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# Literacy Breaks Mirror Invariance for Visual Stimuli: A Behavioral Study With Adult Illiterates

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The ability to recognize 2 mirror images as the same picture across left–right inversions exists early on in humans and other primates. In order to learn to read, however, one must discriminate the left–right orientation of letters and distinguish, for instance, *b* from *d.* We therefore reasoned that literacy may entail a loss of mirror invariance. To evaluate this hypothesis, we asked adult literates, illiterates, and ex-illiterates to perform a speeded same–different task with letter strings, false fonts, and pictures regardless of their orientation (i.e., they had to respond "same" to mirror pairs such as "iblo oldi"). Literates presented clear difficulties with mirror invariance. This "mirror cost" effect was strongest with letter strings, but crucially, it was also observed with false fonts and even with pictures. In contrast, illiterates did not present any cost for mirror pairs. Interestingly, subjects who learned to read as adults also exhibited a mirror cost, suggesting that modest reading practice, late in life, can suffice to break mirror invariance.

*Keywords:* mirror invariance, reading expertise, literacy, illiterates

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Mirror invariance (also called mirror generalization) enables one to promptly identify an image regardless of its left–right orientation. Mirror invariance has been demonstrated in human adults (Biederman & Cooper, 1991; Stankiewicz, Hummel, & Cooper, 1998) and infants (Bornstein, Gross, & Wolf, 1978) as well as nonhuman animals (Logothetis, Pauls, & Poggio, 1995; Noble, 1966; Rollenhagen & Olson, 2000), suggesting an old phylogenetic origin or convergent evolution.

In nature, indeed, left–right mirror discrimination is often irrelevant for identification purposes. On the contrary, mirror invariance can represent an advantage for learning and survival, for instance by enabling one to immediately recognize the mirrored version of a previously seen predator. However, when reading and writing, mirror discrimination is needed in order to avoid confusing *b* with *d* or *p* with *q*. Interestingly, children who are just beginning to read and write frequently present mirror confusions, which normally disappear after approximately two years of literacy training (Cornell, 1985). In dyslexic children, mirror confusion takes longer to disappear, and dyslexics present a better performance than do normal readers in a same–different mirror-invariance task where mirror letters should be assigned the response "same" (Lachmann & Van Leeuwen, 2007).

Neuroimaging studies have shown that a restricted area in the left temporo-occipital cortex, the visual word form area (VWFA), responds in a robust way to orthographic stimuli across different written systems (Bolger, Perfetti, & Schneider, 2005; Cohen & Dehaene, 2004; Cohen et al., 2000; Dehaene, Le Clec, Poline, Le Bihan, & Cohen, 2002; Dehaene, Pegado, et al., 2010; Nakamura, Dehaene, Jobert, Le Bihan, & Kouider, 2005). Importantly, in literate adults, this region presents mirror invariance for pictures but mirror discrimination for letters (Pegado, Nakamura, Cohen, & Dehaene, 2011) and words (Dehaene, Nakamura, et al., 2010). These findings suggest that literacy may be directly responsible for the loss of mirror invariance in this area. We therefore reasoned that, in a same–different task requiring mirror invariance, literates might perform relatively worse than illiterates.

In the present work, we evaluated whether literacy influences mirror invariance behavior. The same literate, illiterate and ex-illiterate adult subjects who took part in our earlier functional magnetic resonance imaging (fMRI) work (Dehaene, Pegado, et al., 2010) performed a same–different identity task where the left–right orientation of stimuli was manipulated, separately for alphabetic, false-font, and pictorial stimuli.

# Method

## Subjects

We tested a group of 10 adult Brazilian illiterates (mean age 53.3 years, range 44–64) who had not been schooled, could not read simple words, and even failed to identify some letters. They were compared to Brazilian and Portuguese literates ($n = 32$) and ex-illiterates (i.e., those who learned to read as adults; $n = 21$) with variable reading skills. Detailed behavioral performance measures and sociodemographical data are described elsewhere (Dehaene, Pegado, et al., 2010). Out of the original data set of 63 subjects, two literates did not take this test. Among the remaining 61 subjects, two other literate subjects were excluded from the analysis for failing to follow the instructions. A subset of 31 Brazilian subjects (10 illiterates, 10 ex-illiterates, and 11 literates, referenced, respectively, as ILB, EXB and LB2 in Dehaene, Pegado, et al., 2010) was matched for origin, age, and socioeconomic status, and we verified that our results for response times (RTs), error rates, d-primes, and regression analysis still held when analyzing just these subgroups (see the online supplemental material). Analyses of variance (ANOVAs) on log-transformed RTs, taking into account group differences in variance, gave similar results.

## Same–Different Task

Five categories of visual stimuli were intermixed in random order: letter strings, false fonts, and three pictorial categories (faces, houses, and tools). Stimuli were presented sequentially as pairs that could be physically identical, left–right mirrored, or different (see Figure 1; we only studied invariance for reflection around the vertical axis, but see Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008, and Gregory & McCloskey, 2010, for studies of invariance around another axis). Subjects judged if the pairs were same or different, pressing the right or left button, respectively. They were carefully instructed to respond "same" to mirror pairs (identity judgment regardless of orientation). Ten trials were presented for each of the five visual categories and each of the three condition types (same, different, and mirror), for a total of 150 trials per subject.

Materials are described thoroughly in (Dehaene, Pegado, et al., 2010) and in the online supplemental material (examples appear in Figure S1). In the string category, we used pseudowords instead of real words to avoid lexical–semantic interference. The pseudowords were four-letter strings such as "obli," written exclusively with the lowercase letter set "bdmnlpqiou" and using a modified Arial font where letters were strictly reversible, so that after mirroring, the stimuli still looked like possible pseudowords. Each included a single asymmetric letter (*b, d, p,* or *q*). False-font stimuli were matched one-to-one with the pseudowords by replacing each letter with a pseudoletter of similar complexity. Within each category, the "different" pairs were created by pairing each exemplar with another maximally different one (see the online supplemental material for details). For strings, the "different" pairs shared, on average, 0.21 letters at the same location (out of four letters).

# Results

We collapsed faces, tools, and house into a single picture category after ANOVA revealed no significant interaction with group or condition in order to simplify the description of the data. Separate results for each pictorial category can be found in Tables 1 and 2 in the online supplemental material.

## Response Times (RTs)

We used natural logarithmic-transformed RTs as the dependent measure in order to reduce differences in variance across groups (mean RTs can be found in the online supplemental tables). We first focused on the "same" versus "mirror" conditions only. The Group (3) × Category (3) × Condition (2) ANOVA revealed main effects of group, $F(2, 56) = 7.2$, $p = .002$; category, $F(2, 112) = 45.7$, $p < .0001$; and condition, $F(1, 56) = 95.0$, $p < .0001$. More importantly, these main effects were qualified by the following

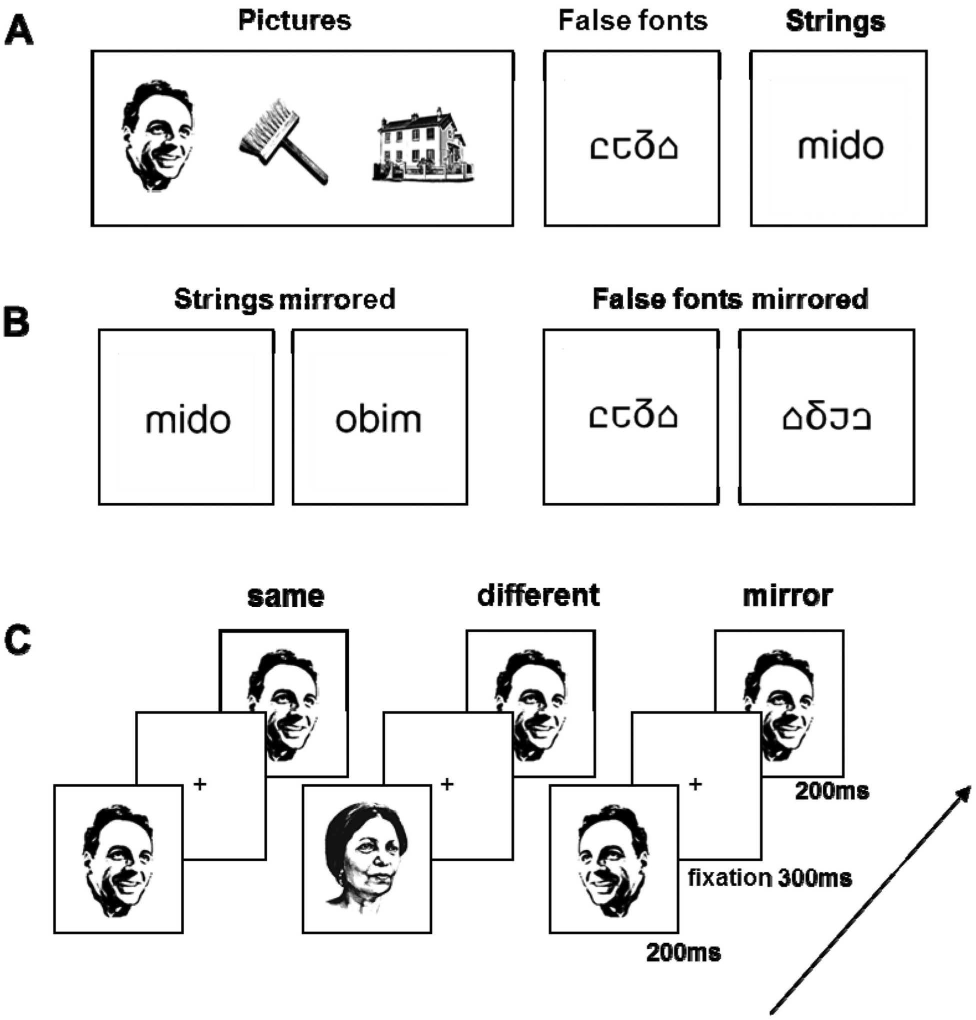

*Figure 1.* Experimental design. A: Examples of the five stimulus categories used: pictures (faces, tools, and houses), false fonts, and letter strings. B: Examples of mirror-reversed stimuli for strings and false fonts. C: On each trial, a pair of stimuli was presented for 200 ms each, separated by a 300-ms interval. The relationship between the first and second stimuli could be exactly the same ("same"), a different exemplar within the category ("different"), or a mirror reflection of the same exemplar ("mirror"). Subjects were asked to judge if the stimuli were the same or different exemplars by pressing the right or left button, respectively. They were carefully instructed to respond "same" to mirror pairs (identity judgment regardless of orientation).

interactions: Group × Category, $F(4, 112) = 3.9, p = .005$; Group × Condition, $F(2, 56) = 13.9, p < .0001$; Category × Condition, $F(2, 112) = 6.7, p = .002$; and the triple interaction, $F(4, 112) = 3.2, p < .02$ (see Figure 2A).

Pairwise group comparisons (*t* tests, Holm-Bonferroni-corrected for multiple comparisons) showed that illiterates were overall slower in their responses than ex-illiterates ($p = .001$) or literates ($p = .01$), presumably due to a lack of familiarity with testing situations and time pressure, as previously reported in similar populations (see Experiment 2B in Kolinsky et al., 2011; Ventura, Kolinsky, Querido, Fernandes, & Morais, 2007). No difference in response time was found between literates and ex-illiterates ($p = .20$), suggesting that late reading acquisition effectively allowed ex-illiterates to match the overall speed of literates for visual decisions. Interestingly however, when comparing IAs with literates, the significant Category × Group interaction, $F(2, 72) = 6.7, p = .002$, showed that this between-groups difference was less pronounced for strings ($p = .19$) than for false fonts ($p = .015$) or pictures ($p = .001$). A similar tendency was present when illiterates were compared to ex-illiterates ($p = .02$ for strings, $p = .001$ for false fonts, and $p < .001$ for pictures), although the Category × Group interaction was not significant in this case, $F(2, 58) = 1.8, p = .18$.

We then turned to mirror discrimination effects. To address the main goal of our study (automatic mirror discrimination), we examined the additional cost of assigning the "same" response to mirror pairs relative to identical pairs, and how this cost varied with literacy and stimulus category. The literate group exhibited a significant delay for responding "same" to mirror relative to identical trials, with a 0.21 log-RT difference for pictures, 0.38 for false fonts, and 0.50 for strings (paired *t* test: $p < .0001$ for each;

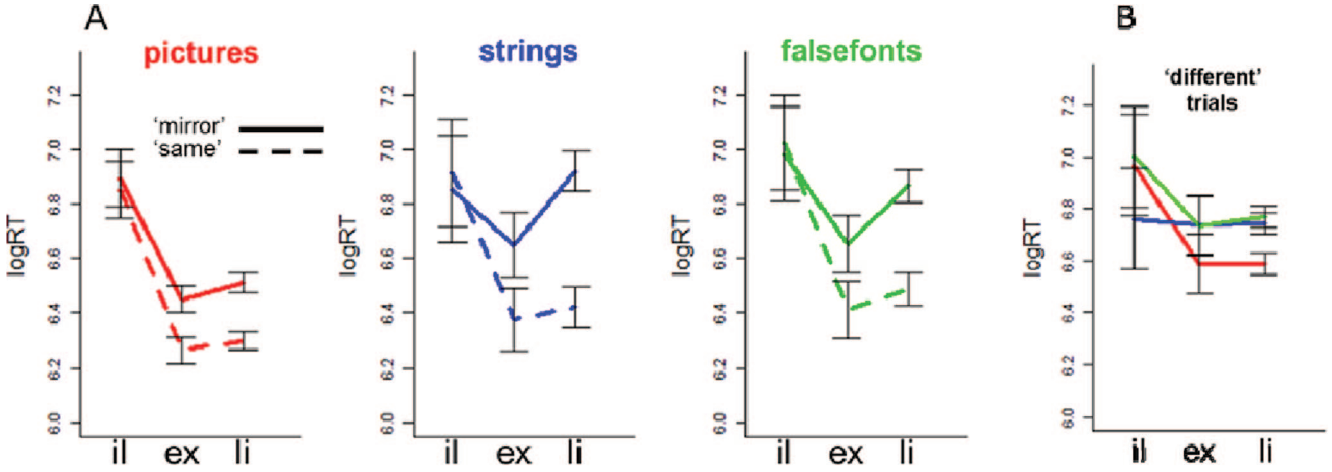

*Figure 2.* Log-transformed response times (logRTs). Response times were transformed according to a natural logarithm to correct for group differences in variance. A: "Same" trials (dashed lines) and "mirror" trials (solid line) are plotted for each literacy group and category. B: "Different" trials are plotted for each literacy group and category. il = illiterates; ex = ex-illiterates; li = literates. The same color code for categories in Panel A is used in Panel B. Error bars represent 95% within-subject confidence intervals (see Equation 3 in Masson & Loftus, 2003).

see Figure 2A). Ex-illiterates also presented an additional cost for all categories (i.e., 0.19 for pictures, 0.24 for false fonts, and 0.27 for strings stimuli; $p < .001$ for each). In clear contrast, illiterates did not exhibit any additional cost for strings, false fonts, or pictures ($p > .45$ for each).

We then tested directly for group differences in mirror cost for each category, using a normalized index: $(\text{logRT}_{\text{mirror}} - \text{logRT}_{\text{same}})/(\text{logRT}_{\text{mirror}} + \text{logRT}_{\text{same}})$. We observed main effects of group, $F(2, 56) = 14.0$, $p < .0001$, and category, $F(2, 112) = 6.4$, $p < .005$, and a significant Category × Group interaction, $F(4, 112) = 3.0$, $p < .03$, indicating that the mirror cost was greatest when the subjects were literate and the materials were written words. The literate group showed a greater mirror cost index than did illiterates in all categories ($p < .002$ for pictures, $p < .001$ for false fonts, and $p < .001$ for strings). Most importantly, ex-illiterates also showed a greater mirror cost than did illiterates for strings ($p = .04$), false fonts ($p < .02$), and pictures ($p < .01$). Overall, the results indicate that literacy, whether early or late, reduces the efficiency with which one judges two mirror images as "same."

We then analyzed the "different" trials by performing an ANOVA with literacy group and category as factors. The results showed a main effect of category, $F(2, 112) = 7.8$, $p < .001$, and no effect of group ($p = .16$) but a Category × Group interaction, $F(4, 112) = 3.6$, $p < .01$ (see Figure 2B). While literates presented significant category effects, $F(2, 54) = 21.7$, $p < .001$, with slower responses to strings and false fonts relative to pictures (respectively, $p = .03$ and $p = .01$), the other groups did not suffer a modulation of category on the speed of "different" responses ($p > .7$). This result could reflect a direct consequence of the fact that the different trials were intermixed with mirror and same trials with strings and false-fonts categories, with which the literates experienced special difficulty (see Figure 2A). Literates knew that strings and false-fonts trials were especially difficult for them, and this could have imposed an extra evaluation step in order to judge the "different" trials of these categories as different, thus selectively slowing the responses of literate subjects.

Because there was high variability in reading performance within each group, we also replicated the above analysis with a potentially more sensitive regression approach. We thus regressed each subject's mirror cost index on reading fluency scores (number of words and pseudowords read per minute; see Figure 3). For strings, the mirror cost was strongly positively correlated with reading fluency ($r^2 = 0.22$, $p = .0001$): The better readers were also those who exhibited the strongest mirror cost. Such was also the case for false fonts ($r^2 = 0.17$, $p < .001$). For pictures, there was again a small but significant correlation ($r^2 = 0.07$, $p < .03$), suggesting a partial transfer of the literacy effect on mirror discrimination to visual categories irrelevant to reading.

Interestingly, even when excluding illiterates, there was still a significant correlation between reading scores and the mirror cost for strings ($r^2 = 0.14$, $p < .005$) and false fonts ($r^2 = 0.06$, $p < .05$), though no longer significantly for pictures ($r^2 = 0.01$, $p = .5$). Thus, the effect cannot be solely imputed to a distinct strategy or poor performance in illiterates, but reflects a continuous impact of increasing reading fluency on mirror invariance for strings and false fonts. Note, however, that this analysis remains partially confounded with groups, since ex-illiterates showed on average a worse performance than did literates in our sample. No significant correlation was found when the analysis was restricted within either the ex-illiterate or literate groups, a null effect probably due to lack of power.

## Signal Detection Theory (SDT) Analysis

In order to evaluate the sensitivity and possible bias in subjects' responses, we performed a signal detection theory (SDT) analysis. Because there were three conditions (same, different, and mirror), two of which (same and mirror) had to be responded with the "same"

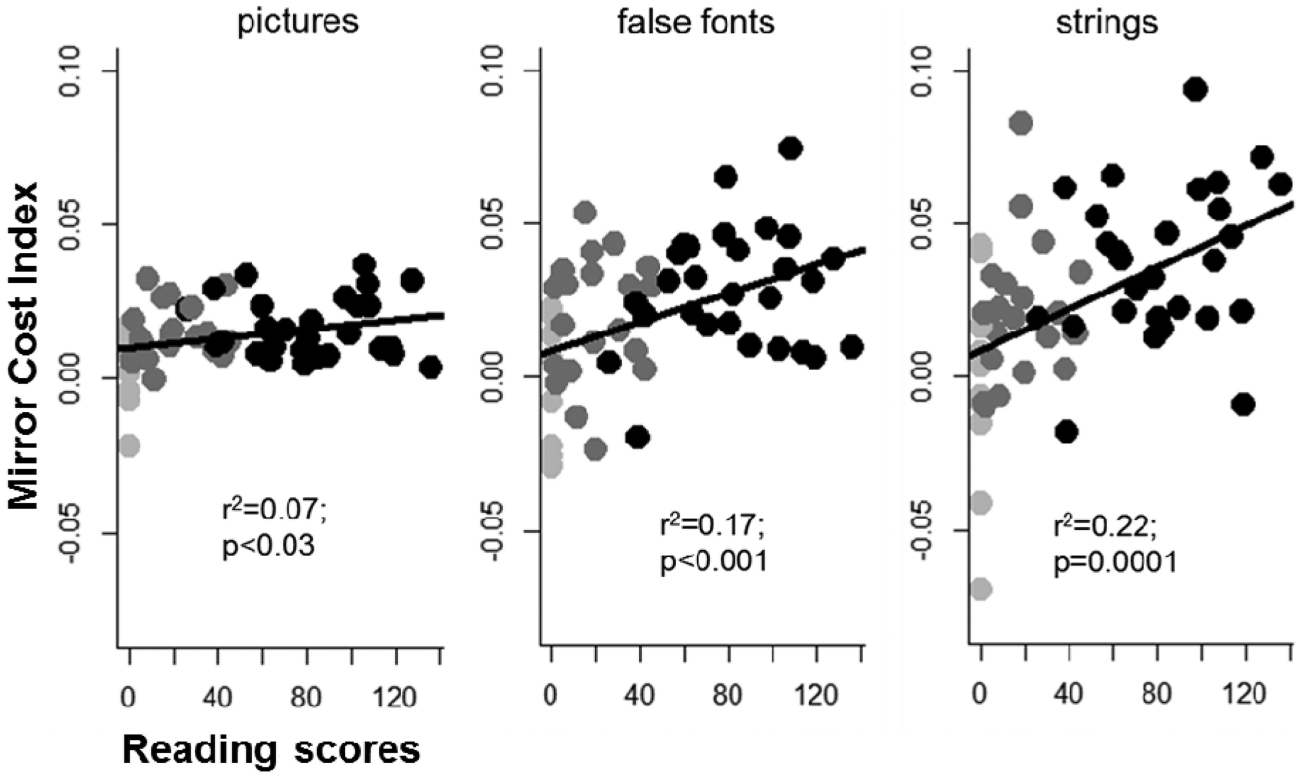

*Figure 3.* Correlations between the response time (RT) mirror cost index—that is, $(\log RT_{mirror} - \log RT_{same})/(\log RT_{mirror} + \log RT_{same})$—and reading performance (average of words and pseudowords read per minute) for each of the three categories of stimuli. Literate subjects are plotted in black, ex-illiterates in dark gray, and illiterates in light gray. Greater literacy is associated with a worse mirror cost, for strings and to a lesser extent for false fonts and for pictures.

response, we performed two successive SDT analyses. The first focused on the ability of the subjects to distinguish “mirror” versus “different” trials; we therefore coded the data in the following manner: hits = different trials answered “different” and false alarms (FAs) = mirror trials answered “different.” The second SDT analysis examined the discrimination between same versus different trials, in which hits = different trials answered “different” and FAs = same trials answered “different.” (the hit rates and false alarms can be found in separate online supplemental tables).

**Sensitivity ($d'$).** We calculated $d'$ (Z scores hits – Z scores FA) for each subject, category, and SDT matrix type to use them as the dependent variable in a 3 × 3 × 2 ANOVA declaring literacy group (illiterates, ex-illiterates, literates) as a between-subjects factor and visual category (pictures, strings, false fonts) and $d'$ type (“same” vs. “different,” “mirror” vs. “different”) as within-subject factors. The results revealed main effects of group, $F(2, 56) = 29.1$, $p < .0001$; category, $F(2, 112) = 158.6$, $p < .0001$; and $d'$ type, $F(1, 58) = 81.1$, $p < .0001$, and the following interactions: Category × Group, $F(4, 112) = 3.9$, $p = .005$, and $d'$ Type × Category, $F(2, 112) = 51.8$, $p < .0001$, and a marginal interaction of $d'$ Type × Group, $F(2, 56) = 3.0$, $p = .057$ (see Figure 4).

The main effect of $d'$ type shows that it was easier for subjects to distinguish “same” versus “different” trials than “mirror” versus “different” trials ($d' = 2.1$ and 1.3, respectively). Pairwise group comparisons ($t$ tests, Holm-Bonferroni-corrected for multiple comparisons) revealed better $d'$ for literates ($d' = 2.2$) than for either ex-illiterates ($d' = 1.6$, $p = .001$) or illiterates ($d' = 0.6$, $p < .0001$). Ex-illiterates were also significantly better than illiterates ($p < .0001$), suggesting an overall improvement of visual decisions with literacy. The main effect of category demonstrated that it was easier to judge pictures ($d' = 2.5$) than strings ($d' = 1.5$, $p < .0001$) or false fonts ($d' = 1.1$, $p < .0001$). Additionally, a higher $d'$ was found for strings relative to false fonts ($p < .02$), but this effect should be properly qualified by the Category × Group interaction: While for literates ($p < .005$) and ex-illiterates ($p < .01$) strings were easier to judge than false fonts, no difference between these two categories was found for illiterates ($p > .5$; see Figure 4), indicating that, unsurprisingly, literacy improved sensibility for letter strings.

We then turned to the crucial part of our analysis: the difference between the two $d'$ types (indexing the level of mirror invariance) and the influence of literacy on it (i.e., $d'$ Type × Group interaction). First, note that the illiterates performed better than the chance level of zero for both $d'$ types (“same” vs. “different”: $d' = 0.86$, $t = 2.8$, $p = .02$; “mirror” vs. “different”: $d' = 0.68$, $t = 3.8$, $p = .004$). This observation confirms that the illiterate group was not simply guessing but was correctly performing the task. More importantly, no significant difference between the two $d'$ types was found for illiterates, either at a global level (all categories collapsed; $p = .23$) or for each of the

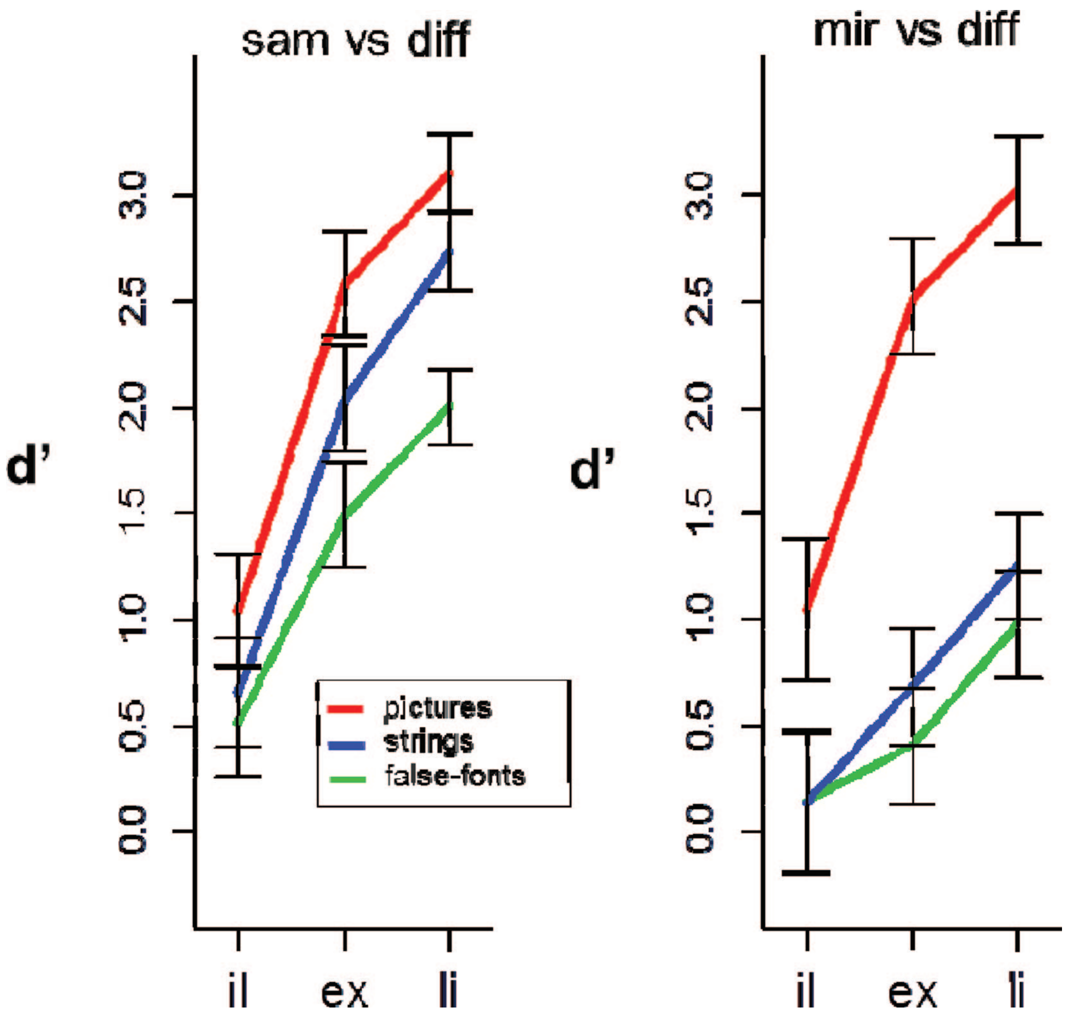

*Figure 4.* D-primes. D-primes for "same" versus "different" and "mirror" versus "different" are plotted for each literacy group and category. sam = same; diff = different; mir = mirror; il = illiterates; ex = ex-illiterates; li = literates. Error bars represent 95% within-subject confidence intervals (see Equation 3 in Masson & Loftus, 2003).

visual categories (pictures: $d' = 1.047$ vs. 1.046, $p > .9$; strings: $d' = 0.66$ vs. 0.13, $p = .22$; false fonts: $d' = 0.52$ vs. 0.14, $p = .20$). These results indicate an invariant mirror representation in illiterates (i.e., "mirror" images were not treated significantly differently from "same" images) for all visual categories. In a clear contrast, literates showed much higher $d'$ for "same" versus "different" ($d' = 2.6$) than for "mirror" versus "different" ($d' = 1.8$, $p < .0001$), reflecting a lower mirror invariance level in this group. This difference in literates $d'$ was also present for each of the three categories ($p < .005$ for each). Additionally, ex-illiterates also presented a higher $d'$ for "same" versus "different" than for "mirror" versus "different," at a global level (respectively, $d' = 2.0$ and $d' = 1.2$, $p < .0001$) and separately for strings and false fonts ($p < .005$ for each), although not for pictures ($p > .2$). The between-groups comparisons showed that literates exhibited higher $d'$ differences (i.e., reduced mirror invariance) compared to illiterates for strings ($p < .0001$) and false fonts ($p < .0001$) but only marginally for pictures ($p = .09$). Ex-illiterates showed also reduced mirror invariance compared to illiterates for strings ($p < .0001$) and false fonts ($p < .0001$) but not for pictures ($p > .4$). Finally, literates presented reduced mirror invariance compared to ex-illiterates for all categories (pictures: $p = .005$; strings: illiterates for all categories (pictures $p < .0001$; false fonts: $p = .005$).

These results suggest that the reduction in mirror invariance with literacy can be observed even when literacy is acquired late in life for visual objects related to reading (letter strings) or physically similar stimuli (false fonts). However, the transfer of this mirror discrimination to visual categories outside the reading domain (pictures) may depend on early literacy acquisition.

We then regressed the difference between the two $d'$ types ("same" vs. "different" minus "mirror" vs. "different") for each subject and category with the reading scores of the subjects. At a global level (mean of all categories), the results revealed a significant positive correlation (Pearson's $r = .26$, $p < .05$). However, this effect was driven by the strings category (strings: $r = .30$, $p = .02$; false fonts: $r = .17$, $p = .19$; pictures: $r = .06$, $p = .65$), again demonstrating an impact of literacy on the loss of mirror invariance, especially for the visual objects of reading expertise: letter strings.

**Bias.** Results of bias analysis can be found in the online supplemental materials (see also Figure S3). Briefly, this analysis showed that as literacy increased, there was an increasing bias to judge mirror-symmetrical images such as "ildo" and "obli" as different images, consistent with the above interpretation.

## Additional Control Experiment

Our crucial observation of a mirror cost on response times, even outside the reading domain (i.e., for pictures), could potentially be due to our use of a mixed design where pictorial stimuli were intermixed with letters strings, for which the normal reading strategy requires inhibiting mirror generalization. To evaluate this possibility, we performed an additional experiment with a new group of literate subjects by using exactly the same paradigm but without the strings category (with the same number of trials for the remaining categories; i.e., 120 trials). Eleven subjects (8 female, mean age = 30 years, range = 22–46) participated in this experiment conducted in Belgium. We found that even in the absence of letter strings, literates showed a significant mirror cost for pictures, one-sample $t$ test: $t(10) = 6.28$, $p < .0001$, and false fonts, $t(10) = 4.81$, $p < .001$. Crucially, while presenting the same variance level, $F(21, 55) = 1.2$, $p = .64$, the literates in this new experiment showed a mirror cost that did not differ from that of literates in our original experiment, both for pictures (respectively, 0.0162 vs. 0.0165; two-sample unpaired $t$ test: $t(37) = -0.11$, $p = .91$) and false fonts (0.032 vs. 0.028; $t(37) = 0.43$, $p = .67$). Thus, in good readers, the generalization of the mirror cost to pictures exists even in a context without letter strings. This finding suggests that reading acquisition produces a small but permanent inhibition of mirror invariance that generalizes to other visual categories even outside the context of reading.

## Discussion

Our results suggest that learning to read impacts on mirror invariance in visual recognition, not only for letter strings but also for false fonts and even slightly for pictorial stimuli, suggesting a partial transfer of this culturally learned skill outside the familiar alphabetic domain. The effect observed with letter strings in literates might be due not only to visual familiarity but also to additional interference arising from higher processing levels (e.g., phonological), because a string and its mirror image also form distinct pseudowords that are pronounced radically differently. However, no such explanation exists for false-font and pictorial stimuli, for which our same–different task specifically tapped an abstract, orientation-invariant level of visual representation. The fact that literate subjects had trouble responding "same" to mirror pairs suggests that, with literacy, the visual system loses some of its mirror invariance and automatically encodes mirrored stimuli as different. As a result, literates have to spend relatively more time scrutinizing a pair of mirror images before deciding that they are, in fact, the same.

Importantly, reduced mirror invariance was also found in ex-illiterates who had learned to read in adulthood. This indicates that the acquisition of automatic mirror discrimination is specifically due to literacy and not to schooling. It also confirms the absence of a critical period for literacy during childhood (Dehaene, Pegado, et al., 2010).

Our results confirm and extend previous findings in normal and dyslexic children (Cornell, 1985; Lachmann & van Leeuwen, 2007) and in literate adults from different cultural backgrounds and writing systems (Danziger & Pederson, 1998; Dehaene, Nakamura, et al., 2010; Kolinsky et al., 2011; Pederson, 2003). Mirror invariance is well established in the primate nervous system, both from an ontogenetic point of view (starting as early as 4 months of age in humans; Bornstein et al., 1978) and from the phylogenetic perspective, as explained earlier. Thus, it is remarkable that this capacity can be partially *unlearned* for alphabetic stimuli. Such superseding of an older evolutionary mechanism may be considered a by-product of a neuronal recycling induced by the novel cultural activity of reading (Dehaene, 2009; Dehaene & Cohen, 2007). What could be the neural mechanism of this "unlearning" process? After reading acquisition, the visual word form area (VWFA) in the left occipito-temporal cortex exhibits a loss of mirror invariance for letters and words, while still presenting it for pictures (Dehaene, Nakamura, et al., 2010; Pegado et al., 2011). One may speculate that during learning to read, this part of the visual system receives top-down inputs from other circuits that contribute to disambiguate the left–right orientation of letters. First, the motor system (including Exner's area) can provide a unique representation of the writing trajectory for each letter (e.g., *b* vs. *d;* Nakamura et al., 2012). Second, areas involved in phonological coding (including *planum temporale*) also acquire a distinct phonological correspondence for each printed letter and may influence the VWFA in a top-down manner (Dehaene, Pegado, et al., 2010; Yoncheva, Zevin, Maurer, & McCandliss, 2010).

The negative effect of literacy should be properly qualified. First, with pictures, the effect was quite small. Only the speed of mirror judgments was affected, while accuracy remained very high in literates. This result is in agreement with our previous finding of an overall preservation of mirror invariance for pictures in the fusiform gyrus using fMRI (Dehaene, Nakamura, et al., 2010; Pegado et al., 2011). The small impact of literacy on picture processing may relate to the fact that literacy transforms only a specialized subpart of the left ventral visual pathway, leaving much of the ventral picture recognition system unaffected (Dehaene, Pegado, et al., 2010). Second, although illiterates showed no mirror cost, they were overall much slower and more error-prone than literates. Thus, the literate mirror cost is only relative: On absolute scores such as RTs and percentage correct, literacy has an overall positive effect, and literacy has also been reported to improve early visual processing (Dehaene, Pegado, et al., 2010) and the ability to carry out a response-time task.

Third, there is a flip side to the illiterates' greater capacity for mirror invariance. Because illiterates literally tend to treat shapes like *p* and *q* as identical, mirror *discrimination* tasks can be very difficult for them, for both alphabetic and nonalphabetic stimuli, for instance in deciding that rightward- and leftward-pointing triangles are different (Danziger & Pederson, 1998; Dehaene, Izard, Pica, & Spelke, 2006; Kolinsky et al., 2011) and in discriminating mirror images of familiar objects like tools, furniture, or clothes (Fernandes & Kolinsky, 2013).

Overall, our study highlights how literacy acquisition selectively improves the visual discriminations that are relevant for reading. In the Latin alphabet, mirror discrimination of letters is relevant to reading, and we showed here that this discrimination becomes automatic and compulsory after reading acquisition, in parallel to the response of the VWFA (Dehaene, Nakamura, et al., 2010;

Pegado et al., 2011). In Tamil script, by contrast, there are no mirror pairs of letters like *b* and *d,* and Tamil readers seem to maintain their mirror invariance and remain poor at mirror discrimination of geometric figures (Danziger & Pederson, 1998; Pederson, 2003). Discrimination of size, case, absolute location, or spacing of letters is also irrelevant for reading, and indeed previous behavioral and brain-imaging studies have shown that the literate brain shows invariant responses for these dimensions (Dehaene, Cohen, Sigman, & Vinckier, 2005; Dehaene et al., 2001; Vinckier, Qiao, Pallier, Dehaene, & Cohen, 2011). Our current results are consistent with these studies in emphasizing the close relationship between literacy and visual discrimination, and our results point to the possibility that training in mirror shape discrimination may be useful during preliteracy instruction.

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