

Published in final edited form as:

Mind Brain Educ. 2013 June 1; 7(2): . doi:10.1111/mbe.12017.

The influence of reading expertise in mirror-letter perception: Evidence from beginning and expert readers

Jon Andoni Duñabeitia¹, María Dimitropoulou¹, Adelina Estévez², and Manuel Carreiras^{1,3}

¹Basque Center on Cognition, Brain and Language (BCBL); Donostia, Spain

²Universidad de La Laguna; Tenerife, Spain

³Ikerbasque, Basque Foundation for Science; Bilbao, Spain

Abstract

The visual word recognition system recruits neuronal systems originally developed for object perception which are characterized by orientation insensitivity to mirror reversals. It has been proposed that during reading acquisition beginning readers have to “unlearn” this natural tolerance to mirror reversals in order to efficiently discriminate letters and words. Therefore, it is supposed that this unlearning process takes place in a gradual way and that reading expertise modulates mirror-letter discrimination. However, to date no supporting evidence for this has been obtained. We present data from an eye-movement study that investigated the degree of sensitivity to mirror-letters in a group of beginning readers and a group of expert readers. Participants had to decide which of the two strings presented on a screen corresponded to an auditorily presented word. Visual displays always included the correct target word and one distractor word. Results showed that those distractors that were the same as the target word except for the mirror lateralization of two internal letters attracted participants’ attention more than distractors created by replacement of two internal letters. Interestingly, the time course of the effects was found to be different for the two groups, with beginning readers showing a greater tolerance (decreased sensitivity) to mirror-letters than expert readers. Implications of these findings are discussed within the framework of preceding evidence showing how reading expertise modulates letter identification.

Letter identification is a basic aspect of visual word recognition (e.g., Grainger, Rey & Dufau, 2008; Grainger, 2008; Pelli, Farell & Moore, 2003), as shown by the evidence obtained from expert readers (e.g., Carreiras, Duñabeitia & Perea, 2007; Jordan, Thomas, Patching & Scott-Brown, 2003; Rayner, White, Johnson & Liversedge, 2006; Ziegler, Ferrand, Jacobs, Rey & Grainger, 2000). However, studies exploring letter-in-string identification processes in beginning readers are very scarce, and so is research on the influence of experience and reading proficiency in letter-in-string processing. The present study focuses on how formal reading instruction and reading expertise influences the way in which readers perceive words with reversed or mirrored letters.

Letter identity coding corresponds to the set of cognitive mechanisms devoted to the identification of the individual letters that constitute a given string, while letter position coding corresponds to the mechanisms leading to the accurate identification of the position that those letters occupy within the string, both at an absolute-position level (the precise position of the letters *C* and *T* in the word *CAT*) and at a relative-position level (the notion that *C* precedes *T*). Even though some models of visual word recognition do not explicitly distinguish between letter identity and letter position assignment processes (e.g., Coltheart et

al., 2001; Grainger & Jacobs, 1996; but see Adelman, 2011, for a notable exception), there is evidence showing that these two sub-processes of letter processing are indeed different (e.g., Duñabeitia & Carreiras, 2011; Perea & Lupker, 2004). On the one hand, letter position assignment progressively develops from infancy to adulthood producing gradually different effects (e.g., Castles, Davis & Forster, 2003; Grainger et al., 2012; Perea & Estévez, 2008). On the other hand, beginning readers quickly develop specialized perceptual skills that lead to correct letter identification. Based on this early acquisition of conceptual-lexical differences among alphanumeric characters, it has been proposed that letter identity assignment barely changes as a matter of reading proficiency (e.g., Guttentag & Haith, 1980).

However, there is one aspect of letter recognition that has been proposed to markedly change as a function of experience: the orientation sensitivity of the visual word recognition system. Humans, as well as other primates, have a high tolerance to laterally reversed images (i.e., the mirror version of an image). In fact, it has been shown that reduced populations of neurons at the inferotemporal cortex of monkeys and the human lateral occipital complex are selective for image orientation (e.g., Gross, Bender & Rocha-Miranda, 1969; Rubin, 2001), and respond to both the original and the lateral mirror versions of an image (e.g., Rollenhagen & Olson, 2000; Tomasino, Borroni, Isaja & Rumiati, 2005). This insensitivity to image orientation is of special relevance for object recognition, since the mirror clone of an object provides essentially the same information on that object (“*a tiger is equally threatening when seen in right or left profile*”, Rollenhagen & Olson, 2000, p. 1506). However, given that the mirror version of a letter changes its canonical representation, thereby changing the available information for letter processing substantially, the orientation insensitivity property might lead to erroneous letter identification (Caramazza & Hillis, 1990). Taking this into consideration, it has been assumed that “*mirror generalization is an intrinsic property of the primate visual system, which must be unlearned when learning to read*” (Dehaene, Cohen, Sigman & Vinckier, 2005, p. 339). Dehaene and colleagues proposed that the neural substrates of reading are established by reconfiguring a pre-existing visual architecture (see also Schlaggar & McCandliss, 2007). Considering that the visual system is based on a principle of mirror-image generalization, it is relatively easy to understand why pre-reader children often produce mirror-letters as if they were normal letters (Cornell, 1985; Rudel & Teuber, 1963; Terepocki, Kruk, & Willows, 2002). However, during reading acquisition, the beginning reader has to inhibit the orientation insensitivity in order to efficiently differentiate among letters and to attain the correct letter identity. In Lachmann’s words, “*whereas symmetry generalization is beneficial to vision directly related to behavior, it may be detrimental for vision as part of a symbolic processing such as reading*” (Lachmann & Geyer, 2003, p. 59). It is feasible to assume that such an “unlearning” process might not be completely accomplished during the first years of reading exposure, and that a general neural property of the human brain such as insensitivity to mirror images (a property presumably deeply rooted by evolution; see Kolinsky et al., 2011, for a detailed description) cannot be totally suppressed for the benefit of a recently acquired skill. Correspondingly, and despite the fact that letter identity processing does not seem to notably vary with increased exposure to print, it is plausible to expect different sensitivity levels to mirror-letters between beginning and expert readers, due to the difficulty that this “unlearning” process entails. Nevertheless, to our knowledge, no previous empirical support for this assumption has yet been provided.

As commented above, several authors have suggested that in the process of learning to read the visual word recognition system and the neural network supporting it become progressively tuned to canonical orthographic representations, consequently acquiring fast-acting mechanisms that allow for discrimination between canonically oriented and incorrectly oriented letters (e.g., mirror-letters (e.g., Dehaene et al., 2010; Pegado et al.,

2011; see Kolinsky et al., 2011, for review). Indeed, in some alphabetic languages lateral reversals of some letters result in different letter representation (e.g., b-d, p-q), and recent behavioural evidence from masked priming lexical decision suggests that when individual letters within a word are reversed, readers are highly sensitive to mirror-letter manipulations if the letters are non-reversible (i.e., b/d/p/q; Perea, Moret-Tatay & Panadero, 2011). Interestingly, recent electrophysiological evidence has revealed that mirror invariance still takes place for written words at early visual stages of word identification in expert readers, and that it is at late lexico-semantic stages of word processing when the canonicity of writing direction plays a role. In a series of two masked priming semantic categorization ERP experiments, Duñabeitia, Molinaro and Carreiras (2011) showed that as a consequence of mirror generalization, experienced readers initially treat briefly presented masked word primes containing mirror-letters as normally written words, and more critically, fully reversed masked word primes (namely, mirror-words) as canonically oriented words in a time window between 150 and 250ms after target word presentation¹. These results highlight the presence of an early automatic mirror generalization stage during reading for expert readers, as is the case for other visually presented objects. Furthermore, they call into question accounts that posit that expert readers can effectively discriminate between correctly oriented letters and words and their mirror reversals. In fact, these data demonstrate that a general property of the human visual system such as mirror generalization cannot be “unlearned” as a mere consequence of the acquisition and consolidation of reading. Still, even if one accepts that tolerance to mirror reversals of the letters is still present in expert readers as a consequence of the general mirror-invariance principle of the visual system, it is not clear whether or not novice readers would show a similar tolerance to mirror-letters, or in contrast, as predicted by the hypothesis of an inverse correlation between reading experience and sensitivity to mirror reversals, they would show greater confusion with mirror-letters than expert readers.

The present study is aimed at exploring the influence of mirror reversals of internal letters of a word in a group of beginning readers as compared to a group of expert adult readers. To this end, participants’ eye movements to visual displays that included correctly written words and words with mirror-letters were recorded. In essence, the present study is based on a commonly used paradigm (namely, the visual-world paradigm) and adapts this to the processing of two written letter strings simultaneously presented. Typically, in visual-world experiments a visual display containing pictures is presented to a participant while he/she listens to an auditorily presented word or sentence and the eye movements on the scene are tracked. The eye movements are affected by properties of the linguistic input that enable the identification of the depicted items (e.g., Allopenna, Magnuson, & Tanenhaus, 1998; Duñabeitia, Avilés, Afonso, Scheepers & Carreiras, 2009; Huettig & Altmann, 2005; Scheepers, Keller & Lapata, 2008). Importantly, McQueen and Viebahn (2007) showed that the effects previously found with pictures could be replicated when the visual display included printed words. The proportion of looks to a printed element that is related to the auditory word provides an index of the strength of that relationship. This way, we aimed at exploring the extent to which a word that includes mirror reversals of some of the internal letters represents an attractive distractor for the correctly (canonically) written word, as compared to other control conditions. Although the number of studies that have measured eye movements of beginning readers is extremely low (see Sekerina & Brooks, 2007), this paradigm can be satisfactorily used with children, providing compelling evidence about the

¹Given the lack of differences between the mirror condition and the identity condition in the early stages of processing, in our previous ERP study we did not find any clear signs of either orientation-sensitive or orientation-insensitive orthographic processing. Nonetheless, considering the relative lack of spatial sensitivity of EEG, we cannot safely conclude that discrimination of mirror-letters or mirror-words does not take place in some specific regions associated with visual word recognition (e.g., in the VWFA; see Dehaene et al., 2010; Pegado et al., 2011).

development of word recognition processes. Firstly, we predicted similar proportion of looks towards the correctly written target word and its mirror version for the two groups (beginning and expert readers) during early time epochs as a consequence of the tolerance to orientation variance. Secondly, if the orientation insensitivity feature of the human visual system is present during initial stages of reading acquisition, as proposed by Dehaene et al. (2005), and disappears with increased reading experience, we expected to find a more persistent mirror-letter influence for beginning readers than for expert readers.

The decision regarding a manipulation involving reversals of letters embedded in words (i.e., mirror-letters within words) as opposed to manipulations involving whole-word reversals (i.e., mirror-words) or reversals of individually presented letters naturally derives from the manner in which reading in alphabetic orthographies develops and the sensitivity of the technique and paradigm used. Letter identification processes are mandatory steps for word recognition (see Pelli, Farell, & Moore, 2003), and it has been recently demonstrated that in spite of the word superiority effect, under normal viewing conditions individual letters presented in isolation are recognized much faster than letters embedded in words (see James, James, Jobard, Wong, & Gauthier, 2005, for review). Therefore, given that we wanted to explore differences in the perception and identification of letter reversals across groups with different reading levels (namely, insensitivity to mirror-letters, which is a process admittedly short-lived and fast-acting; see Duñabeitia et al., 2011), we opted for a manipulation that required participants to focus on some of the individual letters of the words, this way allowing for subtle processing differences to emerge in the time course of word identification. It should also be noted in this regard that manipulations of individually presented letters have led to somewhat contradictory behavioural and neuroimaging results (see Pegado et al., 2010), while mirror-letter similarity effects for letters embedded in words are a well-established and replicated behavioural and electrophysiological finding (see Duñabeitia et al., 2011, Experiment 1, and Perea et al., 2011). Hence, according to these pieces of evidence, we believe that by using mirror-letters embedded in words we maximize the possibilities of obtaining processing differences within and across groups.

Method

Participants

20 children and 20 undergraduates took part in this experiment. All of the children were first graders in a public school, and were tested at the end of the school year with the written permission of their parents. Their mean age was 6.5 (± 0.5) years. They all underwent a brief evaluation of their reading skills before the experimental session, composed of three subtests that measured their letter recognition ability and their word and pseudo-word reading capacity (taken from Cuetos, Rodríguez & Ruano, 2000). Results confirmed the general impression of the teachers, showing that all the children were good readers (their average centile punctuation was 68, well above centile 50 which represents the median value of reading performance in this test). All the participants had normal or corrected-to-normal vision.

Materials

Two sets of 32 Spanish five-letter words were selected, matched for frequency, number of letters, phonemes and syllables, bigram frequency and number of orthographic and phonological neighbours (all $ps > .27$; see Table 1). Each word from set A (e.g., *meter* or *paseo*, the Spanish words for *to put* and *walk*, respectively) was paired to one word from set B, sharing all but two or three letters (e.g., *matar*, the Spanish word for *to kill*, or *pacto*, translated as *pact*). None of the substituted letters occurred in word-initial position and only 4.5% of the replacements took place in word-final position (the remaining 95.5% of the

substituted letters were not outer letters). In order to control for the orthographic similarity between the words from set A and B, a measure of the Levenshtein distance was obtained. The mean number of edits distinguishing the two sets according to this metric was 2.09 (SD=0.30; range=2-3). All the words had two letters that could be changed into a mirror version leading to non-canonical letter representations (e.g., *meter* and *matar*, or *paseo* and *pacto*; see Figure 1). Words from set A were used as targets and were displayed on the screen (either on the left or the right side) accompanied by a distractor string displayed on the opposite side corresponding to one of the three manipulation conditions: Mirror, Control Word and Control Mirror distractor condition. In the Mirror distractor condition, the target word was displayed together with a repetition of that same word which included two internal letters in their mirror form (see Figure 1)². In the Control Word distractor condition the word was displayed together with the correctly written counterpart of set B. In the Control Mirror distractor condition, the word was displayed together with the mirror version of the counterpart of set B, which also included two internal letters in their mirror form. As seen in the examples provided above, the mirrored letters in the two conditions involving letter reversals could be consonants or vowels (59% and 41% of the mirrored letters, respectively). In order to minimize the impact of letter reversals that lead to the creation of another letter (e.g., b/d, p/q), these type of mirror-letters exclusively represented less than 5% of the percentage of letter reversals (see Perea et al., 2011). This way, each target word from set A was presented three times during the experiment, each time with a distractor from a different condition. The target location was systematically rotated across items and conditions. The auditorily presented target words were recorded in a soundproof booth by a male native speaker of Spanish using neutral intonation and were normalized to 700 ms.

Apparatus and procedure

An EyeLink II eye-tracker (SR Research Ltd., Canada) linked to a 17-inch color monitor with a resolution of 1024×768 pixels was used. Both eyes were simultaneously tracked at a 500Hz-sampling rate, although only data from the right eye were analyzed. Participants were seated at a viewing distance of 50cm. A head-tracking camera compensated for potential errors resulting from head movements. Children completed the experiment during school hours in a well-lit room located at their school and adults were tested in an experimental room at the university. After the calibration and validation process, participants were presented with six practice trials. Each experimental trial started with the presentation of a fixation point (⊕) in the centre of the screen. Upon participants' fixation, an automatic drift correction was performed. Therefore, following a classical procedure in eye-movement studies exploring reading processes, the duration of the fixation point on the screen varied across trials and across subjects, since the experimenter had to validate that the eyes were fixating on the cue on a trial-by-trial basis. Next, the target display containing the two letter strings was presented in Courier New white font on a black background. The width of each stimulus according to the viewing distance was 4°, and the height was 1.4°. A horizontal distance of 9.5° separated the two stimuli presented on the screen. The critical letters in the Mirror and Control Mirror distractor conditions were created by rotating in the vertical axis the letters in Courier New font (using a font creation software). Time-locked to the presentation of the visual display, an attention-capturing beep was presented for 100ms, followed by a 200ms-silence. The spoken word was then presented via headphones (see Figure 1). Immediately after the end of each trial (after 3000ms from the auditory words' onset), a response cue (¿?) was presented on the screen for 500ms and participants were

²We decided to manipulate two internal letters (40% of the letters of the words) in order to maintain a similar ratio of within-word mirror-letters to that used in previous literature (e.g., 44% in Duñabeitia et al., 2011, Experiment 1). Nonetheless, it should be kept in mind that recent research has also shown that mirror effects at the letter level can be also obtained with manipulations involving less than 20% of the letters (see Perea et al., 2011).

instructed to indicate by pressing one out of two buttons in a gamepad which of the two previously displayed strings matched the auditory input. Following participants' responses, feedback information about their accuracy was given for 500ms (either a happy or a sad face; i.e., ☺ or ☹). The next trial started with the presentation of the fixation point.

Results

Accuracy data

In order to investigate whether the accuracy rates for the groups of children and adults significantly differed from each other and whether these were different for the three experimental conditions, we performed an ANOVA with the error rates as dependent variable, the distractor condition as a within-subject factor (3 levels: Mirror, Control and Control Mirror), and the group factor as a between-subject factor (2 levels: Beginning readers and Expert readers). Accuracy data from 20 adults and 19 children were analyzed, since the data from one child were lost due to technical problems. Results showed a main effect of group, revealing that adults made significantly less errors than children [$F(1,37)=25.35, p<.001$]. The effect of the distractor condition was also significant, and it interacted with the group factor [$F(2,74)=7.60, p=.001$], suggesting that the impact of each type of distractor on the error data was different in each of the groups of participants. In the following section we report the analysis on the error data for each group separately.

Beginning readers—Children correctly identified the location of the target items 94% of the times. However, there were clear differences on target location identification depending on the distractor condition. They made more identification errors when the target was accompanied by its mirror version (11.1% of errors) than when the target was presented with the control word (3.4% of errors; $t(18)=2.79, p=.01$) or with the mirror version of the control word (3.6% of errors; $t(18)=2.81, p=.01$). No differences were found between the accuracy levels in the two control conditions (Control Word and Control Mirror; $t(18)=.15, p=.88$).

Expert readers—Adults correctly identified 99.8% of the trials in the three display conditions, with no statistical differences between conditions in the percentages of errors ($ps>.95$).

Eye-movement data

Participants' eye movements were recorded time-locked to the presentation of the auditory words. For each of the experimental displays, bitmap templates were created that identified the distractor and the target string. The critical regions were defined in terms of rectangular regions of interest that contained the two strings, and fixations landing within the perimeters of those rectangles were coded as fixations on the strings. The output of the eye-tracker included the x - and y -coordinates of participants' fixations, which were converted into region codes using the templates. The region codes were then mapped onto two scoring regions for analysis, including the target word and the distractor string. Fixations shorter than 80 ms were pooled with preceding or following fixations if these fixations were within 0.5 degrees of visual angle. For the analysis, the time period of the display presentation was divided into 50ms-time slots. For each time slot, the probability of fixating one of the two scoring regions (target or distractor) was determined for each condition (see Figures 2 and 3). The 95% confidence intervals by subjects for these data were calculated, so that statistical consistency of the data could be assessed. Furthermore, in order to assess the statistical significance of the differences between the probability of fixating on each of the two strings in each of the experimental condition and test groups, t -test were run for each of the 50ms-time bins.³ Considering the need for correction for multiple comparisons, a False Discovery Rate (FDR) analysis was carried out together for each of the t -tests' p -values (see

Benjamini, 2010; see also Benjamini & Hochberg, 1995). FDR is a method used to correct for multiple comparisons, controlling for the expected proportion of incorrectly rejected null hypotheses.

Beginning readers—In the Mirror display condition, children equally fixated the two strings during almost half of the trial duration. The distractor string was equally attractive as the target word up until 1550ms after display presentation, and no consistent statistical differences were obtained between the probability of fixating the target and the distractor upon that time bin (as assessed by pairwise *t*-tests and FDR corrections; see Figure 2). Contrarily, when the target word was presented in the Control word condition, participants made significantly more fixations on the target than on the distractor after 850ms. A very similar pattern was observed in the Control Mirror condition, with participants making significantly more fixations on the target item than on the distractor after 850 ms.

Expert readers—In the Mirror distractor condition, adults similarly fixated the target word and the distractor for 700ms. After this, participants significantly made more fixations on the target item than on the distractor. On the contrary, when the target word was displayed in the Control word distractor condition, participants resolved the ambiguity faster, as shown by the higher fixation probabilities on the target than on the distractor from 450ms onwards. This was also the case in the Control Mirror distractor condition, in which participants made significantly more fixations on the target word starting from 500 ms.

The present data offer three critical pieces of information. First, we demonstrated that both novice and expert readers resolved the ambiguity between the target and the distractors significantly faster when the distractors were control words (either normally displayed or presented with mirror-letters) than when the distractors were identical to the targets except for the mirroring of two internal letters (i.e., Mirror condition). Second, these data showed that the two control conditions did not significantly differ from each other, and hence, any effect found for the Mirror condition could not be attributed to the mere presence of unconventional letters, since the Control and Control Mirror conditions showed parallel patterns of eye movements. And third, we critically showed that the attraction derived from the presentation of identical words including mirrored letters was clearly different for expert than for beginning readers, being much larger for the latter group than for the former (a between-group difference of 850ms in the Mirror condition, while differences of only 400ms and 350ms were found in the Control and Control Mirror conditions, respectively).

General Discussion

The present experiment examined how letter identity is attained in beginning and expert readers. Specifically, we explored whether there is a word recognition cost associated with the replacement of canonical letters by their mirror versions (i.e., mirror-letters), and whether this cost varies for beginning and expert readers as a consequence of their difference in reading expertise. The error data revealed that expert readers were more accurate in target identification than children. More importantly, the error data also showed

³In order to examine the statistical differences of the influence of each distractor condition in each of the test groups, other statistical methods could be used, such as the fitting of mathematical functions to each of the curves (see Duñabeitia et al., 2009, and Scheepers et al., 2008, for a similar procedure; see also Huettig, Rommers, & Meyer, 2011, for review). However, the use of the curve-fitting procedure is circumscribed to the type of research questions being explored, and considering that our main goal was to determine whether or not the two test groups differed from each other in terms of the tolerance to mirror-letters, and that this can be assessed by investigating the moment in time in which targets and distractors start to consistently differ across conditions and groups, a curve-fitting procedure would not provide us with additional information with regard to the onset of the differences. Furthermore, when we performed a curve-fitting analysis on these same data, identical results were obtained (see Dimitropoulou, Duñabeitia, & Carreiras, 2009). Hence, for simplicity's sake, we will focus on the time-course of the sensitivity to mirror-letters by statistically assessing the differences between conditions and groups, correcting for the multiple comparisons with the FDR method.

that children mistook the distractor for the target significantly more in the Mirror condition than in the two Control conditions. The fixation data showed that ambiguity resolution occurred much earlier for the expert than for the novice readers for all distractor conditions. Furthermore, as compared to the control conditions (namely, Control and Control Mirror conditions), both beginning and expert readers showed greater difficulty in target identification in the Mirror distractor condition. Critically, results confirmed that this cost was significantly larger for the group of beginning than for the group of expert readers, demonstrating children's greater tolerance to mirror reversals.

These results lead to the conclusion that orientation insensitivity, as a general property of the human visual system, cannot be completely suppressed or inhibited in order to efficiently acquire a new skill like reading or writing. Furthermore, these data demonstrate that in spite of a progressive neural specialization or neural tuning to (canonical) orthographic material, non-canonical orthographic units such as mirror-letters are also processed as correct units to some extent. This was clearly shown in both groups, since there was a greater cost associated to the Mirror distractor condition as compared to the Control and Control Mirror distractor conditions. Accordingly, in a recent masked priming experiment combined with event-related brain potential recording that explored the influence of mirror-letters in a group of expert adult readers, Duñabeitia et al. (2011) found that skilled readers are insensitive to mirror-letters inserted in unconsciously presented words at the beginning stages of visual word processing. Thus, the visual property of orientation insensitivity has a clear impact on readers' performance across different levels of reading expertise.

It is important to note that it is not the specific non-canonical nature of mirror-letters that attracts participants' fixations. If this had been the case, a clear "general mirror-letter attraction" effect should have been seen in the Control Mirror condition as well. The higher number of fixations on the distractors in the Mirror condition cannot be attributed to a general saliency of their mirror-letters, but more plausibly, to the fact that these mirror-letters activate the correct letter representations, and therefore make target selection harder (note that in fact, participants made very similar proportions of looks towards the two control distractors, that were actually the same unrelated word, either in the canonical or the mirror version).

In this same line, it should be noted that the effects here reported could hardly be accounted for by explanations based on visual similarity differences between the targets and the different types of distractors. Visual similarity between characters has been shown to be an important factor determining the accuracy and speed of letter and word identification, given the relevance of perceptual factors in reading (e.g., Fiset et al., 2008; Grainger, Rey, & Dufau, 2008; Mueller & Weidemann, 2012). As we pointed out in a previous study, "it should be considered that the most stable existing attractor for a mirror-letter will undeniably be the correct letter, due to the high visual overlap between them" (Duñabeitia et al., 2011, p. 3006). Therefore, one could tentatively argue that the mirror-letter confusability effect reported in this study is the consequence of the greater visual similarity between the stimuli in the Mirror condition and the targets, as compared to the two control conditions. However, if visual similarity per se were the factor driving the effects, and considering that the pattern of effects found for the two control conditions (i.e., Control and Control Mirror conditions) did not differ from each other, a basic similarity analysis of the items in the different conditions with respect to the targets should show a greater visual similarity for the Mirror condition than for the two control conditions, which in turn should not differ from each other. In order to explore this possibility, we performed a byte-based comparison of the different stimuli in the different conditions converting all the words used in the experiment to individual picture files (normalized for size and font) and processing them with specialized software for image comparisons (see Figure 4). The similarity scores obtained

for the items in each condition as compared to the targets confirmed that the visual overlap for the distractors in the Mirror condition was significantly larger than the visual overlap for the distractors in the other conditions (Mirror vs. Control: $t(31)=4.10$, $p<.001$; Mirror vs. Control Mirror: $t(31)=11.92$, $p<.001$). Critically, the items in the Control condition were also more similar to the targets than the items in the Control Mirror condition, as attested by a series of t-tests performed on the similarity scores (Control vs. Control Mirror: $t(31)=7.69$, $p<.001$). Hence, in spite of the irrefutably greater visual similarity of the items in the Mirror condition with regard to the targets as compared to the other conditions, which could have somewhat contributed to the observed effects, we believe that the visual overlap factor cannot be entirely responsible for the whole pattern of effects presented in this study, given that the visual similarity between the two control conditions and the targets was found to be significantly different too, while the eye-movement data for these conditions did not differ substantially.

In spite of the persistent influence of mirror generalization in beginning and expert readers, this effect is attenuated by increased exposure to print. In accordance to Dehaene and colleagues (2005), insensitivity to lateral reversals has to be “unlearned” in the process of reading acquisition in order to correctly distinguish among letters. We predicted that this unlearning process would lead to a greater influence of mirror-letters (namely, a more marked insensitivity to mirror lateralization) for beginning learners with reduced experience with print than for expert readers. As shown by the fixation and error data reported in the present study, this seems to be the case. Beginning readers made significantly more errors in target word identification when the target was accompanied by its mirror distractor, as compared to the other distractor conditions (note that this difference was absent in the group of expert readers). Similarly, children took longer than adults to correctly differentiate between the two strings that only differed in the mirror reversal of two of the internal letters.

A general assumption in reading acquisition, especially relevant for languages with transparent orthographies like Spanish, is that, when children access the visual code of written words, the phonological code is also activated (Goswami & Ziegler, 2006). Bowers, Vigliocco and Haan (1998) suggested that “the activation time courses for abstract orthographic letter and word representations, as well as for phonological letter codes, are different” (p. 1718), with the former faster than the latter, and the reliance on orthographic or phonological codes during initial stages of reading acquisition seems to depend on the degree of transparency of the language (i.e., the degree of consistency of spelling-sound correspondences). Children who are learning to read consistent alphabetic orthographies can solve the problem of mapping units of print (letters) to units of sound (phonemes) with relatively little effort and consequently may make a predominant use of the phonological route in initial stages of reading acquisition (Cuetos, 1989), changing to a predominant use of the lexical route when they become skilled readers. For the two words in the Mirror display condition, children initially (mis)perceived both stimuli to be the same, as a consequence of the visual property of mirror generalization, and consequently both items activated the same phonological word representation. Since the task required a single answer (which is the string that corresponds to the auditory input?), children had to turn to more detailed graphemic analyses of the printed strings, relying on fine-grained discriminations, to finally resolve the ambiguity. This fine-grained graphemic discrimination process was not required to satisfactorily resolve the ambiguity in the Control and Control Mirror conditions, because distractors in these conditions activated phonological representations that did not match the auditory input, and consequently made the selection process easier. When reading and writing proficiency is achieved and tolerance to mirror-letters is attenuated, the ambiguity resolution is fulfilled much faster, as shown by our adult data.

How can the progressive disappearance of insensitivity to mirror-letters be explained in terms of reading acquisition and development models? Even though there does not seem to be a clear answer to this question, the undeniable influence of exposure to print has to be considered. In spite of the lack of behavioural evidence, neuroimaging studies have shown that specific areas in the visual cortex receive increase activation when reading reaches a certain proficiency level (Cohen & Dehaene, 2004; McCandliss, Cohen & Dehaene, 2003). The left fusiform gyrus becomes more active as reading evolves (e.g., Dehaene et al., 2010), reflecting the experience-dependent development of an orthographic lexicon (see Goswami & Ziegler, 2006). Developmental neuroimaging studies suggest that basic structural features of the network specialized in visual word processing are already present in beginning readers, but that at a functional level, finer tuning to letters is only achieved with increased reading experience (Maurer, Brem, Bucher & Brandeis, 2005; Rossion et al., 2002). Furthermore, brain activity in visual areas is modulated as a function of augmented exposure to print (Brem et al., 2006; Maurer et al., 2005, 2006; Maurer & McCandliss, 2008; Schlaggar & McCandliss, 2007). In line with this view, the faster rejection of the Mirror distractor string by the adult group in the present experiment suggests that expert readers are able to make finer and faster orthographic discriminations than beginning readers (see also Grainger et al., 2012). We interpret this difference between children and adults in terms of a progressive diminishing of the tolerance to violations of letter canonicity that, together with more finely tuned feature discrimination and letter identification visual system, leads to an easier inhibition of orientation insensitivity. One issue that should be mentioned in this regard is that the current set of data, as well as preceding evidence from similar studies (see Duñabeitia et al., 2011; Perea et al., 2011), exclusively refers to the processing of (mirror-) letters embedded in words. Whether or not the same results would be expected for letters embedded in pseudowords is not entirely clear. Given the straightforward grapheme-to-phoneme mappings in transparent orthographies, one could tentatively expect similar findings in a pseudoword-based manipulation due to the minimized impact of lexical factors in orthographies such as Spanish. Similarly, most models of orthographic processing assume an interactive bidirectional flow of activation from lexical levels to orthographic levels, but not to lower levels of basic graphemic encoding based on visual analysis (see Grainger & Ziegler, 2011, for a comprehensive summary). Hence, there is no a priori reason to expect differences between within-word and within-pseudoword mirror-letter confusability effects. Nonetheless, given that the literature at this regard has exclusively focused on the processing of mirror-letters embedded in words, this is a question that remains open for future research.

Grainger and Ziegler (2011) have recently proposed a dual-route model of visual word recognition supporting the existence of two orthographic coding mechanisms or principles: a fine-grained and a coarse-grained orthographic code. The fine-grained orthographic analysis proposed by these authors is based on mechanisms by which highly predictable letters and letter combinations are broken apart and processed. In contrast, the coarse-grained analysis corresponds to the selection and processing of those letter combinations that allow for a fast lexico-semantic access (see Grainger & Ziegler, 2011, p. 3). We suggest that mirror generalization is a visual process that underlies both processing strategies. Mirror-letter confusability effects would be better captured by the fine-grained orthographic analysis, insofar as it focuses on individual letters to a greater extent than the coarse-grained orthographic analysis. In contrast, the coarse-grained orthographic code would be responsible for the mirror-word confusability effects (see Duñabeitia et al., 2011, Experiment 2). We have recently tested this hypothesis in an EEG experiment (Duñabeitia, Carreiras, & Molinaro, under review) testing canonically oriented and mirrored letter strings and strings made of unknown characters, since according to the processing strategies proposed by Grainger and Ziegler, the latter type of stimuli would not be encoded by coarse-grain principles, consequently blocking whole-string effects that require coarse-grain access. Our results confirmed these hypotheses, since whole-string mirror confusability effects were

exclusively found for letter strings, being completely absent for strings made of unknown characters.

Finally, we wish to stress the relevance of these data and of the whole literature on mirror-letter and mirror-word processing for educational practices from a psychological perspective. As recently pointed out by Dehaene (2011), mirror confusion in late childhood has been typically taken as a sign of dyslexia (see also Lachmann & van Leeuwen, 2007). This argument is further reinforced by theoretical proposals indicating that children progressively acquire sensitivity to mirror reversals of letters and words as a function of increased exposure to print, and consequently explicit manifestations of insensitivity to mirror reversals (that is, confusion with mirror-letters and mirror-words) can be taken as a psychological marker of reading disorders. However, in light of the current findings one should be cautious with regard to the validity and generalizability of such a psychological marker of reading disabilities. While it seems to be the case that insensitivity to lateral reversals of orthographic material reaches its maximum in pre-readers and that reading acquisition and consolidation favours an apparently progressive loss of such a capacity in respect to letters and words, current evidence also demonstrates that the tolerance to letter and word reversals does not vanish in expert readers, as evidenced from studies using techniques and paradigms that tap into automatic and early stages of processing (e.g., masked priming paradigm combined with EEG recordings, or eye-movements). On the one hand, in the present study we have shown that adult readers are more sensitive to (that is, less confused by) mirror-letters than novel readers. But critically, on the other hand, the present experiment and our previous ERP study (Duñabeitia et al., 2011), together with the study by Perea et al. (2011), clearly reveal that expert readers also exhibit certain tolerance to mirror reversals of orthographic units. Hence, according to the bulk of evidence demonstrating that experienced readers also mentally rotate letters and words in an automatic manner, we suggest that insensitivity to mirror-letters and mirror-words should not be taken as a trustworthy marker of reading disabilities.

At a functional and structural neural level, it has been recently shown by Ilg et al. (2008) that a 15-minute training session on mirror reading prolonged for a relatively short period (e.g., 2 weeks) leads to grey matter increase in the right dorsolateral occipital cortex, thus suggesting that short training on mirror reading leads to structural cerebral changes that may lead to enhanced visuospatial functioning. This, together with other pieces of evidence endorsing the use of mirror reading techniques for rehabilitation and for the cognitive improvement of the retained skills of different patients (e.g., schizophrenics; see Takano et al., 2002), suggests that mirror reading is a valuable tool that should not be despised in educational practice⁴. In line with this idea, we are currently exploring the extent to which explicit training in mirror reading leads to observable benefits in general orthographic coding processes during the early stages of reading acquisition and consolidation.

In summary, we have shown that a general neural property of the visual system like orientation insensitivity cannot be totally suppressed for the benefit of a recently acquired skill like reading. In light of these results, we can conclude that reading expertise strongly modulates the sensitivity to mirror-letters, with beginning readers more insensitive (that is, more tolerant) than expert readers to the mirror cloning of letters embedded in words. Hence, our data clearly show that reading expertise modulates letter identification and that mirror generalization has its greatest impact at the beginning stages of reading acquisition. As a final remark, we would like to highlight the appropriateness of the eye-tracking technique for exploring children's reading. Despite of the non-invasive nature of this

⁴At this regard, we would want to highlight some recent pedagogical trends such as the proposal suggested by the Mirror Read community (www.mirrorread.com), endorsing the generalization of mirror reading as a constructive technique.

technique, it is noteworthy that the number of studies that have measured eye movements of novel readers is extremely low (see Sekerina & Brooks, 2007). We believe that this study could encourage a generalization of the use of eye-tracking techniques with children.

Acknowledgments

This research was partially supported by grants CSD2008-00048 and PSI2012-32123 from the Spanish Government, ERC-AdG-295362 from the European Research Council and PI2012-74 from the Basque Government.

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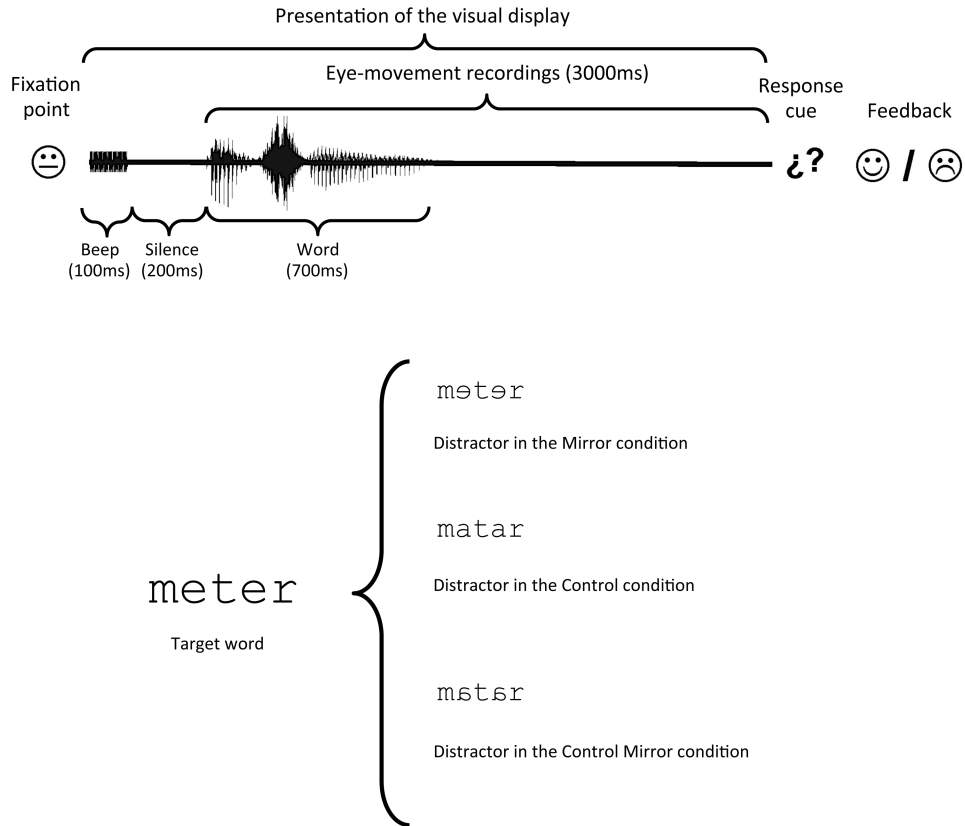


Figure 1. Schematic representation of an experimental trial and examples of the target item and each distractor condition.

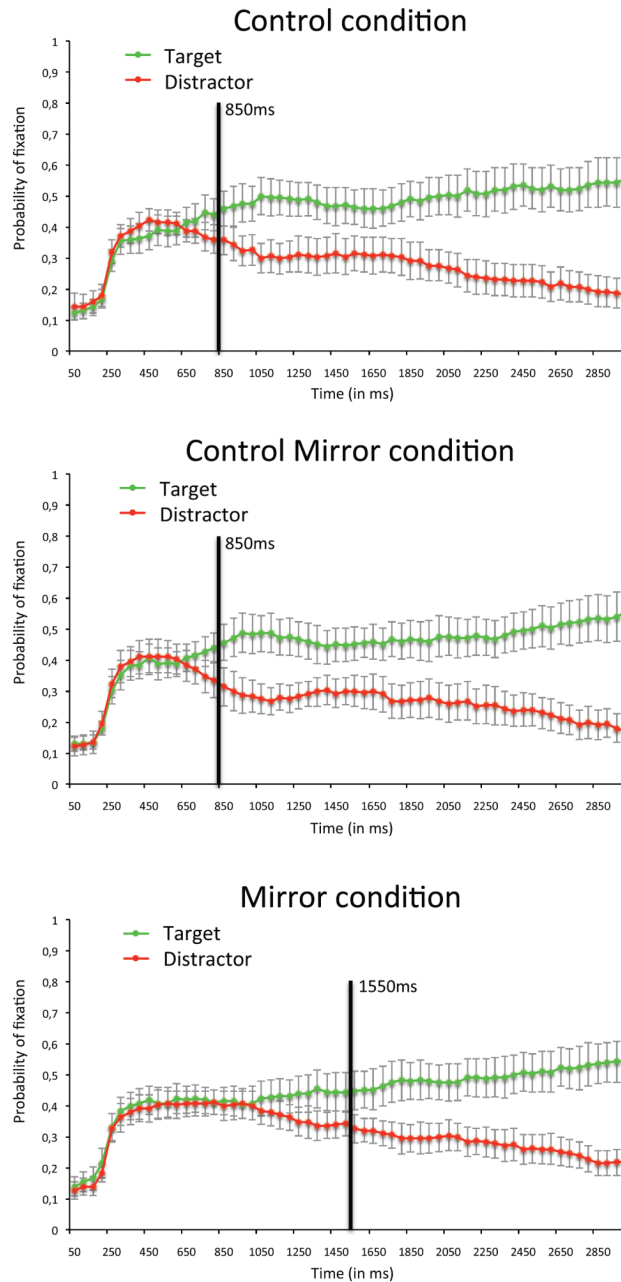


Figure 2. Probabilities of fixations on the target word (green markers) and on the distractor (red markers) in each display condition for the subgroup of *beginning readers*. Time is plotted on the *x*-axis (in 50ms-bin resolution). Error bars represent upper and lower 95% confidence limits, such that no overlap between conditions indicates a significant target-distractor difference. The solid black line in each graph corresponds to the time bin from which the two strings attracted significantly more (FDR-corrected) fixations.

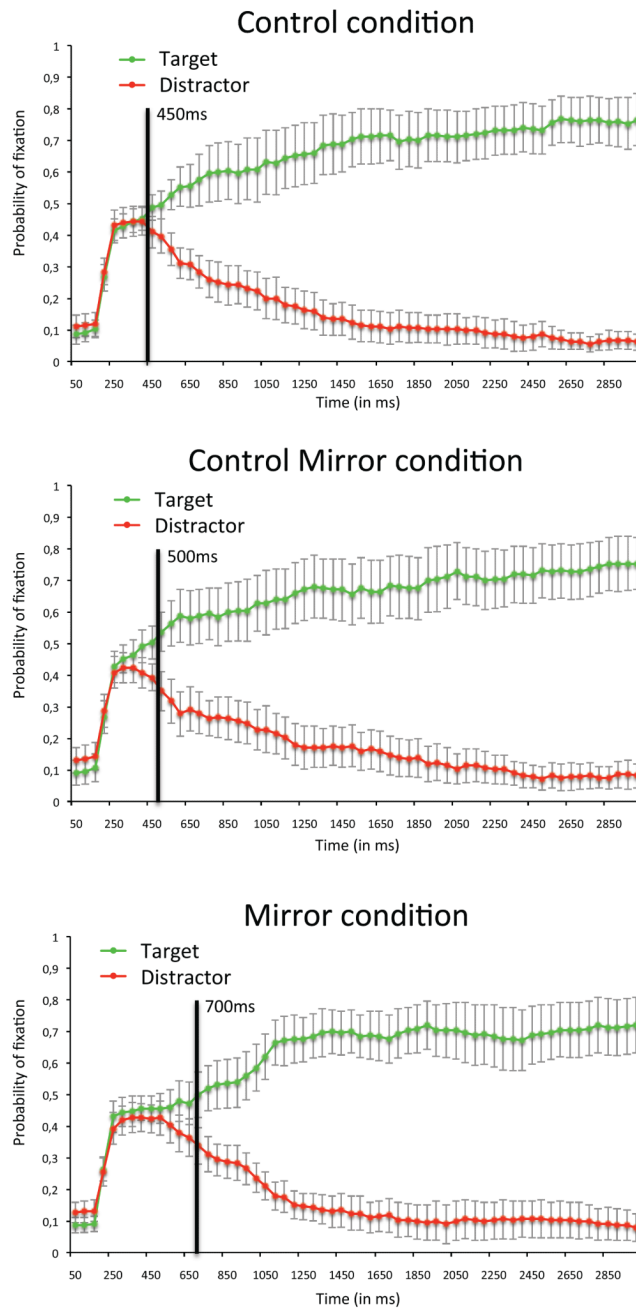


Figure 3.

Probabilities of fixations on the target word (green markers) and on the distractor (red markers) in each display condition for the subgroup of *expert readers*. Time is plotted on the *x*-axis (in 50ms-bin resolution). Error bars represent upper and lower 95% confidence limits, such that no overlap between conditions indicates a significant target-distractor difference. The solid black line in each graph corresponds to the time bin from which the two strings attracted significantly more (FDR-corrected) fixations.

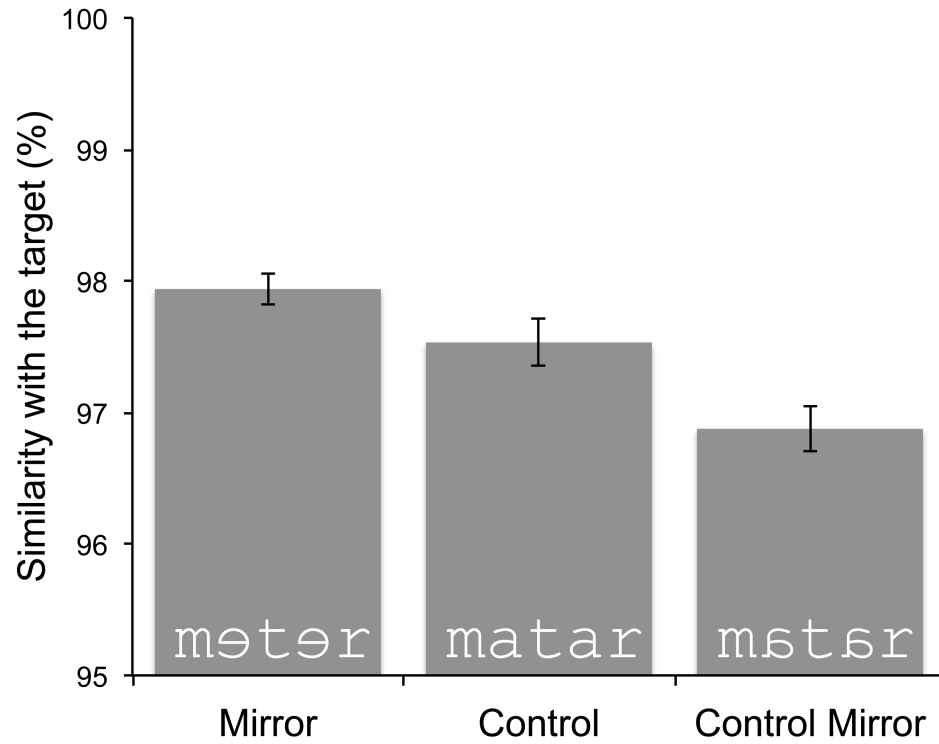


Figure 4. Percentage of visual similarity between the items in the different conditions and the targets. Error bars represent upper and lower 95% confidence limits. All the statistical comparisons between conditions resulted significant (all $t_s > 4$ and $p_s < .001$).

Table 1

Mean word frequency (per million), length (in number of letters and phonemes), number of syllables, bigram frequency (type and token) and number of orthographic and phonological neighbors (N and PN size, respectively) of the words used in the experiment. Standard deviations are provided within parentheses.

| | Frequency | Letters | Phonemes | Syllables | Bigram token | Bigram type | N size | PN size |
|---------------------------|------------|--------------|--------------|--------------|--------------|-------------|--------------|--------------|
| Set A (<i>meter</i>) | 31 (21) | 5.0 (0.0) | 4.9 (0.2) | 2.2 (0.4) | 747 (375) | 37 (14) | 3.5 (2.4) | 5.5 (3.2) |
| Set B (<i>matar</i>) | 24 (26) | 5.0 (0.0) | 5.0 (0.3) | 2.2 (0.4) | 791 (396) | 39 (13) | 3.6 (2.7) | 5.5 (3.3) |

Note: Statistics were taken from Davis and Perea (2005).