for adult skilled students. Taken together, these findings are consistent with the view that symmetry generalization is partially inhibited or 'unlearned' when learning to read (Lachmann & van Leeuwen, 2007; see also Dehaene et al., 2010, for a similar claim). Furthermore, our data strongly suggest that the suppression of mirror generalization works differently for reversible and non-reversible letters.

Before attempting to examine the implications of the present data, it is important to rule out alternative explanations. For instance, one could argue that the present findings merely reveal that illegal combinations/letters from masked primes (as in aɾena-ARENA) are 'normalized' in the cognitive system (e.g., see Perea & Carreiras, 2008, for evidence with illegal bigrams) – and this may not necessarily reflect the suppression of mirror generalization. However, this reasoning cannot explain why the orthographic control priming condition ilea-IDEA produces substantially faster response times than the mirror-priming ibea-IDEA. Unless one assumes that there is some form of suppression of mirror generalization for the reversible letters d/b, response times should have been quite similar for ilea-IDEA and ibea-IDEA. In short, the most parsimonious explanation of the present data is that reversible letters enjoy a particular role during the process of visual-word recognition.

How can computational models of visual-word recognition explain the present findings? The most influential computational model in masked priming research has been the interactive activation (IA) model (McClelland & Rumelhart, 1981; e.g., see Davis and Lupker (2006), for extensive work on this model) and its successors (e.g., multiple read-out model, Grainger & Jacobs, 1996; dual-route cascaded model, Coltheart et al., 2001). The present data demonstrate that an orthographic control pseudoword (e.g., ilea) facilitates target processing (IDEA) to a larger degree than a pseudoword with a reversible mirror letter (ibea). This pattern of data can be attained by modifying the parameters responsible for letter-to-letter inhibition of reversible letters at the letter level. Given that there

[5] Once the present experiments were completed, we became aware of a recent semantic categorization experiment with a group of adult students. Duñabeitia, Molinaro, and Carreiras (2011) investigated masked priming effects for primes which contained mirror images of non-reversible letters (e.g., bperación-OPERACIÓN vs. bpeɿaɔión-OPERACIÓN). They found that the N250 component (an index of early sublexical processing) was remarkably similar in the identity priming condition and in the mirror priming condition – no latency data were collected however. This finding is consistent with the small differences between the identity-priming and mirror-priming conditions with non-reversible letters obtained in Experiments 2 and 3.

are no letter units corresponding to the mirror images of non-reversible letters (i.e., no inhibitory links between ɿ and r), this inhibitory effect would be restricted to reversible letters. This modified IA model would also readily capture the greater difference between mirror-letter primes and identity primes for reversible than non-reversible letters. Unfortunately, as stated in the Introduction, the current implementation of the IA model only includes uppercase letters (i.e., both prime and targets would be presented in uppercase). Thus, the IA model would need to add a set of lowercase and uppercase letters – a similar argument applies to the spatial coding model (Davis, 2010). Even if that were the case, one remaining question would be to see how the model copes with the processing of mirror images of non-reversible letters (e.g., ɿ in arena) or even of rotated letters (e.g., ∢). Clearly, one would need to establish a highly flexible input coding scheme in which the letter features may be partially activated regardless of one's viewpoint – this enterprise would be beyond the scope of the present paper. A similar argument applies to the specifications of the letter features in computational models of visual-word recognition: there is recent evidence to show that subtle variations in the font have an impact on visual-word recognition and reading (e.g., Moret-Tatay & Perea, in press; Slattery & Rayner, 2010; see also Fiset et al., 2008, for evidence of critical low-level information in the recognition of letters). Clearly, more research should be devoted to examine the influence of perceptual factors during the recognition of written words.

What are the implications of the present data for the models of reading development? We obtained a similar pattern of findings for fourth graders and for adult readers. Therefore, the simplest explanation is that the mechanism of active suppression of mirror generalization for letters is already at play for fourth graders – after all these children have already been trained in the Roman alphabet for several years. (In the Spanish educational system, children start to develop their reading skills at the level of pre-elementary education, from ages 3–6, that is, before entering primary/elementary school.) In other words, for normal-reading children, mirror generalization can be unlearned reasonably early in the development of reading. The specific sensitivity of reversible letters to reversed primes could be interpreted as evidence of functional tuning of the letter identification system. Thus, it is not necessarily surprising that this sensitivity appears early in reading development because letter knowledge is one of the earliest predictors of reading development. A longitudinal study would be necessary to examine in depth *when* the process of suppression of mirror generalization with letters starts to take place – and *how* it varies across individuals.[6]

In the present experiments, we focused on normal-reading readers – either children or adults. One important question for future research is whether or not dyslexic children – or rather a subgroup of dyslexic children – also show a suppression of mirror generalization for reversible/non-reversible letters. In this respect, the data from Lachmann and van Leeuwen (2007) are particularly relevant. They used a same-different task with two sequentially presented rotated stimuli (e.g., "are A and ∢ the same?") and found faster response times for symmetrical letters (A) than for asymmetrical letters (e.g., R) in children with dyslexia but not in a control group of normal-reading children. Interestingly, when a nonlinguistic stimulus was employed (i.e., dot patterns, as in ⁝˙⁚), both dyslexic and normal-reading children showed an advantage for symmetrical patterns. The data from Lachmann and van Leeuwen strongly suggest that children with dyslexia fail to unlearn symmetry generalization for linguistic stimuli. We believe that further research using a masked priming paradigm may provide important insights on whether there are any differences between reversible and non-reversible letters for dyslexic children.

One final methodological note: The go/no-go variety of the lexical decision task employed in the present experiments produced a low rate of errors (less than 3% of errors in fourth graders). In previous experiments using a yes/no lexical decision task, error rates for young readers were much higher than in the present experiment (around 35–45%; e.g., Acha & Perea, 2008; Goikoetxea, 2005). (Importantly, the pattern of effects is very similar in the two tasks; see Gómez et al., 2007; Perea, Rosa, & Gómez, 2003; Perea et al., 2002.) Although an experiment using a within-subject design is necessary to directly assess the potential differences between the yes/no and go/no-go procedures (e.g., error rates, rapidity of the responses, variability in the data), the present experiments suggest that the go/no-go lexical decision task may be preferable to the yes/no variant in experiments with young readers. Of course, we acknowledge that the effect sizes are relatively small, as in the typical masked priming experiments, but the present experiments have shown that it is possible to obtain reliable masked priming effects with subtle manipulations in the go/no-go lexical decision task.

In conclusion, the masked priming experiments reported here reveal that the cognitive system actively suppresses mirror images of reversible letters (e.g., b, d), but not of non-reversible letters (e.g., r, c). Further research using other techniques (e.g., ERPs) is necessary to reveal the time course of activation of mirror images of reversible/non-reversible letters embedded in words – as well as the processing of mirror words. In this light, a recent fMRI priming study of Dehaene et al. (2010), using the BOLD signal as the dependent variable, found significant mirror priming effects with objects, but not with mirror words (e.g., prime: onsiq, target: piano) in a brain area close to the so-called "visual-word form" area. Finally, it will be of interest to examine to what degree mirror priming with whole words is also modulated by the presence/absence of reversible letters.

[6] We conducted an additional go/no-go lexical decision experiment with the materials of Experiment 1 with 21 second graders (mean age: 7.7 years) at the end of the academic year – the children were recruited from the same school as in Experiments 1–3. We found that, on average, latencies were 35 ms slower in the mirror-related condition (e.g., ibea-IDEA) than in the control condition (ilea-IDEA) (1117 vs. 1075 ms, respectively; the *p* values were .078 and .12 in the *F*1 and *F*2 analyses, respectively). Although we acknowledge that further research is necessary to confirm this result, it suggests that mirror-letter generalization can be unlearned reasonably early in the development of reading.

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