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Enantiomorphy Through the Looking Glass: Literacy Effects on Mirror-Image Discrimination

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To examine whether enantiomorphy (i.e., the ability to discriminate lateral mirror images) is influenced by the acquisition of a written system that incorporates mirrored letters (e.g., *b* and *d*), unschooled illiterate adults were compared with people reading the Latin alphabet, namely, both schooled literate adults and unschooled adults alphabetized in adulthood. In various sorting and same–different comparison tasks with nonlinguistic materials, illiterate participants displayed some sensitivity to enantiomorphic contrasts but performed far worse than all the other participant groups when the task required paying attention to such contrasts. The difficulties of illiterate participants were more severe with enantiomorphs than with rotations in the plane or shape contrasts. Learning a written system that incorporates enantiomorphic letters thus pushes the beginning reader to break the mirror invariance characteristic of the visual system, and this process generalizes beyond the realm of symbolic characters.

Keywords: enantiomorphy, mirror invariance, attentional and postperceptual processing, literacy effects, orientation processing

In the present study, we examined whether the acquisition of literacy in the Latin alphabet influences the ability to discriminate lateral mirror images, also called *enantiomorphs*. Mirror-image discrimination, or *enantiomorphy,* has been defined as the ability to give different, nonenantiomorphic responses to each mirror image, namely, encoding the left–right difference into some response dimension (Corballis & Beale, 1976).

Two pairs of letters in the Latin alphabet are characterized by lateral mirror symmetry (*p* vs. *q* and *b* vs. *d*), so being successful in learning to read and write in this system requires enantiomorphy either to be already present at the beginning of literacy acquisition or, alternatively, to be promoted by it.

Difficulties in differentiating and remembering lateral reflections have been reported in infants (e.g., Bornstein, 1982; Bornstein, Gross, & Wolf, 1978), children (e.g., Casey, 1984; Cronin, 1967; de Kuijer, Deregowski, & McGeorge, 2004; Gibson, 1969; Gibson, Gibson, Pick, & Osser, 1962; Rudel & Teuber, 1963; Shepp, Barrett, & Kolbet, 1987), and even adults (e.g., Butler, 1964; de Kuijer et al., 2004; Farrell, 1979; Martin & Jones, 1997; Nickerson & Adams, 1979; Rentschler & Jüttner, 2007; Sekuler & Houlihan, 1968; Standing, Conezio, & Haber, 1970; Wolff, 1971). Consistently, in adults, long-term priming (with primes and probes separated by some minutes) is unaffected by left–right reflection (e.g., Biederman & Cooper,

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1991; Fiser & Biederman, 2001; Stankiewicz, Hummel, & Cooper, 1998).

The tendency to confuse enantiomorphs, or *mirror generalization*, actually seems to have been deeply rooted by evolution into the visual system: Many nonhuman species (e.g., fishes, octopuses, rodents, and monkeys) are also confused by enantiomorphs (e.g., Sutherland, 1960; see a review, e.g., in Corballis & Beale, 1976), and neurons in the monkey's inferotemporal cortex generalize over mirror reversal (Baylis & Driver, 2001; Logothetis & Pauls, 1995; Logothetis, Pauls, & Poggio, 1995; Rollenhagen & Olson, 2000).

In fact, mirror generalization, or *invariance*, may be an adaptive mode of processing rather than a perceptual limitation. Given that many objects in the natural world remain the same under lateral reflection, it would be advantageous to represent enantiomorphs by similar visual codes, a notion also referred to as the *equivalence of left and right* (e.g., Corballis & Beale, 1976; Gross & Bornstein, 1978). In line with the view that mirror generalization is adaptive because the left–right orientation of an object is generally irrelevant to the object's identity, brain damage may selectively impair enantiomorphy, leaving object recognition spared (e.g., Davidoff & Warrington, 2001; Priftis, Rusconi, Umilta, & Zorzi, 2003; Turnbull & McCarthy, 1996).

However, people are perfectly able to distinguish between shapes such as ⌈ and ⌉. Therefore, although mirror generalization seems to characterize the visual system, we have in some ways unlearned this principle. According to Gibson (1969), the acquisition of a writing system that includes pairs of mirrored letters is critical in this process. In this case, mirror generalization interferes with correct identification, explaining why many normal children go through a phase of mirror writing during the scribbling period and early stages of learning to write (e.g., Cornell, 1985; for a review, see Schott, 2007) and why reversal errors such as reading *d* for *b* are common in beginning readers (e.g., Davidson, 1935; Gibson & Levin, 1975; Ilg & Ames, 1950).

The necessity of taking enantiomorphic contrasts into account when learning the Latin alphabet seems to push the reader to unlearn mirror generalization. As a matter of fact, the greatest improvement in discriminating between mirrored letters occurs at the beginning of reading and writing instruction, both in U.S. children between the ages of 5 1/2 and 6 1/2 years (e.g., Rudel & Teuber, 1963; see also Frith, 1971) and in Zambian children between the ages of 7 1/2 and 10 1/2 years (Serpell, 1971). This process may generalize to nonlinguistic enantiomorphs: Although these remain harder than other orientation contrasts even for adults (e.g., Corballis & Beale, 1976; Gregory & McCloskey, 2010), literate children and adults can discriminate them far better than preliterate children (e.g., Casey, 1984; Cronin, 1967; Gibson, 1969; Gibson et al., 1962; Rudel & Teuber, 1963; Serpell, 1971; Shepp et al., 1987). Unfortunately, in these studies, literate children were older than preliterate ones, as were the more skilled compared with the less skilled readers. This confound led to the view that enantiomorphy, although modulated by learning, would mainly depend on neural maturation (e.g., Corballis & Beale, 1976; Orton, 1937).[1]

Nonetheless, the proposal made by Gibson (1969) leads to another prediction: Bornstein et al. (1978) proposed that "nonliterate adults or even adults literate in languages devoid of orthographic mirror images would show greater mirror-image confusion than literates in a Western orthography" (p. 112). Danziger and Pederson (1998) reported data that are consistent with this forecast. The participants were submitted to a part-verification task adapted from Gottschaldt (1926) by Palmer (1977) and later used by Kolinsky, Morais, Content, and Cary (1987) with unschooled adults (see also Kolinsky, Morais, & Brito-Mendes, 1990). In contrast to these studies, participants had to reject both clear nonparts (e.g., a square instead of a triangle) and mirrored parts. Testing 10 different language communities around the world, Danziger and Pederson showed that readers of the Tamil syllabary, a system devoid of enantiomorphs, were as poor as illiterate individuals at rejecting mirrored parts. They suggested that the difference between the Tamil literate individuals and the literate individuals of the other communities reflected the fact that enantiomorphic contrasts are used to different degrees in their respective scripts. Consistent with this theory, Pederson (2003) found that Tamil monoliterate individuals were poorer at rejecting mirror parts than biliterate individuals who also knew the Latin alphabet. Although the scale of literacy was highly correlated with degree of education in these samples, literacy per se accounted for a significant part of the variance.

Still, the reported evidence for the role played by learning a written system that includes enantiomorphs is not fully demonstrative. First, the whole system of spatial organization and description varies largely across cultures. Therefore, people may encode spatial relationships in radically different ways across languages and cultures. For example, as suggested by Levinson and Brown (1994), the absence of terms referring to left–right contrasts in their language may explain why Tenejapan speakers of the Mayan language Tzeltal (in southern Mexico) also performed poorly in the task designed by Danziger and Pederson (1998). Second, the effect may be general, encompassing other orientation contrasts or even other visual characteristics, depending, for example, on the visual complexity of the written system. Third, in Danziger and Pederson's study, the inclusion of trials with a clear nonpart could have lowered the performance of the less educated participants by making them focus on shape rather than on orientation. Therefore, we do not know whether poor results would also be found if participants were pushed to focus their attention exclusively on orientation contrasts.

The fact that people have to discriminate between enantiomorphs only under particular conditions—for most of us, while learning to read in the Latin alphabet in order to deal efficiently with the difference between *d* and *b* and between *p* and *q*—warrants systematic examination of the hypothesis that

[1] On the basis of the hypothesis first proposed by Enrst Mach (1897) in the 19th century, these views argue that it is the bilateral symmetry of the brain and body of the perceiver that underlies mirror-image confusion. According to Orton (1937), the representation of an asymmetric stimulus in one hemisphere is a lateral mirror image of its representation in the other hemisphere, and this dual representation somehow leads to the confusion of enantiomorphs. Corballis and Beale (1976), acknowledging the fact that an asymmetric stimulus does not produce enantiomorphic patterns of activation in the visual brain areas, attributed the problem to mirror reversing through inter-hemispheric transfer of the representations. Under both hypotheses, successful enantiomorphy would depend on the development of asymmetry in the organism, such as hemisphere dominance or handedness (see a critical review in Gross & Bornstein, 1978).

enantiomorphy is a special case of image discrimination and that literacy acquisition in the Latin alphabet enhances it.

In the present study, we compared illiterate, ex-illiterate, and literate adults, all native speakers of Portuguese (in each experiment, the participants were either all Portuguese or all Brazilian). The following characteristics held true for participants in all experiments and are therefore indicated here once and for all. The illiterate participants and the ex-illiterate participants had never attended school in childhood, for socioeconomic reasons, with the exception of a few participants (always fewer than 20% of the participants in the sample) who had attended school irregularly for a few months. Notably, this did not occur more often in any of the ex-illiterate samples than in the corresponding illiterate samples. No illiterate participant was able to read simple words—most were unable to sign their own name. The ex-illiterate participants learned to read and write in special alphabetization classes for adults, but otherwise the socioeconomic origin and the educational level of the participants of these two groups were similar. All ex-illiterate participants had obtained or were about to obtain the certificate delivered at the end of the alphabetization classes, usually after 2 years of class attendance (a diploma officially considered equivalent to a Grade 4 reading level). Most of these participants began alphabetization classes under pressure from their environment (e.g., when enrolled in the army or because their employer insisted on it). However, because they still read at a quite rudimentary level, most continued to lead the same lives after these classes, remaining on a low income. Like illiterate people, they were working as farm workers, shoemakers, masons, or maids with the others being retired or unemployed.

These characteristics of the ex-illiterate samples allowed us to verify whether a relatively small amount of practice in learning to read and write was enough to trigger enantiomorphy, even if literacy learning took place in adulthood. Although ex-illiterate individuals read at a rudimentary level, they were expected to perform better than illiterate individuals in tasks requiring enantiomorphy. The comparison between these two unschooled groups offers a more stringent test of the hypothesis of an impact of literacy than the comparison between unschooled illiterate individuals and schooled literate individuals. Indeed, a difference in cognitive performance between the latter groups may reflect educational, sociocultural, or even health disparities, aside from the absence versus presence of literacy (see discussions in Kolinsky, 1999; Morais & Kolinsky, 2001, 2005).

We expected, in turn, that ex-illiterate individuals would be less efficient than people who went to school in childhood, were skilled readers, and were trained in other learning domains. Indeed, enantiomorphy is likely to be acquired or reinforced during a child's education through drawing objects and graphs, geometry lessons, and recognition of geographic representations, for example. Moreover, other symbolic systems beyond the alphabet are acquired at school, and they may be relevant to enantiomorphy. This may be the case for formal mathematics, in which $<$ and $>$ have different meanings (Walsh, 1996). Moreover, the observation of similar performances in the two literate groups together with a large inferiority of illiterate individuals would offer evidence for the bolder hypothesis that literacy acquisition in the Latin alphabet is, at least among the school activities, the most important factor enhancing enantiomorphy.

We expected to find that people literate in the Latin alphabet had not merely developed the ability to discriminate between mirrored letters but that they were able to generalize this ability to other materials. We tested this idea with nonlinguistic stimuli, which are obviously more adequate than letters or words for this purpose. Indeed, in addition to the fact that literate individuals are, by definition, more familiar with written forms than illiterate individuals, written forms are an exception to the principle of mirror invariance. Their discrimination requires a representational system that follows rules that are distinct from those of the more general system of visual form identification, including number identification (e.g., Friedmann, Dotan, & Rahamim, 2010; Polk & Farah, 1998). These distinct rules may include enantiomorphy, as suggested by the following facts. In an identity-based same–different comparison task in which participants had to respond *same* to both physically identical and mirror images, Dehaene et al. (2010) observed that, relative to physically identical images, participants were much slower to respond *same* to mirror images of written scripts than to mirror images of nonlinguistic objects (e.g., tools and faces). Congruent results were observed when participants had to judge whether a target was larger or smaller in real life than a standard computer screen, when each target was preceded by either the same or a different prime that appeared either in the same orientation or mirrored. Size judgments were accelerated by mirrored primes much more for pictures than for words. In addition, with this task, functional magnetic resonance imaging activations showed that mirrored primes induced repetition suppression (i.e., decreased activation due to processing subsequent stimuli with identical attributes) only for nonlinguistic objects and not for words. This was the case even if the visual word form area, a major site of learning during reading acquisition (Cohen & Dehaene, 2004; Cohen et al., 2000), did show repetition suppression when primes and targets were in the same orientation. The distinct status of linguistic versus nonlinguistic objects has also been demonstrated by the fact that brain-damaged individuals unable to discriminate nonlinguistic enantiomorphs are still able to discriminate mirrored letters (Davidoff & Warrington, 2001; Priftis et al., 2003), pseudowords (Vinckier et al., 2006), and words (Turnbull & McCarthy, 1996).

To qualify illiterate individuals' predicted difficulties with enantiomorphy, we thus used nonlinguistic stimuli in all experiments, either geometric figures (Experiments 1–5A) or bloblike figures (Experiment 5B). We exploited sorting tasks in Experiments 1 and 2, contrasting mirror-image sorting with sorting of other visual dimensions, such as size, shape, or color. In Experiments 3 and 4, we verified that illiterate individuals would also experience difficulties in same–different comparison tasks in which mirrored geometric figures had to be considered different. In Experiments 5A and 5B, we checked whether these difficulties concern enantiomorphy specifically or encompass other orientation contrasts. To this end, we compared enantiomorphs to nonenantiomorphic plane rotations in both experiments. Furthermore, in Experiment 5B, we examined whether literacy impacts the discrimination of other visual contrasts that may also sustain graphemic distinctions, as is the case of tiny shape differences. In both Experiments 5A and 5B, we also checked that the results did not stem from variability in general cognitive skills.

Experiment 1: Sorting on Orientation or Size and Comparison With Sorting on Color or Shape

In this experiment, we tested the idea that the irrelevance of lateral mirror-image contrasts for illiterate adults would often lead them to disregard these contrasts, particularly when stimuli present other variations. To this end, we compared illiterate individuals to ex-illiterate individuals and schooled literate individuals in sorting tasks of the type designed by Garner (1974).

Such tasks present two interesting features. First, by including conditions in which the task remains formally the same but varies in difficulty according to whether irrelevant variations must be filtered out, these tasks enable us to distinguish attentional difficulties from more basic discrimination troubles. Consider the material used here (presented in Figure 1). Stimuli varied according to the size of the circles and the orientation of their printed diameter. On each trial, participants were presented with one circle and were required to classify it according to a preset sorting criterion, or *target dimension*. When this was orientation, participants had to decide whether the diameter was tilted to the left or to the right from the vertical. In the baseline, standard condition, only orientation varied: Circle sizes were similar across trials, with the diameter tilted either left or right. In the other two conditions, the irrelevant dimension, here size, also varied across trials. These variations were either *redundant*, that is, perfectly correlated with the orientation variations (e.g., circles were always smaller when diameter was tilted left and always larger when it was tilted right), or *orthogonal* to the variations of orientation (for both large and small circles, the diameter could be tilted left or right). It is thus only in the orthogonal condition that participants had to filter out the irrelevant size variations to correctly sort the stimuli on the basis of orientation. Poor performance in this condition would thus reflect difficulties at paying attention to the target dimension (e.g., Thibaut & Gelaes, 2002) rather than more basic discrimination difficulties with this dimension, which would be revealed in the standard condition. The second interesting feature of this task design is that in the redundant and orthogonal conditions, it enables one to compare orientation and size sorting of the very same material, given that only the sorting criterion varied depending on instructions.

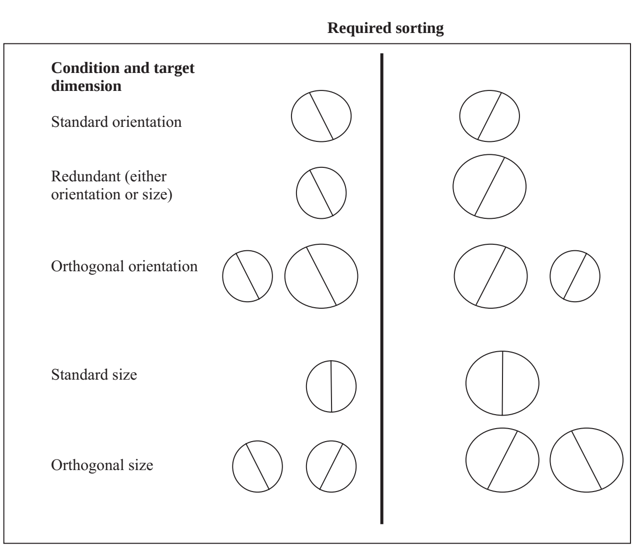

Figure 1. Illustration of the stimuli and of the several experimental conditions used in Experiment 1 in the test of sorting on orientation or size.

According to our hypothesis, compared with ex-illiterate individuals and schooled literate individuals, illiterate individuals' difficulties would be observed mainly with orientation (less with size) and mainly when the task required attending to orientation while size also varied, as was the case in the orthogonal condition. Indeed, if illiterate individuals' difficulties were due to a lack of attention to orientation contrasts, these would be reduced in the standard condition, because presenting them with stimuli varying only by orientation would favor attention to these contrasts and hence would boost their performance. Thus, we predicted a Group × Dimension × Conditions interaction.[2]

The illiterate individuals' difficulties in sorting on orientation could stem either from unfamiliarity with the task and resulting problems in understanding the task requirements if they were first tested on this dimension or, on the contrary, from a difficulty with shifting their focus of attention if they began the test by sorting on size. To check that neither of these effects could account for the illiterate individuals' difficulties, we counterbalanced the order of these two sorting dimensions between participants and analyzed the effect of this variable. In addition, we verified whether training on an easier material would help illiterate individuals on orientation sorting. To this end, we also presented them with a material varying in color and shape and counterbalanced order of materials between participants (either orientation and size first or color and shape first).

With both materials, the task was presented as a card game. Having been given a pile of 32 cards, the participant had to sort the cards manually into two piles on the table, one on the left and one on the right, according to the target dimension. This procedure was used because most illiterate individuals are unfamiliar with computers, with some being afraid to touch the keyboard. However, as a consequence, sorting times were somewhat imprecise because time was measured (per pile of 32 cards) with a chronometer that was controlled manually by the experimenter. Moreover, we know from earlier research that illiterate people have difficulties at speeded responses (e.g., Morais & Kolinsky, 2002; Ventura, Kolinsky, Querido, Fernandes, & Morais, 2007), which they are not used to. Hence, although instructions emphasized both speed and accuracy,

[2] Because we predicted that illiterate individuals would display a huge performance difference between the two sorting dimensions when one of these was orientation, in none of the sorting experiments did we systematically compare the patterns of dimensional interaction between groups. Indeed, these patterns are known to depend on the relative discriminability of the dimensions (e.g., Garner, 1974; Garner & Felfoldy, 1970): If one dimension is more salient than the other, the former is processed more rapidly (which is observable by comparing performance in the standard conditions), providing more opportunity for it to interfere on the processing of the latter (Garner & Felfoldy, 1970; but see Ben-Artzi & Marks, 1995). A difference of discriminability may also impact the *redundancy gain*, namely, the benefit afforded by correlated variations on the nontarget dimension: Participants may rely on the more salient, easier, dimension to perform the task (a strategy that Garner, 1974, called *selective serial processing*), hence displaying an asymmetric redundancy gain (Ashby & Maddox, 1994).

in this experiment (as in most of the present experiments), we considered accuracy (average raw error rate per pile of 32 cards) as the main dependent measure. Nonetheless, we always checked that there was no speed–accuracy trade-off.

Method

Participants. The 24 illiterate individuals (16 women, eight men; ages 16–77 years, average age = 49 years) who were presented with the sorting task on both the orientation and size and the color and shape materials were from the Alentejo and Lisbon regions of Portugal. Of these, half (eight women, four men; ages 20–57 years, average age = 47.9 years) were presented with the orientation and size materials first and with the color and shape materials later. The others (eight women, four men; ages 16–77 years, average age = 50.5 years) were presented with the materials in the reversed order. The ex-illiterate individuals and the schooled literate individuals were presented with only the orientation and size material. The 12 ex-illiterate individuals (11 women, one man; ages 22–67 years, average age = 51 years) were from the Ribatejo and Lisbon regions of Portugal. There were 12 schooled literate individuals (seven women, five men; ages 30–72 years, average age = 54 years). All had a superior degree, and six were attending courses at the Senior Citizens' University of Lisbon.

Materials. The orientation and size materials were inspired by the ones Garner and Felfody (1970) used with university students. The stimuli were circles appearing with their printed diameter (see Figure 1). They varied in size (2.6 vs. 2.2 cm in diameter for large vs. small circles, respectively) and orientation of the tilted diameter (tilted 20° left or right from the vertical). Three conditions were used for each dimension. In the standard condition, there were only two types of cards in the original pile. When participants had to sort according to size, the orientation of the diameter was kept constant within a pile: Both small and large circles appeared with a vertical diameter. For sorting regarding orientation of the diameter, size was kept constant (2.4-cm diameter). In the redundant condition, for both orientation and size sorting, the diameter of the large circle was tilted 20° to the right, whereas the diameter of the small circle was tilted 20° to the left. In the orthogonal condition, the four stimuli were used within a pile, and it was only the sorting criterion (size or orientation) that varied according to instructions.

The materials used in the test on color and shape included circles (1.8-cm diameter) and squares (1.6-cm side), which were either red or green. In the standard condition, both stimuli were squares when sorting on color, and both were red when sorting on shape. In the redundant condition, for both shape and color sorting, stimuli were red circles and green squares. In the orthogonal condition, the four stimuli were used within a pile.

For both sets of materials, each stimulus was centered on a white 6.2 × 10 cm plastic card. Within each set of materials, there were three piles of 32 cards (stimuli) for each combination of dimension and condition. Within a pile, cards were presented in random order. Because within each set of materials there were three conditions per dimension, there were nine piles in total, corresponding to sorting on a specific dimension. These nine piles were blocked, with half of the participants starting sorting on size and the others starting sorting on orientation. Within each dimension, order of the standard, redundant, and orthogonal conditions was also counterbalanced between participants. There were thus 12 different testing orders by group. For illiterate individuals, order of the materials (color and shape first or size and orientation first) was also counterbalanced between participants.

Procedure. Instructions were given before each sorting pile. They emphasized both speed and accuracy and were illustrated by examples that remained in front of the participants (on the top of the left–right positions where the response cards were to be placed) the whole time they sorted on a dimension. When sorting for the first time on a specific dimension, participants could choose the attribution of responses to the left and right sides (e.g., for size, small circles on the left and large ones on the right or the reverse); this attribution was maintained for that dimension throughout all conditions.

Participants were presented with a pile of cards that were upside down. Participants were then instructed to turn the pile over and begin sorting when told to do so by the experimenter. The experimenter started the chronometer at this time. The chronometer was stopped when the last card of the pile was put on the table, which allowed sorting times to be registered with an accuracy of roughly 0.1 s. The experimenter also noted errors. Testing lasted for about 45 min per type of material.

Results

Comparison of illiterate individuals, ex-illiterate individuals, and schooled literate individuals on orientation and size. Performance of the 12 illiterate participants who sorted by orientation and size first was compared with performance of the ex-illiterate and schooled literate participants, who were presented with only this material. Figure 2A shows the error rates in percentages, and Figure 2B provides a more detailed view of the distribution of these scores in each group for orientation sorting in the standard and orthogonal conditions. Indeed, as already illustrated by the large standard deviations depicted in Figure 2A, illiterate individuals and, to a lesser extent, ex-illiterate individuals displayed highly variable results in these two conditions. Hence, the distributions do not present homogeneous variances across groups, and some are skewed. For these reasons, we checked that nonparametric tests (Kruskal–Wallis one-way analysis of variance [ANOVA] plus post hoc Mann–Whitney tests) led to results that were similar to the parametric ANOVAs and *t* tests. Because this was the case for the present experiment as for all others, only the latter are presented.

The ANOVA on error rates included group and sorting order of the dimensions (orientation vs. size first) as between-participants variables and included sorting dimension (size vs. orientation) as well as condition (standard, redundant, orthogonal) as within-participants variables. This ANOVA showed significant effects of group, $F(2, 30) = 5.11$, $p = .01$, and of dimension, $F(1, 30) = 20.13$, $p < .0001$, as well as a significant interaction between these two variables, $F(2, 30) = 4.67$, $p < .025$. Groups differed from each other for sorting on orientation, $F(2, 30) = 4.95$, $p < .025$, but not for sorting on size, $F < 1$.

The three-way Group × Dimension × Condition interaction was also significant, $F(4, 60) = 4.15$, $p = .005$. This interaction reflects the fact that the Group × Condition interaction was significant for orientation, $F(4, 60) = 4.62$, $p < .005$, but not for size, $F < 1$. For orientation, the group effect was significant in

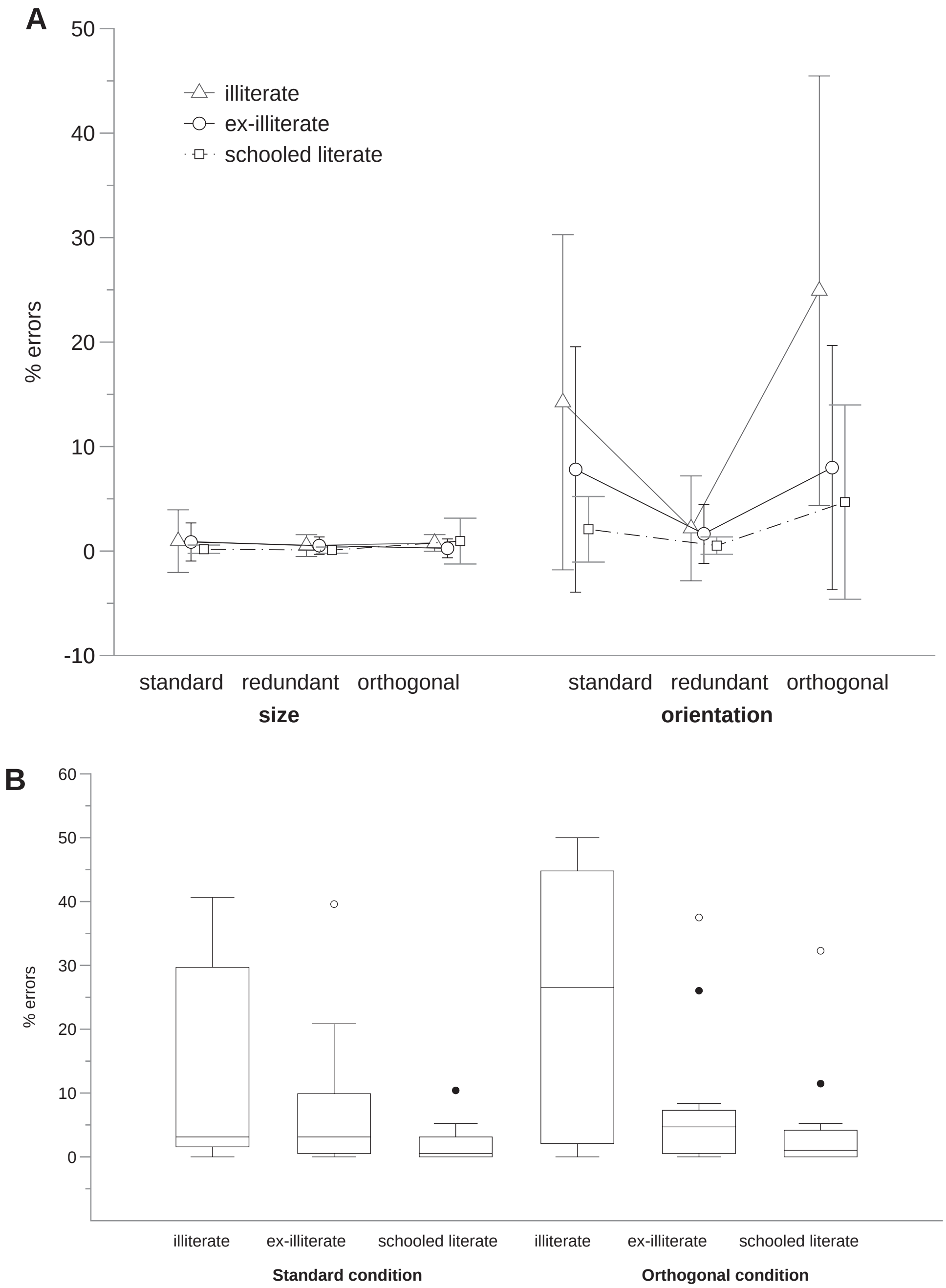

Figure 2. A: Average error rates (in percentages) observed in Experiment 1 for the 12 illiterate individuals tested first with the orientation and size materials, the ex-illiterate individuals, and the schooled literate individuals, shown separately for each condition and dimension. Errors bars represent standard deviations. B: Summary of the distribution of error scores (in percentages) for orientation sorting in the standard and orthogonal conditions, in the 12 illiterate individuals tested first with the orientation and size material, the ex-illiterate individuals, and the schooled literate individuals tested in Experiment 1. The bottom and top of the boxes represent the 25th and 75th percentile (lower and upper quartiles), respectively, with a line at the median. Errors bars represent the lowest and highest scores within 1.5 interquartile range. The circles indicate the outliers, with open circles specifying extreme outliers (interquartile range larger than 3).

both the standard and orthogonal conditions, $F(2, 42) = 4.46$, $p < .05$; $F(2, 42) = 5.89$, $p < .01$, respectively. In the standard condition, Scheffé's tests showed that illiterate individuals made more errors than schooled literate individuals, $p < .025$, but not more errors than ex-illiterate individuals, $p > .10$ (the latter did not differ from schooled literate individuals either, $p > .10$). In the orthogonal condition, illiterate individuals made more errors than both ex-illiterate individuals, $p = .05$, and schooled literate individuals, $p < .025$, whereas the two literate groups did not differ from each other, $p > .10$. Nevertheless, univariate *t* tests showed that illiterate individuals performed above chance (50%) in both the standard and orthogonal conditions, $t(11) = 7.72$, $p < .0001$; $t(11) = 4.23$, $p < .001$, respectively.

No significant group difference was observed in the redundant condition, $F(2, 42) = 1.45$, $p > .10$, probably because both illiterate individuals and ex-illiterate individuals took advantage of the correlated variations of size, performing better in the redundant than in the standard condition, $F(1, 20) = 5.51$, $p < .025$; $F(1, 20) = 4.73$, $p < .05$, respectively. This was not the case of the schooled literate individuals, who, contrary to the two other groups, showed no significant condition effect, $F(2, 20) = 1.96$, $p > .10$; for illiterate individuals, $F(2, 20) = 11.58$, $p < .0005$; for ex-illiterate individuals, $F(2, 20) = 3.24$, $p = .06$. As is often the case when dimensions vary in discriminability (e.g., Garner, 1974), illiterate individuals and ex-illiterate individuals may have used the correlated variations of the easier dimension (here, size) strategically while ignoring orientation. Consistent with this idea is the fact that both groups performed at the same level in this redundant condition as they did when they sorted according to size in the standard condition (cf. Shepp et al., 1987), both Fs < 1.

It is worth noting that sorting order of the dimensions neither affected performance nor interacted with any other factor, all Fs $<$ 1. Even participants who sorted the stimuli on orientation before sorting them on size sorted orientation rather poorly in the standard and especially in the orthogonal conditions, with about 13% and 22% average error rates, respectively.

Illiterate individuals' performance on orientation and size versus color and shape. The next analysis was mainly aimed at verifying whether sorting initially on presumably easier dimensions, namely, color and shape, could have helped illiterate individuals to sort on orientation. To this end, we performed an ANOVA on the error rates displayed by the 24 illiterate individuals presented with both materials (see average scores in Table 1). It included condition, dimension, and materials (size and orientation vs. color and shape) as within-participants variables, plus order of materials (sorting first on either size and orientation or on color and shape) as a between-participants variable.[3]

This analysis showed a significant effect of materials, $F(1, 22) = 29.32$, $p < .0001$: Sorting was far easier on the color and shape materials than on the orientation and size materials. Indeed, as shown in Table 1, on color and shape the 24 illiterate individuals presented less than 1% error in all conditions. Materials interacted with both condition, $F(2, 44) = 17.31$, $p < .0001$, and dimension, $F(1, 22) = 31.61$, $p < .0001$. The three-way Materials $\times$ Condition $\times$ Dimension interaction was also significant, $F(2, 44) = 16.17$, $p < .0001$. As a matter of fact, orientation led to more errors than the three other dimensions (size, color, and shape) in the standard condition, $F(1, 44) = 62.02$; $F(1, 44) = 68.34$; $F(1, 44) = 66.73$, respectively, all ps $< .0001$, as well as in the orthogonal condition, $F(1, 44) = 146.28$; $F(1, 44) = 154.58$; $F(1, 44) = 149.25$, respectively, all ps $< .0001$. On the contrary, size was sorted as accurately as color and shape in all conditions, all Fs < 1.

Most important, order of materials did not affect performance and did not interact with any other variable, all Fs ≤ 1. This held true when we restricted our analysis to the orientation and size material, all Fs < 1. Thus, even illiterate individuals who had the opportunity to practice sorting on the easier material before sorting on orientation and size experienced serious problems for orientation sorting.

Discussion

The present results show that illiterate adults had difficulties sorting on the basis of lateral mirror differences, particularly when other aspects of the stimuli—here size—varied across trials. In this case, illiterate individuals performed far worse than both literate groups and performed more poorly than when sorting the same stimuli on size. Indeed, for size sorting, all groups made virtually no errors, whatever the condition. Although this ceiling effect prevents us from concluding that illiterate individuals differed from literate individuals only for orientation and not for size, the important point is that in the orthogonal condition they differed much more dramatically on orientation.

Preliminary experience with an easier dimension (size) or material (varying by color and shape) did not help the illiterate individuals when sorting on the basis of the orientation contrasts. This suggests that their difficulties were unlikely to have stemmed from unfamiliarity with the task and resulting problems in understanding the task requirements. Their poor results also cannot reflect difficulty with shifting the focus of attention. As a matter of fact, even those who sorted on orientation before sorting on size displayed orientation-sorting difficulty, with much poorer scores than the two literate groups.

However, the fact that the illiterate individuals' inferiority in orientation sorting was much weaker in the standard than in the orthogonal condition suggests that illiterate individuals display some sensitivity to enantiomorphic contrasts when they are not distracted by variations in other aspects of the stimuli.

In the next experiment, we checked whether this result pattern would be replicated with stimuli contrasting orientation with shape rather than size.

Experiments 2A and 2B: Sorting on Orientation or Shape

The results of the former sorting experiment suggest that illiterate people struggle to pay attention to lateral mirror orientation differences between geometric figures when other aspects of the stimuli vary. However, because the illiterate participants' results were highly variable, especially in the orthogonal condition, and because only one specific orientation contrast was used in Experiment 1, for the sake of generalization, we here tested the same idea on fresh participants, using a similar task but different materials.

This test involved more complex geometric figures, which participants had to sort according to either the orientation of their diagonal (tilted 45° left or right from the vertical) or overall shape (triangles or arrows; see Figure 3). Given that former studies using similar materials have shown a huge discriminability advantage for shape compared with orientation even in schooled literate individ-

[3] Because order of the sorting dimensions did not affect performance and did not interact with any other variable in the ANOVAs run on each of the materials separately, all Fs < 1, this variable was not considered in the present analysis.

Table 1
Average Error Rates of Illiterate Participants in Experiment 1 With the Size and Orientation Materials as Well as the Color and Shape Materials, as a Function of Order of Test

	Size conditions			Orientation conditions		
Test order	Standard	Redundant	Orthogonal	Standard	Redundant	Orthogonal
First	0.95 (2.99)	0.52 (1.04)	0.78 (0.79)	14.24 (16.04)	2.17 (5.02)	24.91 (20.56)
Second	0.61 (1.51)	2.43 (4.45)	1.39 (3.31)	15.19 (13.20)	3.38 (4.74)	20.05 (20.36)
Average	0.78 (2.32)	1.48 (3.31)	1.08 (2.37)	14.71 (14.37)	2.78 (4.81)	22.48 (20.16)
	Color conditions			**Shape conditions**		
Test order	Standard	Redundant	Orthogonal	Standard	Redundant	Orthogonal
First	0.17 (0.60)	0.17 (0.40)	0.17 (0.60)	0.17 (0.60)	0.52 (1.21)	0.17 (0.40)
Second	0.00 (0.00)	0.00 (0.00)	0.78 (2.71)	0.35 (1.20)	0.00 (0.00)	1.56 (5.10)
average	0.09 (0.43)	0.09 (0.29)	0.48 (1.94)	0.26 (0.93)	0.26 (0.88)	0.87 (3.61)

Note. Average error rates are in percentages. Standard deviations are in parentheses.

uals (Pomerantz, 1983; Wandmacher & Arend, 1985), we tried to reduce this advantage as much as possible by lowering the visual saliency of the shape through the use of dotted rather than plain angle lines.

In Experiment 2A, illiterate, ex-illiterate, and schooled literate participants had to sort piles of cards manually, as in Experiment 1. The aim of Experiment 2B was to make sure that similar results would be obtained with illiterate individuals tested in a more controlled situation, in which response times (RTs) were also examined. The study by Pederson (2003), which examined enantiomorphy in illiterate individuals by using computer presentations and RTs, found results coherent with those observed with the card presentation used by Danziger and Pederson (1998). Nevertheless, Pederson tested only four fully illiterate participants; the others were either Tamil monoliterate individuals or biliterate individuals. Hence, both the task (part verification) and the samples were quite different from the ones studied here. This is why, in Experiment 2B, we presented another group of illiterate individuals with the same materials as in Experiment 2A but in a computerized setting in which stimuli presentation and data recording were controlled through a computer. This required, however, considerable familiarization of the illiterate individuals with the experimental situation, through presentation of a sorting task of animal drawings.

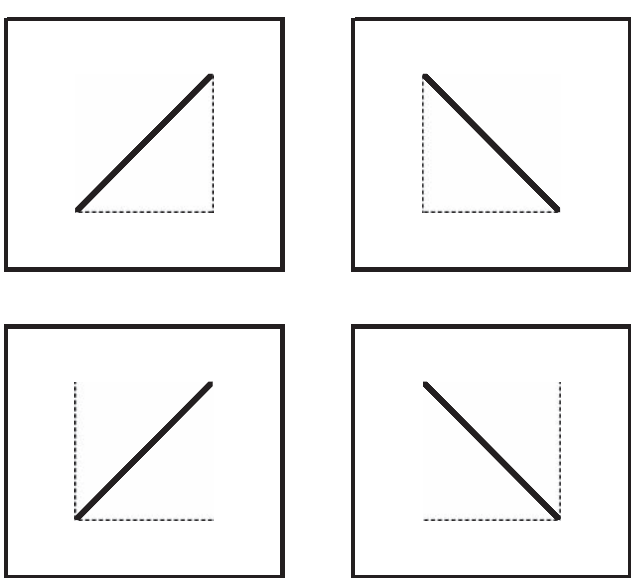

Figure 3. Illustration of the stimuli used in Experiment 2.

Moreover, Experiments 2A and 2B were run in different countries—Portugal and Brazil, respectively—in an attempt to widen our findings across different cultures, mostly South European rural versus South American urban.

Method

Participants. Experiment 2A was run in Portugal. There were 12 illiterate individuals (nine women, three men; ages 33–68 years, average age = 55 years) and two groups of literate individuals matched in age to the illiterate individuals. One included 12 ex-illiterate individuals (10 women, two men; ages 25–72 years, average age = 53 years), and the other included 12 schooled literate individuals (10 women, two men; ages 34–70 years, average age = 56 years). Illiterate individuals were from Beira Baixa, a mostly rural region of Portugal remote from Lisbon. The ex-illiterate individuals had been living in Lisbon for several years. They had moved to Lisbon from rural or industrial suburbs to find work. All schooled literate individuals had at least a secondary school degree, and most had either a university or a superior school degree.

Experiment 2B was run at Universidade Federal de Santa Catarina, in Florianópolis, the capital city of the State of Santa Catarina, in southern Brazil. It examined 12 illiterate individuals (seven women, five men; ages 25–51 years, average age = 37 years) living in the town. They were paid for their participation.

Materials and procedure.

Experiment 2A. The materials, adapted from Pomerantz (1983), were four different geometric figures (see Figure 3). Each side of the figure was 1.5 cm. They were drawn in black ink and centered on a white 5.6 × 9.5 cm plastic card.

For each sorting dimension (orientation of the diagonal or overall shape), each participant was presented with one redundant condition, one orthogonal condition, and two standard conditions. In the latter, when participants had to sort on shape, the diagonals of the triangles and arrows were both tilted either 45° to the left or 45° to the right of the vertical. When participants had to sort on orientation, stimuli were either only triangles or only arrows. Two different redundant materials were used: In one, the diagonal of the triangles was tilted 45° to the left and the diagonal of the arrows was tilted 45° to the right of the vertical; in the other, the opposite assignment was used. Assignment of these two redundant materials to dimensions (shape vs. orientation sorting) was counterbalanced between participants. In the orthogonal condition, all four stimuli were used.[4]

As in Experiment 1, for each condition there were three piles of 32 randomly mixed cards, and all the piles (and hence conditions) corresponding to sorting according to a specific dimension were blocked, with order of the dimensions and conditions counterbalanced between participants. Procedure was also the same. The whole session lasted for about one hour.

Experiment 2B. Materials and procedure were the same as in Experiment 2A, except for the following: Stimuli were presented on a computer screen, and participants had to provide their answers by pushing on one of two external response keys with their left or right hand. Before the main test, illiterate individuals were presented with a familiarization task that required sorting animal drawings according to their identity. In a series of eight trials, they had to push on the left key with the left hand when the stimulus was a dragonfly and had to push on the right key with the right hand when the stimulus was a butterfly. In another series of eight trials, participants had to answer on the left when the stimulus was a snake and on the right when the stimulus was an alligator. This familiarization task was introduced through four examples. Participants then began the first series of eight familiarization trials. On each trial, verbal feedback was provided. At the end of the first series, performance was evaluated. The few participants who performed poorly (≤50% correct) in this first series were presented with an additional series of eight familiarization trials. All these participants performed almost perfectly in this second series, except one illiterate individual who was dropped from the study because he pushed alternatively on the right and left response keys without taking the stimulus identity into account. The whole session lasted for about 45 min.

Results

Experiment 2A: Manual sorting of piles of cards. The ANOVA on error rates included group (illiterate individuals, ex-illiterate individuals, literate individuals) and sorting order of the dimensions (first shape or first orientation) as between-participants variables and included dimension (shape vs. orientation) and condition (standard, redundant, orthogonal) as within-participants variables.

Sorting order of the two dimensions did not affect performance, $F(1, 30) = 1.97$, $p > .10$, and did not interact with any other effect, all *p*s > .10. There were significant effects of group, $F(2, 30) = 29.58$, $p < .0001$, and of dimension, $F(1, 30) = 35.19$, $p < .0001$, as well as a significant interaction between these two variables, $F(2, 30) = 22.51$, $p < .0001$. As illustrated in Figure 4, which presents the average error rates in percentages, illiterate individuals did not differ significantly from other participants when sorting on shape, $F(2, 30) = 2.73$, $p = .08$ (Scheffé's tests: all *p*s > .10) but presented far more errors when sorting on orientation, $F(2, 30) = 26.37$, $p < .0001$.

The three-way Group × Dimension × Condition interaction, illustrated in Figure 4, was also significant, $F(4, 60) = 15.81$, $p < .0001$. Indeed, for orientation, condition interacted with group, $F(4, 60) = 18.27$, $p < .0001$, which was not the case for shape, $F(4, 60) = 2.32$, $p = .07$ (Scheffé's tests: all *p*s > .10). For orientation, groups differed from each other in both the standard and orthogonal conditions, $F(2, 30) = 4.04$, $p < .05$, and $F(2, 30) = 34.24$, $p < .0001$, respectively. Scheffé's tests showed that when sorting on orientation, in the standard condition illiterate individuals made more errors than schooled literate individuals, $p < .05$, but only tended to differ from ex-illiterate individuals, $p = .09$ (the latter did not differ from schooled literate individuals, $p > .10$). In the orthogonal condition, although both unschooled groups presented more errors than the schooled literate individuals, both *p*s < .0001 according to Scheffé's tests, illiterate individuals clearly presented the worst performance, significantly inferior to the performance of ex-illiterate individuals, $p < .0001$. Nevertheless, as in Experiment 1, univariate *t* tests showed that illiterate individuals displayed above-chance (50%) performance in both the standard and orthogonal conditions, $t(11) = 8.44$, $p < .0001$, and $t(11) = 2.77$, $p < .01$, respectively.

Also as in Experiment 1, no group effect was observed in the redundant condition, $F < 1$. Both illiterate individuals and ex-illiterate individuals performed better in this condition compared with the standard one, $F(1, 20) = 3.99$, $p = .059$, and $F(1, 20) = 5.7$, $p < .05$, which was not the case of the schooled literate individuals, who, contrary to the two other groups, displayed no significant condition effect, $F(2, 20) = 2.7$, $p = .09$; for illiterate individuals, $F(2, 20) = 20.33$, $p < .0001$; for ex-illiterate individuals, $F(2, 20) = 3.97$, $p < .05$. As in the former experiment, illiterate individuals and ex-illiterate individuals seem to have strategically relied on the easier (here, shape) variations, given that they performed at the same level in this redundant condition as when they sorted shape in the standard condition, both *F*s < 1.

Experiment 2B: Sorting on a computer. As in Experiment 2A, the effect of dimension was significant but only on error rates, $F(1, 10) = 5.7$, $p < .05$; for RTs, $F(1, 10) = 2.21$, $p > .10$. The effect of condition was significant on both error rates and RTs, $F(2, 20) = 22.19$, $p < .0001$, and $F(2, 20) = 10.13$, $p < .001$, respectively. The Dimension × Condition interaction was significant in both analyses too, $F(2, 20) = 6.22$, $p < .01$, and $F(2, 20) = 4.17$, $p < .05$, respectively.

As illustrated in Figures 5A and 5B, these interactions reflect the fact that illiterate individuals presented many more errors and were much slower in the orthogonal condition when sorting

[4] Orthogonality of the stimuli was not perfect: The position of the angle between the horizontal and vertical segments relative to the diagonal was correlated with the relevant dimension of sorting in the standard conditions and varied orthogonally to that dimension in the orthogonal conditions. However, because this held true for both dimensions, it should not impede their comparison.

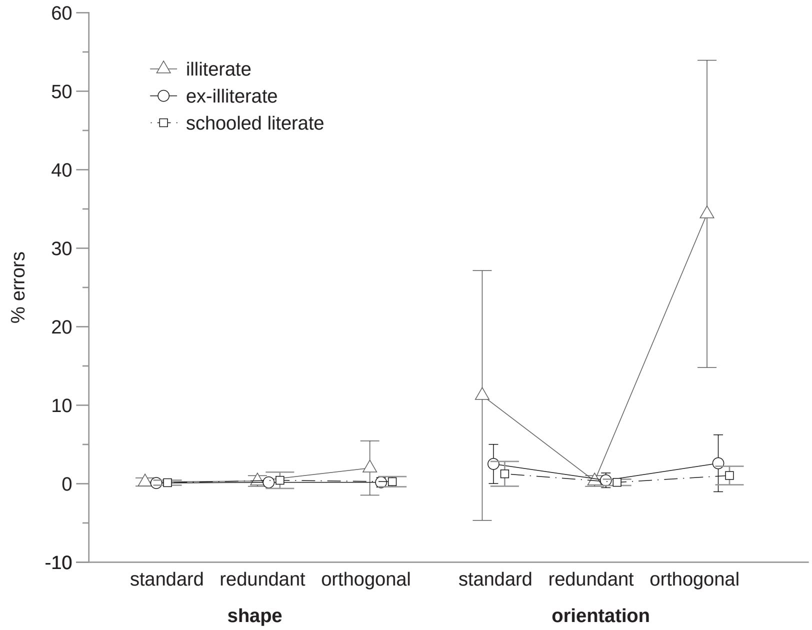

Figure 4. Average error rates (in percentages) observed in the sorting task used in Experiment 2A, shown separately for each group, condition, and dimension. Errors bars represent standard deviations.

on orientation than when sorting on shape, $F(1, 20) = 18.94$, $p < .001$, and $F(1, 20) = 9.87$, $p < .01$, respectively. This was not the case in the standard and redundant conditions, all Fs $<$ 1. Univariate t tests showed that performance was actually better than chance (50%) in the two latter conditions, $t(11) = 29.88$, $p < .0001$, and $t(11) = 14.05$, both ps $< .0001$, but that performance only approached significance in the orthogonal condition, $t(11) = 1.67$, $p = .06$.

Also as in Experiment 2A, sorting order of the two dimensions did not affect performance and did not interact with any other variable, all Fs ≤ 1 in both the error and RT analyses.

Cross-experiment ANOVAs on error rates or on RTs took setting (computerized vs. card sorting) as a between-participants variable in addition to order of the dimensions and in addition to the condition and dimension within-participants variables. Compared with the illiterate individuals who sorted cards, the present participants tended to make slightly more errors overall (12.04 vs. 8.09%, respectively), $F(1, 20) = 3.22$, $p = .09$, probably because they performed more rapidly, $F(1, 20) = 25.98$, $p < .0001$, with about 594 ms per stimulus versus 1,344 ms per stimulus in Experiment 2A. More important, setting did not interact significantly with any other variable in either the error or the RT analyses, all ps $> .10$.

Discussion

Although Experiments 2A and 2B used shape rather than size as the irrelevant dimension, these experiments offer data consistent with those of Experiment 1 in showing illiterate individuals' trouble with enantiomorphs. Illiterate individuals were again much poorer than literate participants in sorting mirror images when an irrelevant dimension varied across trials. In this orthogonal condition, they presented far more errors (about 34%)—not only than schooled literate individuals but also than ex-illiterate individuals, who never presented more than 3% errors, whatever the orientation-sorting condition. Illiterate individuals were also worse at sorting the orientation of the stimuli than at sorting their shape in the orthogonal condition. Experiment 2B confirmed illiterate individuals' difficulties with enantiomorphs in a more controlled, computerized setting.

Nevertheless, as in Experiment 1, illiterate individuals were sensitive to enantiomorphic contrasts. In the standard condition, they correctly sorted mirrored stimuli, with only about 11% errors in Experiment 2A and 4% errors in Experiment 2B. Literacy thus seems to mainly impact on enantiomorphy by enhancing attention to task-relevant mirror-image contrasts.

Also in accordance with our observations for size in Experiment 1, the illiterate individuals' good sorting performance for shape, as well as the fact that sorting order of the dimensions did not affect performance, suggests that they are unlikely to suffer from general problems in understanding the task requirements or shifting their focus of attention. As was the case in Experiment 1 for size sorting, the fact that all groups sorted shape almost perfectly, whatever the condition, prevents one from drawing the conclusion that illiterate individuals did not differ from literate individuals when sorting on shape. However, again, in the orthogonal condition, they differed much more dramatically on orientation sorting.

In short, both these results and those of Experiment 1 show that illiterate adults have difficulties sorting mirrored geometric figures, particularly when other aspects of the stimuli vary. They also clearly show that these difficulties are largely linked to literacy and not merely to level of education. This is consistent with the notion that the need to take mirror-image contrasts

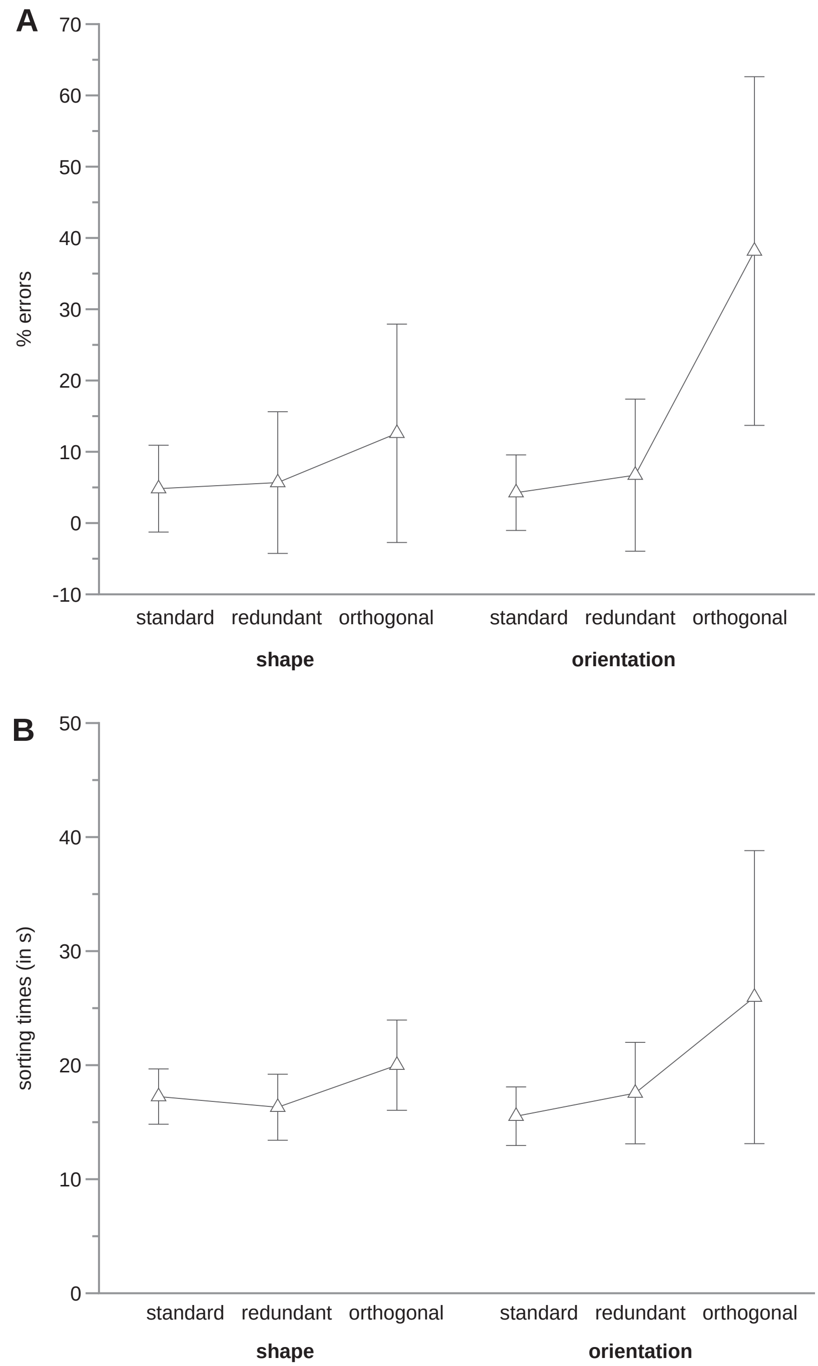

Figure 5. A: Average error rates (in percentages) observed for illiterate individuals in the sorting task used in Experiment 2B, shown separately for each condition and dimension. Errors bars represent standard deviations. B: Average sorting times (in seconds) observed for illiterate individuals in the sorting task used in Experiment 2B, shown separately for each condition and dimension. Errors bars represent standard deviations.

into account when learning the Latin alphabet enhances enantiomorphy. It is worth noting that these difficulties were observed whatever the irrelevant variations (size in Experiment 1, shape in Experiments 2A and 2B), population (Portuguese in Experiments 1 and 2A, Brazilian in Experiment 2B), and experimental setting (card sorting in Experiments 1 and 2A, computerized test in Experiment 2B).

To further generalize our results, the following experiments examined whether illiterate individuals would present similar difficulties in same–different comparison tasks.

Experiment 3: Same–Different Comparison of Sequentially Presented Enantiomorphs

The illiterate individuals' difficulties in processing enantiomorphs, as observed in the sorting tasks used so far, concerned mainly the orthogonal condition; that is, the difficulties occurred when there were cross-trial irrelevant variations on another dimension of the stimuli, either size (about 25% of errors in Experiment 1) or shape (more than 30% of errors in Experiments 2A and 2B). In the standard condition, when only orientation varied, illiterate individuals obtained, on average, less than 15% errors with the 20° mirror-image contrast used in Experiment 1 and less than 8% errors with the 45° mirror-image contrast used in Experiments 2A and 2B. Illiterate people thus present some sensitivity to enantiomorphic contrasts but seem unable to pay attention to them efficiently when the task requires it.

In this experiment, we checked whether similar difficulties would be observed in a simpler same–different comparison situation, a task that has been used in several developmental (e.g., Casey, 1984; Cronin, 1967) and neuropsychological (e.g., Davidoff & Warrington 2001; Valtonen, Dilks, & McCloskey, 2008) studies on enantiomorphy. We thus presented illiterate, ex-illiterate, and literate adults with such a situation, using geometric figures that were designed by Casey (1984) to test enantiomorphy in preliterate children.

Participants were required to pay attention only to the orientation difference between the first (S1) and second (S2) stimulus of the pair of geometric figures presented on each trial (see Figure 6). Given that different figures were used across trials, we predicted that illiterate individuals would hardly pay attention to the mirror-image contrasts: Their performance should be worse than that of literate participants, because they are particularly poor at responding *different* on enantiomorphic trials.

Because same–different tasks are prone to response biases, this prediction was examined through analyses of the signal detection theory d' scores adapted for same–different tasks (Macmillan & Creelman, 2005). Indeed, these scores take both hits (correct *different* responses to enantiomorphs) and false alarms (incorrect *different* responses to same-stimulus trials) into account, thereby providing a better, bias-free estimation of the participants' ability to discriminate the situation in which the two stimuli differ by their orientation from the situation in which they are actually the same. Illiterate individuals should present lower d' scores than either the schooled literate or the ex-illiterate participants—a poorer performance that would be mainly driven by a large number of misses (i.e., of *same* responses on enantiomorphic trials).

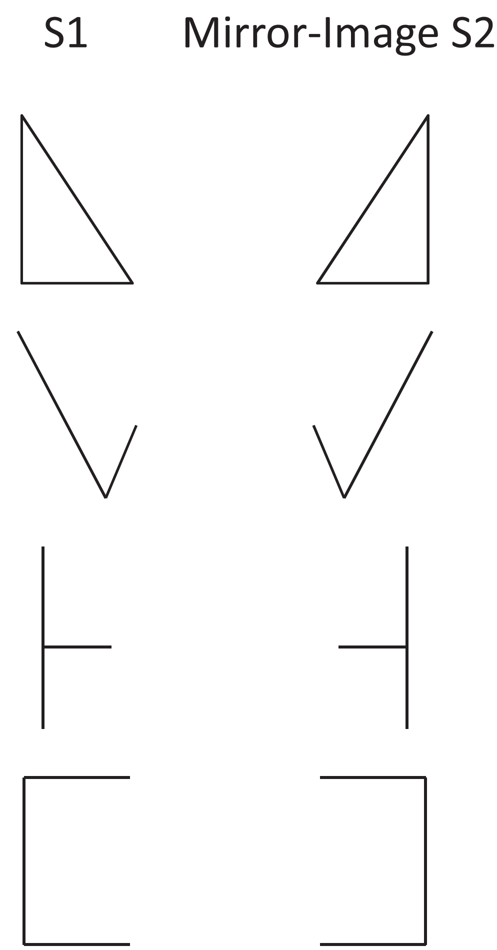

Figure 6. Enantiomorphic figures used in the same–different comparison task of Experiment 3. S1 = Stimulus 1; S2 = Stimulus 2.

Method

Participants. Three groups of 16 participants each were tested: illiterate individuals (13 women, three men; ages 27–74 years, average age = 52 years); ex-illiterate individuals (13 women, three men; ages 18–75 years, average age = 54 years); and schooled literate individuals (10 women, six men; ages 50–62 years, average age = 55 years). The schooled literate participants all had at least a secondary school degree. Half of the participants in each group were randomly assigned to a right-oriented S1; the others were assigned to a left-oriented S1.

Materials and procedure. The geometric figures used are presented in Figure 6. Each figure was drawn in black ink and was centered on a white 7.8 × 11.9 cm plastic card. Each S1 figure was paired five times with a replica and was also paired five times with its mirror image. All 10 trials corresponding to a specific S1 were blocked. Within each of these blocks, trials were presented pseudorandomly, with the constraint that no more than two figures in a row could lead to the same expected response. For half of the participants, S1 was oriented to the right (right-oriented S1, as in Figure 6); for the others, it was oriented to the left (left-oriented S1). An additional block with a different figure served as training.

During each trial, the experimenter presented S1 for 2 1/2 s and then hid it from the participant's view; 5 s later she showed the comparison stimulus, S2, which remained on the table until response. The task was to decide whether S1 and S2 were identical. Instructions, which emphasized accuracy and not speed of response, called attention to the fact that S1 and S2 always had the same shape and, hence, that only an exact match in all visual aspects should lead to the *same* response. The experimenter noted the participants' errors. The whole session lasted for about 20 min.

Results

Accuracy scores are presented in Table 2, together with *p* values of univariate *t* tests comparing correct responses on different-stimuli trials to chance level (50%). On these trials, only illiterate participants performed at chance.

The d' scores were calculated individually for each participant.[5] Average values are presented in Table 2, together with *p* values of univariate *t* tests comparing the d' values to zero. Figure 7 provides a more detailed view of the distribution of d' scores in each group. Although variability was high in illiterate individuals and, to a lesser extent, in ex-illiterate individuals, illiterate participants clearly differed from the other groups. This was confirmed by the fact that the ANOVA run on d' scores, taking group as a variable, led to a highly significant group effect, $F(2, 45) = 16.88$, $p < .0001$. According to Scheffé's tests, illiterate individuals displayed significantly lower d' scores than both ex-illiterate individuals, $p < .005$, and schooled literate individuals, $p < .0001$, whereas these two literate groups did not differ significantly from each other, $p > .10$. Still, illiterate individuals' d' scores were significantly higher than zero (see Table 2), showing that they had not considered the different-stimuli trials as completely equivalent to the same-stimulus ones.

In summary, illiterate participants showed some sensitivity to enantiomorphic contrasts, which led them to nonnull d' scores. This is consistent with the fact that the illiterate individuals examined in the sorting tasks obtained better-than-chance performance even for orientation sorting in the orthogonal condition (except in Experiment 2B). However, contrary to literate individuals, they clearly disregarded these orientation contrasts, performing here at chance on different-stimuli trials and obtaining significantly lower d' scores than ex-illiterate individuals and schooled literate individuals.

The next experiment assessed whether the effect of literacy was related to the presentation conditions and material used here.

Experiment 4: Same–Different Comparison of Either Simultaneously or Sequentially Presented Enantiomorphs, With More Explicit Instructions

In the previous experiments, illiterate individuals displayed poorer same–different judgments on enantiomorphs than ex-illiterate individuals and schooled literate individuals did. However, one potential source of difficulty for the illiterate individuals in Experiment 3 could be related to the memory demand of the task. Indeed, the two stimuli were presented sequentially, requiring participants to memorize S1 until S2 was presented 5 s later. Although illiterate individuals' memory limitations do not seem to be linked specifically with literacy, because ex-illiterate individuals also present such problems (see Morais & Kolinsky, 2001, 2002, 2005), in the present experiment we checked whether illiterate individuals would obtain better scores with simultaneous than with sequential presentations of S1 and S2. We therefore used both presentation modes, with order counterbalanced between participants. We also checked whether the results observed in Experiment 3 would generalize to other geometric figures, including oblique enantiomorphs (see Figure 8). In addition, the instructions regarding orientation differences used in the present experiment were much more explicit than those used in Experiment 3, with a training phase illustrating the enantiomorphic contrast.

Method

Participants. Participants were 36 illiterate individuals (24 women, 12 men; ages 19–70 years, average age = 55 years) and 12 ex-illiterate individuals (nine women, three men; ages 18–66 years, average age = 38 years).[6] Half of the participants came from the region of Porto, Portugal, and the others came from the Lisbon region. The 40 schooled literate individuals (20 women, 20 men; ages 21–70 years, average age = 53 years) had all attended school in childhood for at least 9 years, and 10 had a superior degree.

Materials and procedure. The materials were constructed on the basis of two sets of four figures each. As illustrated in Figure 8, in one set both S1 and S2 were vertical, and in the other they were tilted.

Four pairs of stimuli were constructed for each figure: S1 was either left or right oriented, and S2 was presented either in the same orientation as S1 or mirrored. Each pair was presented twice, which led to a total of 64 pairs per presentation condition: half same-stimulus pairs and half different-stimuli pairs.

Each figure was drawn in black ink centered into a black circle delimited by a circumference of 20 cm diameter, which was itself centered on a white A4 sheet of paper. Two booklets were prepared, one for the sequential and one for the simultaneous presentation condition. We constructed pairs of examples and training pairs on the same principles, using different figures.

In the sequential presentation mode, S1 was presented for 2 s, and 5 s later, S2 was presented and remained in view until response (the 5-s delay allowed for turning two white pages of the booklet). In the simultaneous presentation mode, S1 and S2 were presented side by side, and both remained in view until response.

Trials were presented in pseudorandom order, with the constraint that no more than three figures in a row shared the same orientation (left or right oriented), led to the same expected response, or were either vertical or oblique. Presentation order was the same for the two presentation modes.

Each participant was presented with both presentation modes, their order being counterbalanced between participants. The session started with four example trials (two same-stimulus and two different-stimuli pairs). Instructions were explicit regarding the relevance of orientation, emphasizing that participants should respond *same* only for pairs in which both figures were oriented toward the same side and should respond *different* when each figure was oriented toward a different side. The experimenter illustrated these verbal instructions by mimicking the orientation of the figures by hand movements. Participants were then presented with eight training trials, for which the experimenter gave feedback both verbally and with the help of a transparent plastic

[5] We calculated the d' scores, using the *differencing model* for same–different comparisons (Macmillan & Creelman, 2005). As suggested by these authors, to avoid infinite d' values, proportions of 0 and 1 were adjusted to $1/(2N)$ and $1 - 1/(2N)$, respectively, where N is the number of trials on which the proportion is based.

[6] Ex-illiterate individuals were quite heterogeneous in age: Half were much younger (three men and three women; ages 18–27 years) than the others (all women; ages 39–66 years). A separate ANOVA on error rates showed no effect of age or interaction with the other variables, all Fs < 1.

Table 2
Percentage of Correct Responses (Hits) on Different-Stimuli Trials and of False Alarms on Same-Stimulus Trials and Associated d′ Scores in Experiment 3

		Participant type		
Trial type	Score	Illiterate	Ex-Illiterate	Schooled literate
Different-stimuli trials	Hits	63.15 (39.58)	90.65* (9.81)	98.15* (3.10)
Same-stimulus trials	False alarms	13.75 (14.66)	7.81 (12.51)	1.25 (2.89)
	d′	2.79** (2.10)	4.70** (1.22)	5.68** (0.43)

Note. Standard deviations are in parentheses.
* $p < .001$. ** $p < .0001$, according to univariate *t* tests in comparison either to 50%, corresponding to chance level for correct responses on different-stimuli trials (in illiterate participantss, $p > .10$), or to 0 for *d′* scores.

sheet on which S1 was drawn. The experimenter first placed the plastic figure with S1 over S1, to show that the two figures were identical. She then placed it over S2 to illustrate either a match or a mismatch between S1 and S2. Instructions were repeated if necessary. During this training phase, S1 and S2 were presented simultaneously. Two additional training trials using sequential presentations were presented right before the sequential test. During the experimental phase, no more feedback was given; the experimenter only noted responses. The whole session lasted for about 50 min.

Results

Accuracy scores are presented separately for each presentation mode in Table 3, together with *p* values of univariate *t* tests comparing correct responses on different-stimuli trials to chance level (50%). It was only with simultaneous presentations that illiterate participants performed at chance on these trials.

The *d′* scores were calculated individually for each participant as in the previous experiment. They were calculated separately for each presentation mode and for vertical versus oblique figures.

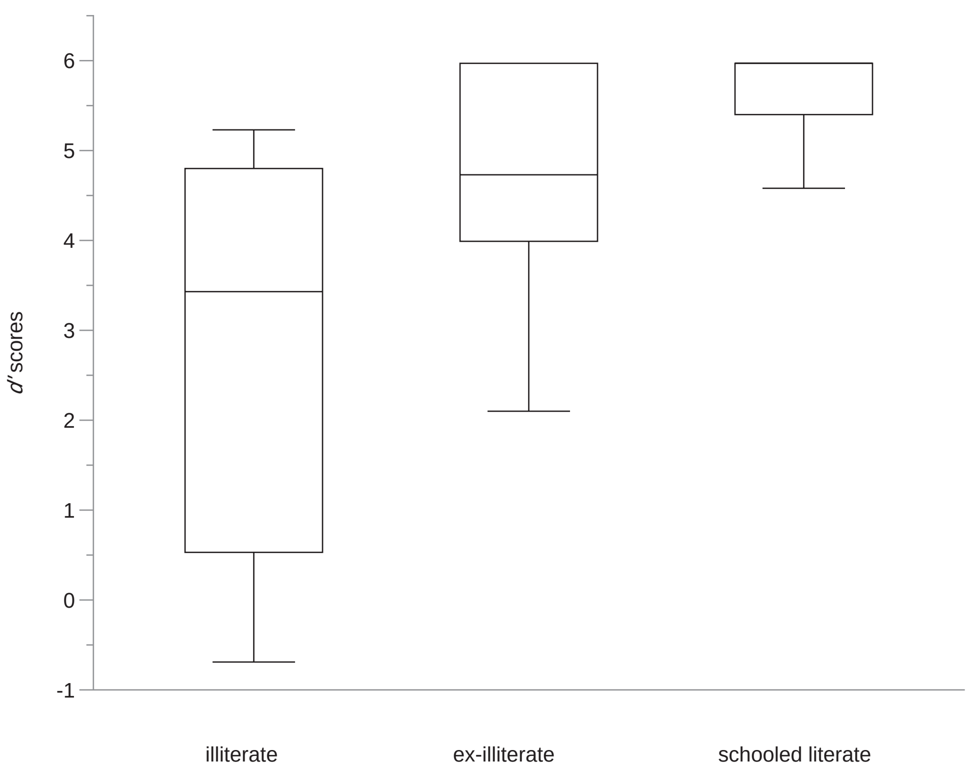

Figure 7. Summary of the distribution of *d′* scores in each group tested with the same–different comparison task in Experiment 3. The bottom and top of the boxes represent the 25th and 75th percentile (lower and upper quartiles), respectively, with a line at the median. Errors bars represent the lowest and highest scores within 1.5 interquartile range.

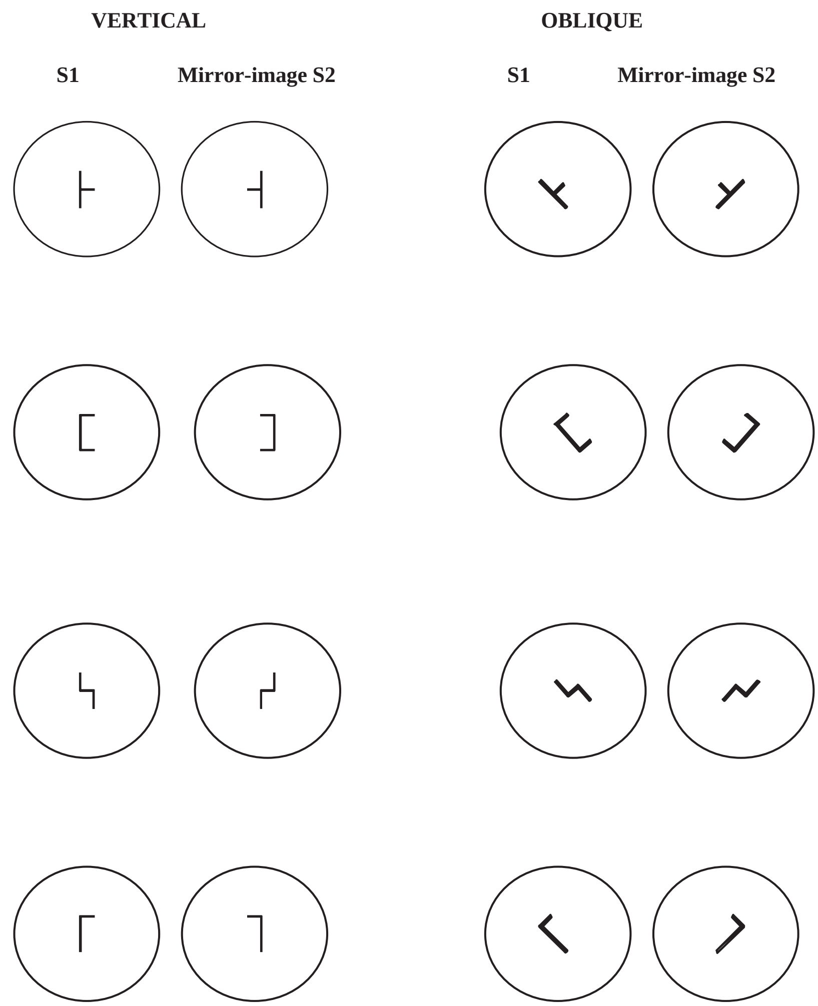

Figure 8. Enantiomorphic figures used in the same–different comparison task of Experiment 4, with vertical pairs on the left and oblique pairs on the right. S1 = Stimulus 1; S2 = Stimulus 2.

Average values of d' scores are presented in Table 3, together with p values of univariate t tests comparing these values to zero. The ANOVA on these scores included presentation mode (simultaneous vs. sequential) and figure tilt (vertical vs. oblique figures) as within-participants variables in addition to the group and order of presentation mode (simultaneous vs. sequential first) between-participants variables. Because order of presentation mode and figure tilt did not affect performance, $F < 1$, and $F(1, 85) = 1.94$, $p > .10$, respectively, and did not interact with any other variable, all ps $> .10$, Figure 9 summarizes the distribution of d' scores in each group averaged across vertical and oblique figures and over orders of presentation modes.

As illustrated in Figure 9, performance varied according to group, $F(2, 82) = 132.79$, $p < .0001$, and presentation mode, $F(1, 82) = 22.14$, $p < .0001$, and the interaction between these variables was also significant, $F(2, 82) = 10.41$, $p < .0001$. The group effect was significant for simultaneous as well as sequential presentations, $F(2, 82) = 134.21$, and $F(2, 82) = 67.57$, respectively, both ps $< .0001$. Indeed, according to Scheffé's tests, illiterate individuals displayed lower d' scores than either ex-illiterate individuals or schooled literate individuals with simultaneous presentations, both ps $< .0001$, as well as with sequential presentations, both ps $\leq .01$. With each of the two presentation modes, ex-illiterate individuals also presented lower d' scores than schooled literate individuals, both ps $<$ .0001 according to Scheffé's tests. In addition, illiterate individuals performed significantly worse with simultaneous than with sequential presentations, $F(1, 34) = 22.59$, $p < .0001$. This effect was nearly significant in ex-illiterate individuals, $F(1, 10) = 4.71$, $p = .055$, but not in schooled literate individuals, $F < 1$. Yet, even with simultaneous presentations, illiterate individuals' d' scores were significantly higher than zero (see Table 3). As in Experiment 3, they did not consider the different-stimuli trials as fully equivalent to the same-stimulus ones.

Discussion

The present results generalize those observed in Experiment 3. As in the former experiment, illiterate participants displayed

Table 3
Percentage of Correct Responses (Hits) on Different-Stimuli Trials and of False Alarms on Same-Stimulus Trials and Associated d′ Scores in Experiment 4

Figure tilt and trial type	Score	Participant type: Illiterate	Ex-Illiterate	Schooled literate
		Simultaneous presentations		
Vertical figures				
Different-stimuli trials	Hits	46.70 (25.38)	66.67 (22.03)	97.66 (4.84)
Same-stimulus trials	False alarms	11.63 (15.32)	8.33 (13.41)	1.09 (2.79)
	d′	2.07 (1.34)	3.32 (1.35)	5.48 (0.46)
Oblique figures				
Different-stimuli trials	Hits	48.61 (29.43)	71.88 (21.4)	97.50 (4.86)
Same-stimulus trials	False alarms	17.19 (20.4)	10.94 (15.79)	0.94 (2.67)
	d′	1.86 (1.53)	3.48 (1.12)	5.47 (0.45)
Average				
Different-stimuli trials	Hits	47.66 (25.63)	69.27* (17.97)	97.58** (4.03)
Same-stimulus trials	False alarms	14.41 (15.90)	9.64 (14.07)	1.02 (2.05)
	d′	1.97** (1.43)	3.40** (1.21)	5.48** (0.45)
		Sequential presentations		
Vertical figures				
Different-stimuli trials	Hits	63.89 (20.98)	76.56 (10.7)	97.50 (5.8)
Same-stimulus trials	False alarms	10.24 (13.79)	6.25 (7.54)	0.63 (1.9)
	d′	2.95 (1.14)	3.70 (0.92)	5.50 (0.45)
Oblique figures				
Different-stimuli trials	Hits	68.23 (23.16)	86.98 (11.14)	98.44 (4.19)
Same-stimulus trials	False alarms	12.33 (19.39)	7.81 (7.6)	1.25 (3.23)
	d′	3.06 (1.74)	4.28 (0.93)	5.52 (0.43)
Average				
Different-stimuli trials	Hits	66.06** (20.19)	81.77** (9.69)	97.97** (4.16)
Same-stimulus trials	False alarms	11.28 (15.73)	7.03 (6.94)	0.94 (2.15)
	d′	3.00** (1.46)	3.99** (0.95)	5.51** (0.44)

Note. Standard deviations are in parentheses.
* $p < .01$. ** $p < .0001$, according to univariate *t* tests run on the average scores observed for simultaneous versus sequential presentations. Observed performance was compared either to 50%, corresponding to chance level for correct responses on different-stimuli trials (in illiterates, $t < 1$), or to 0 for d' scores.

much poorer scores than schooled literate adults and ex-illiterate individuals in a same–different comparison task requiring enantiomorphy. This held true for both vertical and oblique enantiomorphs. The replication of the results of Experiment 3 is particularly remarkable given that the instructions used here explicitly called attention to enantiomorphic contrasts, which were clearly demonstrated during training trials. Illiterate individuals seem to disregard them, even under these conditions.

The present experiment also showed that the illiterate individuals' poor results cannot be accounted for by the memory demands of the task: They performed more poorly than ex-illiterate individuals even with simultaneous presentations of the to-be-compared stimuli. The illiterate individuals' difficulties with enantiomorphs were actually more pronounced with simultaneous than with sequential presentations. In schooled literate adults, sequential presentations have been reported to favor performance (both speed and accuracy) in speeded same–different comparisons (Egeth, 1966; Nickerson, 1967; Palmer, 1978), probably by triggering a fast holistic comparison process. On the contrary, simultaneous presentations would favor a slower process of analysis into components (Bamber, 1969; Reed, 1973). Practice enhances only simultaneous comparison performances, not sequential ones (Palmer, 1978), which suggests that the holistic process involved in the latter is relatively automatic, whereas the slower and serial process involved in simultaneous comparisons would be controlled by more flexible strategies. Thus, with regard to enantiomorphy, simultaneous presentations of the comparison stimuli may put illiterate individuals and (to a lesser extent) ex-illiterate individuals at a disadvantage because such presentations run against their dominant processing mode (see Kolinsky et al., 1987, 1990, for a demonstration of poor analytic visual skills in these two populations).

In short, the results of the same–different comparison tests used in Experiments 3 and 4 cohere with those observed in the sorting tasks. Despite some sensitivity to mirror-image contrasts reflected by significantly higher than zero d' scores, illiterate participants had difficulty paying attention to these contrasts. They often neglected the orientation differences, responding *same* on enantiomorphic trials. Hence, they presented much lower d' scores than the ex-illiterate individuals and schooled literate individuals. In the next experiments, we checked whether this holds true for orientation contrasts other than mirror images.

Experiments 5A and 5B: Comparison of Enantiomorphs, Plane Rotations, and Shape Contrasts

We have shown that illiterate individuals have much more difficulty processing enantiomorphs than literate adults, be they

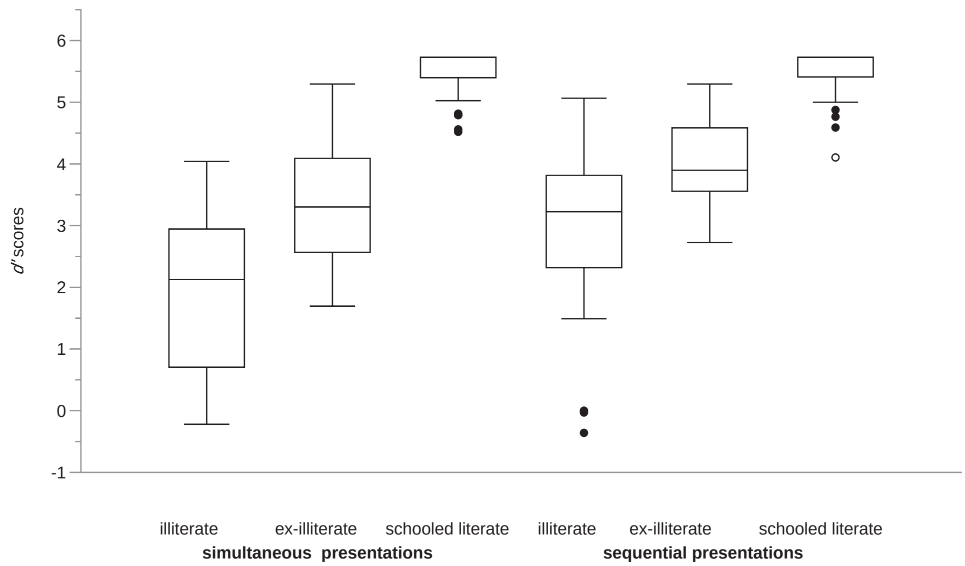

Figure 9. Summary of the distribution of *d′* scores in each group tested with the same–different comparison task in Experiment 4, separately for simultaneous and sequential presentation modes. The bottom and top of the boxes represents the 25th and 75th percentile (lower and upper quartiles), respectively, with a line at the median. Errors bars represent the lowest and highest scores within 1.5 interquartile range (*IQR*). The circles indicate the outliers, with open circles specifying extreme outliers (interquartile range larger than 3).

schooled or not. In the following two experiments, we examined whether being literate in the Latin alphabet is also crucial for processing nonenantiomorphic plane rotations. Under our hypothesis, this should not be the case. Although such rotations induce graphic differences, as when a nonitalicized *p* is confronted with italic *p* or appears more or less tilted in differently slanted handwritten characters, in the Latin alphabet these variations do not define letter identity. Contrary to mirror images, nonenantiomorphic plane rotations do not induce graphemic contrasts, explaining why letter and word recognition occur despite small tilts, being therefore characterized by broad orientation tuning (e.g., Cooper & Shepard, 1973; Koriat & Norman, 1985).

We thus predicted that literacy in this writing system would stimulate enantiomorphy much more dramatically than it might favor discrimination of plane rotations or of shape contrasts that require analytic visual skills. We also checked that other factors, such as general cognitive skills, were not responsible for illiterate individuals' poor enantiomorphy.

Experiment 5A: Discrimination of Enantiomorphs and Plane Rotations by Illiterate Individuals and Semi-Illiterate Individuals

We examined 28 unschooled adults displaying varying degrees of rudimentary alphabetization (hence called *illiterate individuals and semi-illiterate individuals*), most of them attending the first class of an alphabetization program for adults. They were presented with a same–different comparison task similar to the one of Experiment 3, except that it included both enantiomorphs and plane-rotated geometric figures. Note that for most of the figures used in our previous experiments (as well as in many other experiments), enantiomorphs could actually be transformed one into the other not only by left–right reflection, but also by rotation in the picture plane. In fact, these two spatial relationships are confounded when the figure is symmetric across one or more axes (Gregory & McCloskey, 2010). As illustrated in Figure 10, to avoid this confound, most of the figures (except for the two bottom ones) were asymmetric. We expected the participants to be better at discriminating plane rotations than enantiomorphs.

Studying participants with heterogeneous literacy levels also allowed us to examine more closely the relation between reading proficiency and enantiomorphy. Strong correlations were expected between enantiomorphy and literacy-related knowledge. This knowledge was carefully evaluated through various reading-related measures: identification of letter and graphemes, reading tests (word and pseudoword reading plus written text comprehension), and metaphonological tests that required manipulating either syllables (inversion and deletion tests) or phonemes (inversion and deletion tests plus production of acronyms).

Using the Standard Progressive Matrices (PM38; Raven, 1938), we also evaluated participants' analogical reasoning capacity. Because schooling (and to a lesser extent alphabetization) strongly affects performance in such tests (e.g., Ceci & Williams, 1997; Colom, Abad, Garcia, & Juan-Espinosa, 2002; Stelzl, Merz, Ehlers, & Remer, 1995; Verhaeghe & Kolinsky, 2006), illiterate individuals and semi-illiterate individuals were expected to present quite poor PM38 scores. However, if literacy rather than other factors, such as general cognitive skills, was responsible for their poor enantiomorphy, these participants should present much poorer scores on mirror images than on plane rotations irrespective of their achievement on the PM38.

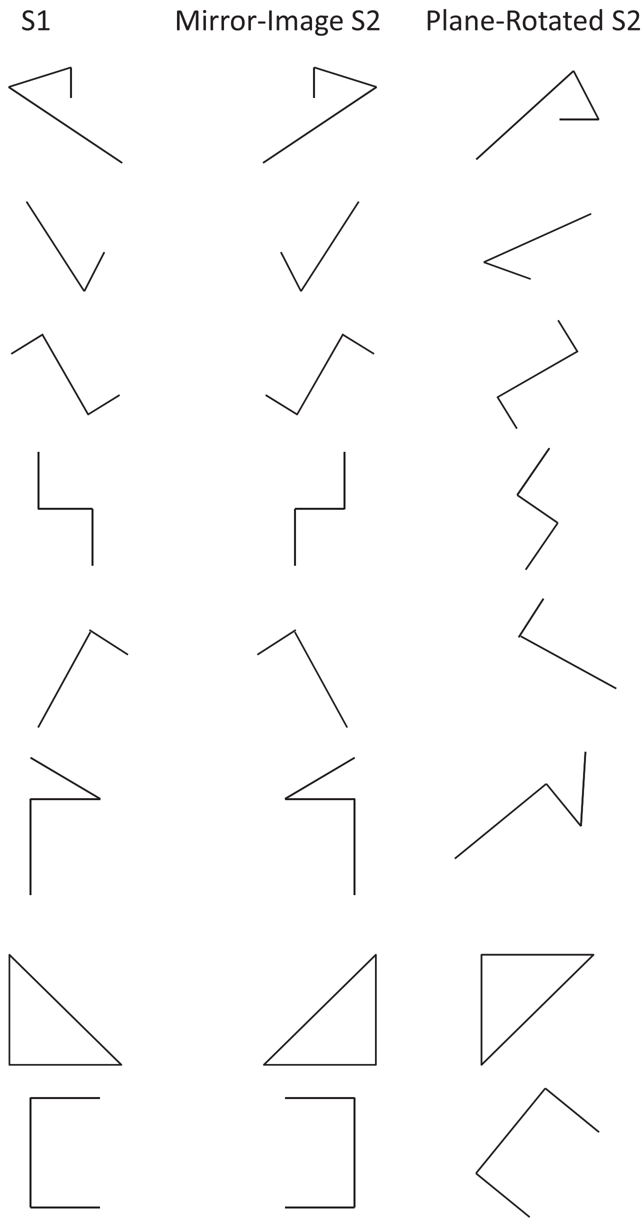

Figure 10. Enantiomorphic and plane-rotated figures used in the same–different comparison task of Experiment 5A. S1 = Stimulus 1; S2 = Stimulus 2.

Method

Participants. Among the 29 illiterate and semi-illiterate participants, 23 were attending the first class of an alphabetization course for adults in the quarter of Capoeiras, Florianópolis, Brazil. The other six were living in the same quarter. Data from one participant (much older than the others: 77 years) were discarded because she did not understand the experimental situation. Of the remaining 28 participants (15 women, 13 men; ages 17–63 years, average age = 36.6 years), 16 had never attended school. Five had attended for some months, and five had attended for a year or more (two for 18 months) but in an irregular way (average = 4.3 months). They were rewarded for participation by receiving school materials.

All participants completed the five series of the PM38 (Raven, 1938) and were screened for reading-related knowledge through the following tests: letter and grapheme identification (44 trials: 23 letters and 21 graphemes, such as *ã*, *im*, *lha*); word reading (20 trials, all with simple frequent words such as *chuva* [rain], *festa* [feast], *tigela* [bowl]); pseudoword reading (20 trials, all derived from the words presented in the former test, e.g., *cuda*, *vesta*, and *figeta*); reading comprehension (11 questions about a short 89-word text called *O tatu encabulado* [The Embarrassed Armadillo]; cf. Scliar-Cabral, 2003); and ability to manipulate syllables or phonemes orally (10 trials of syllable reversal, all consonant–vowel–consonant–vowel [CVCV]; 16 trials of syllable deletion, all CVCV; 20 trials of phoneme reversal, 5 CV, 5 VC, 10 VCV; 26 trials of phoneme deletion, 16 CVC and 10 CCV; most stimuli and responses were pseudowords in these four tests; and 16 trials of auditory acronyms, e.g., *charmosa ilha* [charming island]). As can be seen in Table 4, reading performance was highly variable but remained poor in most participants. Averaged across words and pseudowords, it was 37.77% (*SD* = 32.05), with only three participants reaching 80% correct (*Mdn* = 37.5%) and six performing between 60% and 70%.

Materials and procedure. The same–different comparison test was similar to the one used in Experiments 3 and 4 except that the presentations were only simultaneous and the eight figures were partly different. As illustrated in Figure 10, most (six) were asymmetric. For these, enantiomorphs are never equivalent to plane rotations. Two bilaterally symmetric stimuli (two bottom lines of Figure 10) were also used. Although for the latter there is always some lateral rotation in the viewing plane that is equivalent to a mirror transformation about the horizontal axis, the 90° rotations used were not equivalent to the mirror images.

Because each S1 was paired with either a mirrored or rotated S2, eight fillers were added to obtain the same number of same-stimulus and different-stimuli trials (16 each). There were three example pairs and four training ones, which used other figures and during which the experimenter illustrated the verbal instructions. As in Experiment 4, these instructions explicitly insisted on the relevance of orientation, with the experimenter explaining and illustrating by hand movements that participants should respond *same* only when both figures were oriented toward the same side and that they should respond *different* when one figure was oriented differently. Feedback was provided only during training. The reading-related tests were presented before the same–different comparison task, and the PM38 was presented afterward.

Results

Accuracy scores are presented separately for mirror images and plane rotations in Table 4, together with *p* values of univariate *t* tests comparing correct responses on different-stimuli trials to chance level (50%). As can be seen, only mirror images led to chance performance.

The *d′* scores were calculated as in the previous experiments; their average values, together with *p* values of univariate *t* tests comparing them to zero, are also presented in Table 4. Although

Table 4
Percentage of Correct Responses (Hits) on Different-Stimuli Trials and of False Alarms on Same-Stimulus Trials and Associated d′ Scores in Experiment 5A Plus Correct Scores Observed in the Reading-Related Tests as Well as in the Progressive Matrices 38

Test and trial type	Score	*M*	*SD*	Min	Max
Same–Different Comparison Test					
Different-stimuli trials, mirror images	Hits	56.03	36.30	0	100
Different-stimuli trials, plane rotations	Hits	86.16**	20.22	12.5	100
Same-stimulus trials	False alarms	9.93	17.01	0	81.25
	d′ mirror images	2.71**	1.91	−1.41	5.27
	d′ plane rotations	4.08**	1.15	1.47	5.27
Reading-related tests					
Letter and grapheme knowledge					
Letter knowledge	% correct	77.50	28.86	4.35	100
Grapheme knowledge	% correct	45.50	29.05	0	100
Average letter and grapheme knowledge	% correct	61.50	27.35	2.17	100
Reading skill					
Word reading	% correct	44.64	36.51	0	100
Pseudoword reading	% correct	30.89	28.77	0	90
Written text comprehension	% correct	43.51	39.46	0	100
Average reading score	% correct	39.68	32.68	0	95
Syllable awareness					
Syllable reversal	% correct	31.43	34.50	0	100
Syllable deletion	% correct	53.57	28.80	0	100
Average syllable awareness	% correct	42.50	28.75	0	100
Phoneme awareness					
Phoneme reversal	% correct	17.32	24.70	0	70
Phoneme deletion	% correct	32.83	38.08	0	100
Acronyms	% correct	13.17	27.39	0	87.5
Average phoneme awareness	% correct	21.11	27.71	0	85.83
Standard Progressive Matrices 38	% correct	16.91	5.12	9	29

** $p < .0001$, according to univariate *t* tests in comparison either to 50%, corresponding to chance level for correct responses on different-stimuli trials (in illiterate participants, $t < 1$), or to 0 for *d′* scores.

participants displayed *d′* scores significantly higher than zero even with mirror images, they experienced stronger difficulty and hence obtained significantly lower *d′* scores for these contrasts than for plane rotations, $t(27) = 4.99$, $p < .0001$.

We examined the correlations between the *d′* scores obtained for mirror-image or plane-rotation contrasts and the measures of letter and grapheme knowledge (on average), reading proficiency (average scores for word reading, pseudoword reading, and reading comprehension), phoneme awareness (average scores for phoneme deletion, phoneme reversal, and production of acronyms), syllable awareness (average scores for syllable deletion and reversal) and analogical reasoning (PM38), the mean values of which are presented in Table 4.

As illustrated in Table 5, the abilities to discriminate mirror images and plane rotations were highly correlated with each other, but the former seems more related to the reading-related tests than the latter. We were specifically interested in checking whether the participants' stronger difficulties for enantiomorphs compared with plane rotations are correlated with reading-related and other considered measures. Therefore, we also looked at the correlations between these measures and the difference between the *d′* scores obtained for mirror images and plane rotations. As can be seen in Table 5, these correlations were significant for the measures most related to reading proficiency, namely, performance on reading tests and phoneme awareness. Not surprisingly, letter and grapheme knowledge as well as syllable awareness, which are less

Table 5
Correlations Observed in Experiment 5A

Variable	*d′* mirror images	*d′* rotations	Difference between *d′* scores on mirror images and rotations
d′ mirror images		.65****	
Age	−.01	−.13	−.02
Schooling (months)	.02	.26	−.16
Letter and grapheme knowledge	.40*	.28	.30
Average reading score	.53****	.40*	.37*
Phoneme awareness	.59****	.44**	.40**
Syllable awareness	.51****	.55****	.25
Progressive Matrices 38	.45**	.49***	.20

* $p < .05$. ** $p < .025$. *** $p < .01$. **** $p < .005$.

strongly related to reading proficiency (Morais, Bertelson, Cary, & Alegria, 1986), correlated less with the difference on d' scores.

Finally, although both mirror-image and plane-rotation discrimination performances were significantly correlated with the PM38 score (see Table 5), illiterate individuals' analogical reasoning abilities do not seem to fully account for the stronger difficulty they present for enantiomorphs compared with plane rotations. As can be seen in Table 5, there was no significant correlation between the PM38 score and the difference between the d' scores obtained for mirror images and plane rotations. Consistently, the difference between the d' scores for mirror images and plane rotations remained significant in an analysis taking the PM38 score as covariate, $F(1, 26) = 5.79$, $p < .025$.

Discussion

The whole result pattern shows that, although enantiomorphy and plane-rotation discrimination are partly related abilities, illiterate individuals and semi-illiterate individuals have more trouble with discriminating mirror images than plane rotations, as shown by significantly lower d' scores and by the fact they did not exceed chance level on different-stimuli trials presenting enantiomorphs. In addition, correlation analyses showed that this stronger difficulty is correlated with reading-related measures (both reading proficiency itself and phoneme awareness) and not with their general reasoning abilities. The results of a covariate analysis confirmed that variability in general cognitive skills can hardly account for the participants' stronger difficulties with enantiomorphs.

The final experiment examined illiterate individuals and literate individuals, using enantiomorphs and plane rotations as well as other nonenantiomorphic contrasts.

Experiment 5B: Discrimination of Enantiomorphs, Plane Rotations and Shape Contrasts by Illiterate and Literate Participants

The present experiment had three aims. The first was to determine to what extent Latin alphabetization facilitates the processing of enantiomorphs more than that of plane rotations. As reviewed in the introductory section, enantiomorphy is known to remain difficult even for schooled literate individuals, who make more mirror reflection than plane rotation errors (e.g., Gregory & McCloskey, 2010). Nevertheless, literacy in the Latin alphabet may facilitate enantiomorphy more than the discrimination of plane rotations, as the latter do not define letter identity in this alphabet. Second, we examined whether literacy similarly facilitates attention to other visual contrasts that, as tiny shape differences, may sustain graphemic contrasts. Indeed, expert reading requires effective letter discrimination, which is not limited to mirrored letters but encompasses the ability to identify letters differing by minute but crucial visual details, such as *c* and *e* (e.g., Dehaene, 2009; Vinckier et al., 2006). Third, because the nonlinguistic materials used in the former experiments were geometric figures with rather high similarity to extant graphemes (any one of them could be imagined as a grapheme in a newly discovered writing system), in the present experiment we checked whether literacy acquisition extends enantiomorphy beyond the realm of symbolic characters and their analogs.

With these aims in mind, we compared illiterate individuals with ex-illiterate individuals and schooled literate individuals in a computerized same–different comparison task using bloblike figures adapted from Cooper and Podgorny (1976). These figures included not only enantiomorphs and plane rotations (both with the same angular difference of 180° from S1), but also shape contrasts of varying discriminability, with S2 stimuli called here D1 through D6 when differing from S1 by their shape (see examples in Figure 11). Participants had to respond *same* if S1 and S2 had not only exactly the same shape but also the same orientation and had to respond *different* when S1 and S2 presented either different shapes or different orientations of the same shape. Because shape similarity is algorithmically well defined with such shapes (Attneave, 1957; Attneave & Arnoult, 1956), we jointly considered D1 through D3 (henceforth, D1D3) as presenting shapes quite similar to S1 and jointly considered D4 through D6 (henceforth, D4D6) as presenting rather dissimilar shapes.

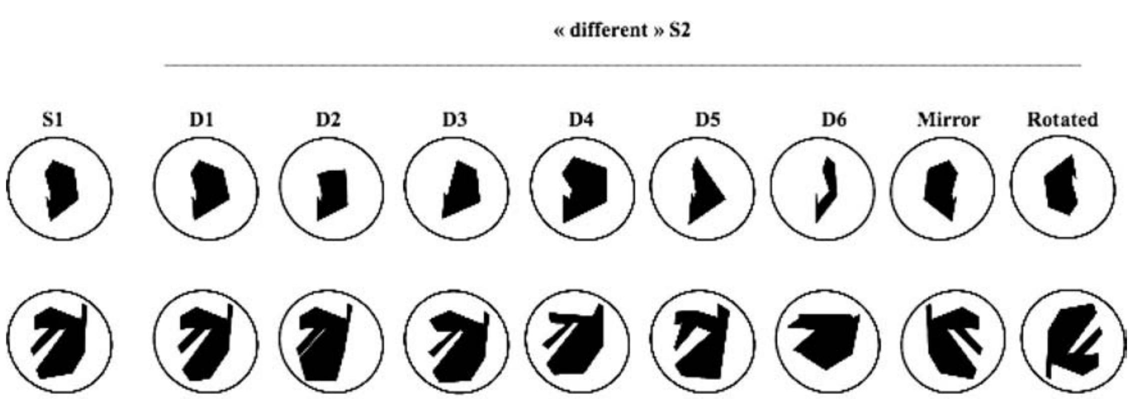

Figure 11. Example of two sets of stimuli (one on each line) used in the same–different comparison task of Experiment 5B. S1 = Stimulus1; S2 = Stimulus 2; D1–D6 = shape contrasts of varying discriminability. Adapted from "Mental Transformations and Visual Comparison Processes: Effects of Complexity and Similarity," by L. A. Cooper and P. Podgorny, 1976, *Journal of Experimental Psychology: Human Perception and Performance, 2,* p. 505. Copyright by the American Psychological Association.

We used these larger shape contrasts, and not only the tiny ones, because they may offer a further control situation, in addition to plane rotations. Indeed, to demonstrate a specific impact of literacy on enantiomorphy, it is necessary to show that when compared with literate individuals, illiterate people are particularly poor at processing enantiomorphs, much poorer than with other visual contrasts. We had already examined this question in Experiments 1 and 2 by comparing sorting on orientation versus on size, shape, or color, but performance on the latter dimensions was close to the ceiling in all groups. The results of Experiment 5A suggested, on the contrary, that performance on plane rotations is far from ceiling (at least in illiterate individuals and semi-illiterate individuals), although not especially related to literacy. We expected that the same would hold true for the D4D6 contrasts: Although these contrasts are clearly larger than the D1D3 ones, they seem nevertheless less obvious than the shape (circles vs. squares), color (red vs. green), or size contrasts that we had used in the sorting tasks. Both the D4D6 and the plane rotation contrasts may thus offer control conditions that, although not at ceiling, are not predicted to benefit as much from literacy as enantiomorphy.

In fact, observing between-groups differences for the D4D6 and plane rotation contrasts would not be surprising. Our earlier research has shown that compared with schooled literate individuals, unschooled adults present less developed visual analytical skills even with nonenantiomorphic stimuli. However, these effects were linked to schooling rather than to literacy per se, because ex-illiterate individuals performed as poorly as illiterate individuals in a part-verification task (Kolinsky et al., 1987, 1990) and performed in a similar holistic, context-dependent way in a test examining visual cognitive styles (Ventura et al., 2008).

Still, between-group disparities in general cognitive skills linked, for example, to linguistic or reasoning abilities may account for at least some of the differences that we predicted to occur between illiterate individuals and literate individuals, including ex-illiterate individuals. Two types of factors may cause the latter group to differ from illiterate individuals in general cognitive skills. First, although there was no self-selection for learning to read as adults (because it was often at the behest of employers or the army that ex-illiterate individuals began alphabetization classes), external selection may itself induce between-group differences—for example, if only the more promising individuals were selected for literacy instruction. Second, even their rudimentary alphabetization may afford ex-illiterate individuals new tools for knowledge acquisition. To evaluate the impact on enantiomorphy of potential resulting cognitive differences, all participants were presented with the Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975), which is known to be sensitive to educational and (correlated) literacy level (e.g., Crum, Anthony, Bassett, & Folstein, 1993).

On the basis of the idea of mirror invariance and former results showing difficulties with enantiomorphs even in schooled, literate adults, we expected all groups to display poorer performance and/or longer RTs for mirror images than for both plane rotations and huge shape contrasts. However, we predicted that compared with literate individuals, illiterate individuals would present a much greater performance difference according to item type, namely, particularly poorer performance for enantiomorphs and, perhaps, for tiny shape contrasts as well.

Method

Participants. Three Portuguese groups matched on age as well as on socioeconomic and residential backgrounds were paid for their participation. The results of two participants (one illiterate participant and one ex-illiterate participant) were discarded because they did not seem to have understood the task, as their average correct score on the larger (D6) shape differences was close to 50%. The final samples included 11 illiterate individuals (nine women, two men; ages 31–74 years, average age $= 65.3$ years), 10 ex-illiterate individuals (nine women, one man; ages 49–71 years, average age $= 60$ years), and 10 schooled literate adults (six women, four men; ages 31–68 years, average age $= 60$ years). All were living in Lisbon. Within each group, order of presentation mode (sequential or simultaneous first) was counterbalanced between participants.

All participants were presented with a Portuguese adaptation of the MMSE (Guerreiro et al., 1994) and screened for letter knowledge (the 23 letters used in Portuguese) and reading (6 words: *vaca, cola, nariz, mesa, amiga, anexo*; 6 pseudowords: *cau, vapa, pesta, benino, tavalo, jalada*). Illiterate individuals recognized only 35.97% of the letters on average ($SD = 30.99$), whereas only three ex-illiterate individuals and one literate individual did not recognize one letter (average scores of 98.7% and 99.57%, respectively). All the illiterate individuals were unable to read any item except for one individual, who deciphered one word (average $=$ 0.76% correct, $SD = 2.51$, $Mdn = 0$), whereas all the ex-illiterate individuals correctly read at least 83.33% of the items, reaching 93.3% correct on average ($SD = 7.66$, $Mdn = 95.83\%$); all the schooled literate individuals read perfectly. The ANOVAs showed a significant group effect for both letter recognition and reading, $F(2, 28) = 41.02$ and $F(2, 28) = 1{,}551.9$, respectively, both ps $<$ .0001. According to Scheffé's tests, illiterate individuals recognized fewer letters and read more poorly than both ex-illiterate individuals and schooled literate individuals (all $p\text{s} \leq .0001$), and ex-illiterate individuals recognized as many letters as schooled literate individuals ($p > .10$) but read less accurately ($p = .01$).

Materials. The materials were adapted from the random polygons originally developed by Attneave and Arnoult (1956; see also Attneave, 1957) and modified by Cooper (1975; Cooper & Podgorny, 1976). Five closed and irregular black-colored shapes served as S1 in a same–different discrimination task. On same-stimulus trials, S2 was an exact match of S1. On different-stimuli trials, S2 differed from S1 either by shape, presenting an increasing difference from D1 to D6 (see Figure 11), or by orientation; in this case, it was either a mirror image or a plane rotation of S1. Plane-rotated S2 had an angular difference of 180° from S1, thus being equal to the (out-of-plane) angular difference presented by mirror images compared with S1. The materials included 40 different-stimuli trials and 40 same-stimulus trials, with each same-stimulus trial being presented eight times.

Procedure. Stimuli were presented on a computer screen. Timing and data collection were controlled by E-Prime Professional 2.0 (Schneider, Eschman, & Zuccolotto, 2002).

Participants were informed that they would see the same materials in two consecutive tests. Before each test, specific instructions were provided. In both tests, the same 80 trials were presented, the only difference being that S1 and S2 were presented either simultaneously, side by side on the screen, or sequentially, with S1 always presented on the right and S2 on the left of the screen. Each trial started with a fixation point presented in the middle of the screen for 500 ms. In the simultaneous test, S1 and S2 were presented simultaneously until response. In the sequential test, S1 was presented for 3 s, followed by a gray screen for 3 s, followed by S2, which remained on the screen until response. Response deadline was 5 s in both tests.

In both tests, participants performed a same–different comparison task through keypressing with a button box (PST SRB 200A), with *same* and *different* responses given with the right versus the left index finger, respectively. They were required to respond *same* if S1 and S2 had not only exactly the same shape but also the same orientation and to respond *different* if they had either different shapes or different orientations.

Contrary to the unschooled participants tested in Experiment 2B, participants in the present experiment had already taken part in other computerized experiments (unrelated to the present topic). For this reason, no special procedure was needed to familiarize them with the computer setting. Before the 80 experimental trials, all participants were presented first with five examples (one same-stimulus, one D1, one D6, one mirror image, one plane rotation) and then with 16 practice trials (eight same-stimulus and one of each type of different-stimuli trials), during which feedback on the correctness of responses was provided.

Results

The d' scores were computed as in the former experiments, separately for each presentation mode (simultaneous vs. sequential) and trial type (mirror images, plane rotations, D1D3, and D4D6). A preliminary ANOVA run on these scores showed a main effect of presentation mode, $F(1, 28) = 9.96$, $p < .005$, reflecting higher d' scores with sequential than with simultaneous presentations (on average, 3.45 and 3.01, respectively). However, contrary to what had been observed in Experiment 4, here presentation mode did not interact with group, $F(2, 28) = 2.3$, $p > .10$ (Presentation Mode × Group × Item Type: $F = 1$). Consequently, data were pooled across presentation modes.

Table 6 presents these pooled d' scores and the corresponding accuracy scores as well as the p values of the univariate t tests. It shows that performance on different-stimuli trials was clearly above chance in all cases, except in illiterate individuals and ex-illiterate individuals for tiny shape contrasts and in illiterate individuals for mirror images. Yet, d' scores were significantly higher than zero in all cases.

The ANOVA run on the pooled d' scores included group and trial type as variables. It showed significant effects of group, $F(2, 28) = 15.14$, $p < .0001$, and trial type, $F(3, 84) = 47.11$, $p < .0001$, as well as a significant Trial Type × Group interaction, $F(6, 84) = 3.49$, $p < .005$. Because groups differed on all trial types, all ps $< .0005$, with illiterate individuals always differing from the two other groups, all ps $\leq .01$ according to Scheffé's tests, and with ex-illiterate individuals never differing from schooled literate individuals, all ps $> .10$, we further compared illiterate individuals to the latter two groups considered jointly. Using planned comparisons on d' difference scores, we checked whether illiterate individuals presented a larger performance drop than literate individuals for enantiomorphs and for tiny shape contrasts compared with plane rotations and D4D6. The two latter trial types were considered jointly, as they led to similar (and not at ceiling) performance overall, $F(1, 28) = 2.25$, $p > .10$; interaction with group, $F(1, 28) = 1.94$, $p > .10$. As illustrated in Figure 12, the performance drop was more severe in illiterate individuals than in literate individuals only for enantiomorphs, $t(29) = 2.27$, $p = .01$, and not for tiny shape contrasts, $t < 1$.

Table 6
Percentage of Correct Responses (Hits) on Different-Stimuli Trials and of False Alarms on Same-Stimulus Trials and Associated d′ Scores in Experiment 5B Presented Separately for Trials With Tiny Shape Contrasts (D1D3), Huge Shape Contrasts (D4D6), Mirror Images, and Plane Rotations

	Participant type		
Trial type	Illiterate	Ex-Illiterate	Schooled literate
	Different-stimuli trials: Hits		
D1D3	48.48 (12.96)	53.03 (15.12)	72.49** (10.06)
D4D6	81.64** (7.84)	85.77** (6.51)	91.18** (7.18)
Mirror images	60.57† (20.60)	90.93** (8.92)	82.68** (16.95)
Plane rotations	81.61** (15.93)	95.30** (4.27)	93.93** (11.89)
	Same-stimulus trials: False alarms		
	26.66 (13.40)	10 (5.90)	14.02 (12.02)
	d'		
D1D3	1.47** (0.56)	2.55** (0.59)	3.05** (0.99)
D4D6	2.97** (0.65)	3.99** (0.52)	4.32** (0.89)
Mirror images	1.90* (1.32)	4.27** (0.72)	3.67** (1.41)
Plane rotations	3.00** (0.84)	4.58** (0.50)	4.32** (1.04)

Note. Standard deviations are in parentheses.
† $p < .10$. * $p < .0005$. ** $p < .0001$, according to univariate t tests in comparison either to 50%, corresponding to chance level for percentage correct on different-stimuli trials, or to 0 for d' scores.

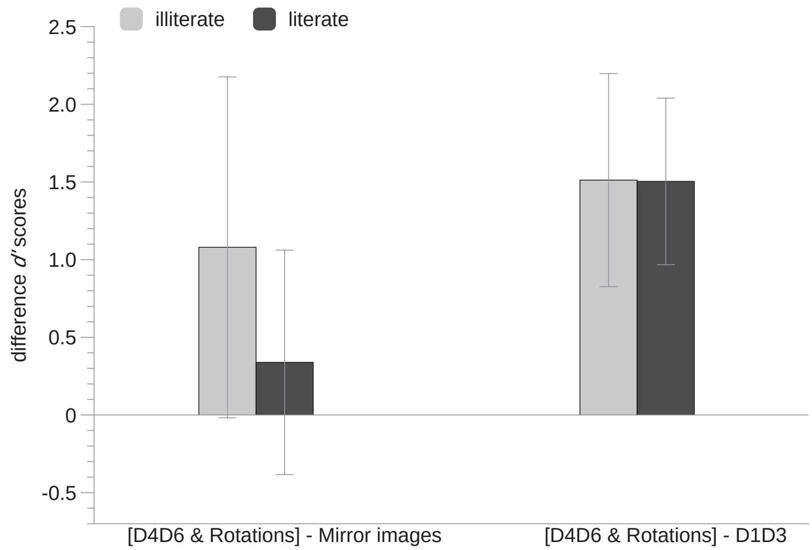

Figure 12. Average differences on d' scores observed for illiterate individuals and literate individuals in the same–different comparison task used in Experiment 5B. These scores correspond to the performance drop for either mirror images or tiny shape differences (D1D3) in comparison to huge shape (D4D6) and rotation contrasts. Errors bars represent standard deviations. D1, D3, D4, and D6 = shape contrasts of varying discriminability.

To examine whether these results stem from variability in general cognitive skills, we used MMSE revised scores as a covariate, recalculating individual scores after discarding the two items that, in this test, examine reading and writing abilities; this led to average scores of 23.18 ($SD = 2.99$), 24.8 ($SD = 1.69$), and 26.6 ($SD = 1.27$) for illiterate individuals, ex-illiterate individuals, and schooled literate individuals, respectively. In the ANOVA on these scores, the significant group effect, $F(2, 28) = 30.6$, $p < .005$, showed illiterate individuals to differ only from schooled literate individuals and not from ex-illiterate individuals, $p < .005$ and $p > .10$, respectively, according to Scheffé's tests;[7] ex-illiterate individuals did not differ from schooled literate individuals, $p > .10$. In the analysis that used these scores as a covariate, the Group × Item Type interaction remained significant, $F(6, 81) = 3.45$, $p < .005$, with groups differing on all trial types, $p \leq .025$. More crucially, in comparison with D4D6 and plane rotations, illiterate individuals still showed a larger performance drop than literate individuals only for enantiomorphs, $F(1, 28) = 4.98$, $p < .05$, and not for tiny shape contrasts, $F < 1$. In fact, the difference between the control trials (D4D6 and plane rotations) and either mirror-image or tiny shape contrasts did not correlate significantly with the MMSE revised scores, $r(29) = -.10$ and .03, respectively, both ps $> .10$.

Also interesting are the qualitatively different within-group patterns. For illiterate individuals, enantiomorphs led to poorer performance than both plane rotations, $F(1, 30) = 13.56$, $p < .001$, and huge shape contrasts, $F(1, 30) = 12.83$, $p < .005$. For this group, enantiomorphs actually led to a level similar to the one obtained for tiny shape contrasts, $F(1, 30) = 2.12$, $p > .10$. This was not the case for plane rotations, which were processed much better than tiny shape contrasts, $F(1, 30) = 26.41$, $p < .0001$; in fact, they were processed as well as huge shape contrasts, $F < 1$. On the contrary, for both ex-illiterate individuals and schooled literate individuals, enantiomorphs turned to be far easier than tiny shape contrasts, $F(1, 27) = 85.05$, $p < .0001$ and $F(1, 27) = 5.65$, $p < .025$, respectively, and for ex-illiterate individuals they were even as easy as huge shape contrasts, $F(1, 27) = 2.13$, $p > .10$.

However, enantiomorphs remained somewhat more difficult than plane rotations even for literate participants. Compared with plane rotations, enantiomorphs tended to elicit lower d' scores in ex-illiterate individuals, $F(1, 27) = 2.91$, $p < .10$, and did elicit significantly lower d' scores in schooled literate individuals, $F(1, 27) = 6.34$, $p < .025$. The latter also displayed significantly lower d' scores for enantiomorphs than for huge shape contrasts, $F(1, 27) = 6.42$, $p < .025$. The special difficulty of enantiomorphy was also manifested for all groups by slower RTs. In the RT analysis on different-stimuli trials, there was a significant effect of trial type, $F(3, 84) = 6.97$, $p < .0005$, without interaction with group, $F(6, 84) = 1.28$, $p > .10$: All participants processed enantiomorphs more slowly than plane rotations and huge shape contrasts, with average RTs of 1,692 ms, 1,542 ms, and 1,451 ms, $F(1, 84) = 4.59$, $p < .05$ and $F(1, 84) = 11.32$, $p < .005$, respectively, whereas the two latter trial types did not differ significantly, $F(1, 84) = 1.49$, $p > .10$.

Discussion

The present experiment showed that, for all the participant groups, discriminating enantiomorphs was more difficult than discriminating plane rotations and huge shape differences. This held

[7] Of course, when the two items that examine reading and writing abilities were also considered in the analysis, illiterate individuals differed from both ex-illiterate individuals and schooled literate individuals, with average scores of 23.18, 26.8 and 28.6, respectively, both ps $< .005$ according to Scheffé's tests.

true even though the angular difference between plane-rotated figures was the same, in the present experiment, as the out-of-plane angular difference between enantiomorphs (180° in both cases). This intrinsic difficulty may be related to the fact that enantiomorphy is acquired quite late, under the pressure to discriminate between mirrored letters.

Consistent with this idea, in contrast to the two literate groups, illiterate individuals were unable to process correctly the mirror-image contrasts: On enantiomorphic different-stimuli trials, their performance dropped to nearly chance level, and in the analysis on d' scores, in comparison with both huge shape contrasts and plane rotations, illiterate individuals displayed a more pronounced performance drop for enantiomorphs than did literate participants. In addition, correlation and covariance analyses showed that the illiterate individuals' increased difficulty with enantiomorphs is unlikely to be fully accounted for by more general differences in cognitive skills.

Of interest, illiterate individuals' performance for tiny shape contrasts (D1D3 different-stimuli trials) was also at chance, this being the case for the ex-illiterate individuals as well. However, on d' scores, compared with huge shape and plane-rotated contrasts, illiterate individuals showed a larger performance drop than literate individuals only for enantiomorphs and not for tiny shape contrasts. Literacy thus seems to impact more on enantiomorphy than on the processing of tiny shape contrasts.

General Discussion

In the present study, we examined whether the acquisition of the Latin alphabet impacts enantiomorphy, that is, the ability to discriminate mirror images. Although the human visual system seems to be characterized by mirror invariance, mastering the Latin alphabet requires taking enantiomorphic contrasts into account to distinguish between letters such as *b* and *d*. Hence, learning this written system may push the beginning reader to unlearn mirror invariance, and this process may generalize to nonlinguistic materials (e.g., Bornstein et al., 1978; Dehaene, 2005; Dehaene & Cohen, 2007; Dehaene, Cohen, Sigman, & Vinckier, 2005, Dehaene et al., 2010; Gibson, 1969).

To test this hypothesis, rather than comparing preliterate and literate children who differ in age, we compared illiterate adults with ex-illiterate and schooled literate adults, using sorting (Experiments 1 and 2) and same–different comparison (Experiments 3–5) tasks. Given that ex-illiterate individuals never attended school and learned to read and write only as adults in special alphabetization classes, their comparison with illiterate individuals is crucial. In schooled literate individuals, enantiomorphy may have benefited from other school activities. Therefore, it is through comparing illiterate individuals with ex-illiterate individuals that we can isolate the specific effect of literacy acquisition. Moreover, according to the stronger hypothesis that literacy acquisition would be the most important factor enhancing enantiomorphy, illiterate individuals should differ from both ex-illiterate individuals and literate individuals, and these two groups should present relatively similar enantiomorphic performance.

In fact, illiterate participants displayed much poorer performance on enantiomorphic contrasts than both ex-illiterate individuals and schooled literate individuals when another, more salient dimension of the stimulus, such as size (Experiment 1) or shape (Experiments 2–5), varied between trials, as was the case in the orthogonal sorting conditions (Experiments 1 and 2) and in the same–different comparisons of enantiomorphs (Experiments 3–5). In these situations, compared with literate individuals (either schooled or not), illiterate individuals displayed lower sorting scores (Experiments 1 and 2) and lower d' same–different scores (Experiments 3–5), with a clear propensity to neglect enantiomorphic contrasts and to respond *same* on enantiomorphic trials.

The illiterate individuals' trouble with enantiomorphs is unlikely to be fully accounted for by misunderstanding the task requirements or by variability in more general cognitive skills. In the sorting tasks, no group difference was observed on either size (Experiment 1) or shape (Experiments 2). Illiterate individuals were also quite good at sorting a material varying in color and shape (Experiment 1), and previous training with these materials did not help them to sort on orientation. Also, when materials included orientation, sorting order of the dimensions did not impact their performance (Experiments 1 and 2).

Certainly, the lack of a group difference in sorting size and shape in Experiments 1 and 2A might have stemmed from ceiling effects, because performance on these dimensions was near perfect for all groups. Hence, we cannot conclude that illiterate individuals differed from literate individuals only for sorting enantiomorphs. In fact, when performance was not at ceiling, as was the case in Experiment 5B, illiterate individuals did present poorer performance than literate individuals on nonenantiomorphic contrasts. However, they differed much more dramatically from the literate individuals on enantiomorphs than on other contrasts. This was the case in the orthogonal sorting conditions as well as when, in Experiment 5B, enantiomorphs were compared with plane rotations and huge shape contrasts, for which performance was not at ceiling.

Tests evaluating illiterate individuals' cognitive skills more directly further confirmed that their stronger difficulty with enantiomorphs could hardly be explained by such general factors. In Experiment 5A, testing illiterate individuals and semi-illiterate individuals who were quite heterogeneous on literacy level showed, through correlation and covariance analyses, that their stronger difficulty for enantiomorphic than for plane-rotation contrasts was unrelated to their reasoning abilities, estimated by the Standard Progressive Matrices. This more acute difficulty was related only to their performance in reading-related tasks. The same conclusion can be drawn for the differences in enantiomorphy between illiterate individuals and the two groups of literate participants tested in Experiment 5B: These remained significant when the analyses factored out variability in general cognitive skills, evaluated through scores derived from the MMSE.

Thus, although illiterate individuals' difficulties may not be specific to enantiomorphs, they are particularly severe with this type of contrast, and this stronger difficulty does not stem from variability in more general cognitive skills. These results support the notion that different processing mechanisms are engaged by rotations in the plane and mirror reflections, which involve a flip out of the plane. Consistently, the brain areas supporting rotation and mirror reflection are largely different, at least for alphanumeric characters. For instance, Núñez-Peña and Aznar-Casanova (2009) found a different scalp distribution of the negative event-related potential waveform elicited by rotated and mirrored letters, and Weiss et al. (2009), using functional magnetic resonance imaging, found rotation-specific activity in dorsal frontoparietal regions, with virtually no overlap with the areas showing stronger activation for enantiomorphs. Neuropsychological cases also suggest that enantiomorphy is a special case of orientation discrimination, because some patients who were very poor at discriminating enantiomorphs were far better at discriminating rotations in the plane (e.g., Davidoff & Warrington, 2001; Priftis et al., 2003; Turnbull & McCarthy, 1996; Valtonen et al., 2008), and at least one participant showed the converse pattern of impaired discrimination of rotated images with spared enantiomorphy (Turnbull, Beschin, & DellaSala, 1997).

However, the impact of literacy on enantiomorphy should be better qualified because, as we had predicted, this effect is restricted to situations in which participants have to pay attention to enantiomorphic contrasts among other variations. Indeed, when only orientation varied (in the standard sorting conditions), illiterate individuals presented reasonable performance, with average correct scores ranging from about 86% in Experiment 1 to 95% in Experiment 2B. In this condition, they even did not differ robustly from ex-illiterate individuals (there was a trend only in Experiment 2A). Given that when they are pushed to focus their attention exclusively on enantiomorphic contrasts, illiterate individuals are able to do so, the effect of literacy is likely to be attentional, not perceptual.

Data from short-term priming studies on schooled literate adults call for further qualification on the exact level at which literacy impacts on enantiomorphy. For example, using an object-naming task, Stankiewicz et al. (1998) found that it was only when the item appeared in the attended location that a significant latency reduction from a previous presentation of the same object occurred both when this was physically identical and when it was mirrored, although the effect was stronger in the first case. When the item appeared in an ignored location, priming occurred only for the identical view, showing that its representation is not orientation independent (see also Eger, Henson, Driver, & Dolan, 2004; Thoma, Hummel, & Davidoff, 2004; Vuilleumier, Schwartz, Duhoux, Dolan, & Driver, 2005). This suggests a preattentive view-sensitive representation and a later attentionally built reflection-invariant representation.

Consistent with this, our earlier work had shown that illiterate individuals process enantiomorphs at the preattentive level in the same way as literate individuals do. As a matter of fact, they displayed the same level of illusory conjunctions as schooled literate individuals in a situation in which the lateral mirror orientation of diagonals (\ vs. /) had to be registered preattentively to perceive the target, an arrowlike figure (Kolinsky, Morais, & Verhaeghe, 1994).

Both these data and those reported by Stankiewicz et al. (1998) probably tap *perceptual* processing, either preattentive or attentional. In Stankiewicz et al., a trial consisted of a cuing box to the left or right of fixation, followed by two line drawings of common objects, one appearing inside and the other outside the cuing box. The task was to name the cued image (the *attended* prime) and ignore the other. Each prime display was followed by a single probe image presented at fixation, the task being again to name the object. Such a situation probably involves mere object recognition and does not require the viewers to analyze the stimulus intentionally or to base their response on a specific aspect of it. On the contrary, the sorting tasks (in particular the orthogonal condition) as well as the orientation-dependent same–different comparison tasks used in the present study tap such *postperceptual*, explicit processes of visual analysis. Thus, our data point to the idea that, at least for enantiomorphy, literate individuals diverge from illiterate individuals at this later, postperceptual representational level.

Former work had already suggested that children's difficulty with left–right mirror images does not reflect an inability to perceive the differences between enantiomorphs (i.e., deficiencies in *input coding*; see discussions in Corballis & Beale, 1976, as well as in Over, 1967). The present data show that the same holds true for illiterate adults. They are not consistent, however, with the idea that such difficulties reflect problems in remembering mirror images as distinct (see discussion in, e.g., Valtonen et al., 2008). Indeed, in the same–different comparison task (Experiment 4), illiterate individuals performed even worse with simultaneously than with sequentially presented enantiomorphs. Most likely, they have problems in labeling and/or categorizing enantiomorphs as distinct, probably because enantiomorphic distinctions are irrelevant to them, given that these distinctions are irrelevant most of the time in everyday life except for people who use a written system that includes such contrasts.

Nevertheless, in accordance with previous data (e.g., Gregory & McCloskey, 2010), Experiment 5B showed that discriminating enantiomorphs remains somewhat more difficult than discriminating plane rotations and huge shape contrasts even for people literate in the Latin alphabet. This persistent difficulty may be related to the fact that enantiomorphy (along with other effective letter discrimination abilities) is acquired relatively late in life, under the pressure to discriminate between mirrored letters. It ought also to be emphasized that in the natural world, animals, including human beings, benefit from being insensitive to mirror contrasts in order to recognize friends, enemies, or food rapidly. It is probably because mirror invariance is so constitutionally primitive in the human mind that even a cultural invention such as writing tends to avoid enantiomorphic characters. Although the Cree syllabary uses them systematically (Berry & Bennett, 1995; Nichols, 1996), in the large majority of writing systems left–right reflections are either noncontrastive or only occasionally contrastive, and, in the boustrophedon preclassical Greek writing, mirrored letters were considered equivalent.

In the Latin alphabet, fewer than one sixth of the letters are left–right reflections of another letter in lowercase, and none are left–right reflections in uppercase. Although some orthographic neighbors differ from each other only by mirrored letters, such as *dear* and *bear*, whole words are rarely mirror reflections of other words, such as *won* and *now*. Notwithstanding, the present study shows that the impact of learning this system extends far beyond the realm of symbolic characters and their analogs: People who learned to read and write in the Latin alphabet generalize enantiomorphy to nonlinguistic materials, both geometric figures (Experiments 1–4) and bloblike shapes (Experiment 5B). It remains to be investigated whether learning the Latin alphabet also impacts on enantiomorphy for real objects such as animals, tools, furniture, and so forth.

Our results also show that a relatively small practice in reading and writing letters and words is enough to found enantiomorphy, and that this holds true even if literacy learning takes place in adulthood. As a matter of fact, in the sorting and same–different comparison tasks used here, individuals who were ex-illiterate always obtained better performance than those who were still illiterate, although most of them read at a quite rudimentary level. The capacity of a writing system that includes only a few enantiomorphs to rapidly break the mirror invariance principle cannot but look extraordinary if one accepts that mirror generalization is natural and that, at least at the postperceptual level, enantiomorphy is learned.

Whether there is an impact, beyond rudimentary alphabetization, of reading and writing proficiency on enantiomorphy is still unknown. Proficient reading and writing goes far beyond the capacity to discriminate between mirrored letters: It encompasses other visual abilities, such as discriminating between letters differing by minute but crucial visual details, categorizing as equivalent different forms of the same letters, and automatically activating the orthographic representations of words. Which of these differences in reading and writing proficiency may explain why ex-illiterate individuals presented somewhat worse enantiomorphic scores than schooled literate individuals remains to be investigated.

The performance difference between ex-illiterate individuals and schooled literate individuals may also reflect the impact on enantiomorphy of activities unrelated to literacy. Preliminary data showed that lace making stimulates enantiomorphy in illiterate people (Verhaeghe & Kolinsky, 1992). Here, we controlled for this variable by making sure that none of the participants made lace, but informal observations suggest that other activities, such as celestial navigation, might also be relevant. This may partly explain why illiterate individuals presented highly variable enantiomorphic scores, with some individuals performing far better than the others. Similarly, school activities, such as object and graph drawing, geometry lessons, recognition of geographic representations, and acquisition of other symbolic systems, such as formal mathematics (Walsh, 1996), may have offered the schooled literate individuals more opportunities to reinforce enantiomorphy than did the adult alphabetization classes attended by the ex-illiterate individuals.

Although the potential influence of those activities should not be neglected, it is worth noting that the performance difference between ex-illiterate individuals and schooled literate individuals in enantiomorphy was far less consistent and dramatic than the difference between illiterate individuals and ex-illiterate individuals: It reached significance in only two experiments, and in one of these, the effect was rather small (less than 2% compared with the 32% effect linked to literacy in the orthogonal orientation sorting condition of Experiment 2A). Compared with the huge impact of literacy, this much smaller additional effect suggests that reading and writing in the Latin alphabet, although probably not the exclusive activity enhancing enantiomorphy, is the most stimulating.

In the future, researchers should try to isolate those mechanisms that might help with individuating mirrored characters. Acknowledging that the period of most rapid improvement in enantiomorphy coincides, in children, with the beginning of instruction in reading and writing, Corballis and Beale (1976) linked this improvement to the reinforcement of hand asymmetries and to the acquisition of lateralized (e.g., left-to-right) visual scanning. However, the proper movements that create enantiomorphic letters in writing may themselves be crucial. The usual way of drawing *p*, beginning with a straight line, is different from the one of drawing *q*, which begins with a curve. In literate adults, letter processing automatically recruits a sensory–motor brain network (e.g., James & Gauthier, 2006), and data on both children (Longcamp, Zerbato-Poudou, & Velay, 2005) and literate adults (e.g., Longcamp, Boucard, Gilhodes, & Velay, 2006) suggest better learning performance for handwritten than for typed characters. In adults, the integration of sensorimotor systems through writing leads to functional specialization in the visual system for letterlike stimuli similar to that reported for letters (James & Atwood, 2009). Thus, in the course of learning to write, individuals most probably dip into movement-related distinctions between enantiomorphs. This requires using egocentric coordinates that illiterate individuals probably also use, an issue that we are currently exploring. A longitudinal assessment of the way beginning readers unlearn mirror generalization would also be highly informative.

Reading acquisition may favor the development of other visual abilities beyond enantiomorphy. The necessity of discriminating letters such as *c* and *e*, which differ by a minute visual detail, may also generalize to nonlinguistic stimuli. We tested this idea in Experiment 5B, using not only enantiomorphs and plane rotations (the latter not sustaining graphemic contrasts in the Latin alphabet), but also shape differences of varying discriminability. Contrary to what we observed with enantiomorphs, compared with plane rotations and huge shape differences, the performance drop observed for tiny shape contrasts was not stronger in illiterate individuals than in the two literate groups. This suggests that, contrary to enantiomorphy, attention to small shape contrasts may be system dependent: The same Roman alphabet reader who immediately differentiates *c* from *e* would probably experience difficulties at rapidly detecting equally small but important shape variations in unknown scripts, such as the difference between the Hebraic letters ה and ח and (an example taken from Dehaene, 2009). Future research should examine more systematically whether the shape contrasts sustaining effective letter discrimination generalize to materials other than the letters of the reader's own written system.

To conclude, the present study demonstrates that literacy in the Latin alphabet favors enantiomorphy with nonlinguistic materials and that rudimentary alphabetization in this system is enough to trigger this development. Reading and writing in this alphabet, although probably not the exclusive activity enhancing enantiomorphy, seems to be the most stimulating. Nevertheless, although the difference observed between illiterate and ex-illiterate adults is obviously a genuine effect of literacy, it is restricted to postperceptive attentional processes and does not concern earlier perceptual representations.

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