Acta Psychologica 142 (2013) 51–61

Contents lists available at SciVerse ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/ locate/actpsy

From hand to eye: The role of literacy, familiarity, graspability, and vision-for-action on enantiomorphy

Tânia Fernandes [a,*], Régine Kolinsky [b,c]

[a] Laboratório de Fala, Faculdade de Psicologia e de Ciências da Educação, Universidade do Porto, Rua do Dr. Manuel Pereira da Silva, 4200-392 Porto, Portugal
[b] Unité de recherche en Neurosciences Cognitives (UNESCOG), Centre de Recherche Cognition & Neurosciences (CRCN), Université Libre de Bruxelles (ULB), CP 191, 50, Av. F. Roosevelt, B-1050 Brussels, Belgium
[c] Fonds de la Recherche Scientifique-FNRS, Belgium

ARTICLE INFO

Article history:
Received 23 May 2012
Received in revised form 7 November 2012
Accepted 14 November 2012
Available online 9 December 2012

PsycINFO classification:
2300
2323
2340

Keywords:
Literacy acquisition
Visual processing
Enantiomorphy
Vision-for-perception
Vision-for-action

ABSTRACT

Literacy in a script with mirrored symbols boosts the ability to discriminate mirror images, i.e., *enantiomorphy*. In the present study we evaluated the impact of four factors on enantiomorphic abilities: (i) the degree of literacy of the participants; (ii) the familiarity of the material; (iii) the strength of the association between familiar objects and manipulation, i.e., *graspability*; and (iv) the involvement of vision-for-action in the task. Three groups of adults – unschooled illiterates, unschooled ex-illiterates, and schooled literates – participated in two experiments. In Experiment 1, participants performed a vision-for-perception task, i.e., an orientation-based same–different comparison task, on pictures of familiar objects and geometric shapes. Graspability of familiar objects and unfamiliarity of the stimuli facilitated orientation discrimination, but did not help illiterate participants to overcome their difficulties with enantiomorphy. Compared to a baseline, illiterate adults had the strongest performance drop for mirror images, whereas for plane rotations the performance drop was similar across groups. In Experiment 2, participants performed a vision-for-action task; they were asked to decide which hand they would use to grasp a familiar object according to its current position (e.g., indicating left-hand usage to grasp a cup with the handle on the left side, and right-hand usage for its mirror image). Illiterates were as skillful as literates to perform this task. The present study thus provided three important findings. First, once triggered by literacy, enantiomorphy generalizes to any visual object category, as part of vision-for-perception, i.e., in visual recognition and identification processes. Second, the impact of literacy is much stronger on enantiomorphy than on the processing of other orientation contrasts. Third, in vision-for-action tasks, illiterates are as sensitive as literates to enantiomorphic-related information.

1. Introduction

1.1. Theoretical background

Reading is a highly demanding visual task that requires adapting the existing cognitive and neural architecture. Consequently, learning to read does not only creates a specific circuitry for processing written material in the ventral occipitotemporal region (*vOT*) including the "visual word form area" (*VWFA*, e.g., Cohen et al., 2000; Dehaene & Cohen, 2011), but also deeply impacts on non-linguistic visual processing. This has been shown through studies comparing schooled literate adults to both *illiterate* adults, who did not attend school nor learn to read or write due to socioeconomic reasons, and unschooled *ex-illiterates*, who are from the same socioeconomic background as illiterates but learned to read and write as adults in special alphabetization courses. These studies have shown that at the brain level, learning to read induces a broad enhancement of occipital responses to non-letter stimuli and leads to neural competition in the left vOT between written words and other visual categories, in particular faces (Dehaene et al., 2010). At the behavioral level, learning to read improves contour integration (Szwed, Ventura, Querido, Cohen, & Dehaene, 2012) and boosts the ability to discriminate lateral mirror images (Kolinsky et al., 2011).

The latter ability, also called *enantiomorphy*, was the topic of the present work. Enantiomorphy may be considered as running against a large tendency among humans and animals to consider mirror images as equivalent (see a review e.g., in Corballis & Beale, 1976). This tendency, called *mirror-image generalization* or *mirror invariance*, is considered as evolutionarily advantageous for processing natural objects, which are mostly symmetric (Gross & Bornstein, 1978), and hence, remain the same under lateral reflection. However, mirror invariance needs to be "broken" in order to learn a script with mirrored symbols such as "b" vs. "d" (Gibson, 1969).

In our former work (Kolinsky et al., 2011), we showed that illiterates displayed poor enantiomorphy abilities; for example, they presented far

* Corresponding author. Tel.: +351 226 079 727; fax: +351 220 400 610.
E-mail addresses: taniapgfernandes@gmail.com, tfernandes@fpce.up.pt (T. Fernandes), rkolins@ulb.ac.be (R. Kolinsky).

0001-6918/$ – see front matter
http://dx.doi.org/10.1016/j.actpsy.2012.11.008

poorer performance than schooled literates and ex-illiterates when asked to judge whether two simultaneously or sequentially presented geometrical or blob-like shapes were in the same or in different orientations. In contrast, ex-illiterates were as able as schooled literates to discriminate mirror images (henceforth, *enantiomorphs*). Illiterates' poor results did not reflect general visual processing troubles, as they were quite able to discriminate other orientation contrasts like rotations in the plane (henceforth, *plane rotations*) as well as other dimensions of the stimuli like size, shape, or color. Furthermore, data from literates in a script with no mirrored symbols, namely the Tamil syllabary, refute the idea that the illiterates' results were due to extraneous factors as motivation to the task, for the Tamil literates displayed as poor enantiomorphy as illiterates (Danziger & Pederson, 1998; Pederson, 2003). Thus, the available evidence shows that it is learning to read a script with mirrored symbols that triggers enantiomorphy, an ability that generalizes to novel non-linguistic material.

Nevertheless, several issues remain hitherto unclear as regards the emergence of enantiomorphy. First, to our knowledge, no prior study has evaluated whether enantiomorphy would also generalize to familiar non-linguistic objects (e.g., pictures of tools and clothes), as previous work has only used geometric or blob-like shapes (Danziger & Pederson, 1998; Kolinsky et al., 2011; Pederson, 2003). One could argue that illiterate adults are less familiar with this kind of material than the literate groups, making impossible to disentangle the role of material familiarity from that of literacy on enantiomorphic performance. Yet, rather than being deleterious, material unfamiliarity may in fact benefit enantiomorphy, or, more generally, orientation discrimination. Indeed, participants are extremely sensitive to orientation variations of novel shapes, but not of familiar objects (see e.g., Tarr & Pinker, 1989). Familiar objects have been seen from many viewpoints, allowing observers to develop either orientation-invariant representations (e.g., object-centered structural descriptions: Biederman & Gerhardstein, 1993) or multiple orientation-specific representations (Tarr & Bülthoff, 1995). Thus, they are represented relatively independently of orientation, whereas novel shapes (as geometric and blob-like shapes) seem to be coded in a view-dependent, orientation-specific manner (Tarr & Bülthoff, 1995; Tarr & Pinker, 1989). Although this would hold true for both literates and illiterates, it may thus be the case that illiterates would present even stronger difficulties to discriminate orientation contrasts of familiar objects than of novel shapes.

Second, all the results reported so far were gathered in situations requiring *vision-for-perception*, known to rely massively on the visual ventral stream (including the VWFA) dedicated to object recognition, namely, on the *what* stream projecting from striate cortex to inferotemporal cortex (Goodale & Milner, 1992). Neither this task trait nor the motor-related characteristics of the material were considered as potentially relevant factors.

Task characteristics may be relevant as visual processing depends not only on the ventral stream but also on the dorsal stream, namely on the *how* stream projecting from striate to posterior parietal cortex, responsible for *vision-for-action* (Goodale & Milner, 1992). Although the two streams may operate simultaneously during object recognition, even in passive viewing conditions (e.g., Valyear, Culham, Sharif, Westwood, & Goodale, 2006), they present quite different properties (Creem & Proffitt, 2001): whereas the vOT is sensitive to identity changes and insensitive to orientation changes (Valyear et al., 2006), the lateral occipito-parietal junction, (*lOPJ*), part of the dorsal stream, shows the reverse pattern (for nonhuman primate evidence, see e.g., Murata, Gallese, Luppino, Kaseda, & Sakata, 2000). The two streams also differ by the type of referential frame. While the processes subserved by the ventral pathway use object-centered *allocentric* representations suitable for view-independent object recognition, those subserved by the dorsal pathway use viewer-centered *egocentric* representations appropriate to the moment-to-moment interaction with objects (Goodale, Jakobson, & Keillor, 1994; Milner & Goodale, 1993, 2008). As illiterates are likely to deal correctly with familiar objects in everyday life (they do not seem to have more problems than literates, for instance, in putting the right shoe on the right foot), even though they have troubles with enantiomorphy in vision-for-perception tasks (Danziger & Pederson, 1998; Kolinsky et al., 2011; Pederson, 2003), it would be worth checking whether they perform as well as literates in a vision-for-action task requiring sensitivity to enantiomorphic-related information.

The motor-related characteristics of the material may be relevant as well, even in vision-for-perception tasks. Indeed, in a task that did not involve any object-directed action (an upright/inverted judgment), it has been shown that action-related information is automatically invoked by *graspable* objects, for which there is a strong relationship between shape and manner of being grasped (e.g., a frying pan), leading to stimulus–response compatibility effects (Tucker & Ellis, 1998). Coherently, in a same–different orientation-based comparison task on sequentially presented objects, sensitivity to mirror-image changes in the lOPJ was observed only for graspable objects, not for *non-graspable* objects like a tractor or a sofa (Rice, Valyear, Goodale, Milner, & Culham, 2007; see also Valyear et al., 2006, for similar evidence in passive viewing). Hence, orientation judgments might be more easily performed for graspable than for non-graspable familiar objects.

Finally, we may wonder whether literacy impacts specifically on enantiomorphy or also modulates other orientation judgments. Neuropsychological data have shown that different processing mechanisms supported by largely different brain areas are engaged by plane rotations and mirror reflections (for evidence on the double-dissociation see e.g., Turnbull & McCarthy, 1996; Turnbull, Becshin, & DellaSala, 1997). Furthermore, neuron recordings in monkeys showed that inferotemporal cells are sensitive to plane rotations but not to enantiomorphs (Baylis & Driver, 2001; Logothetis & Pauls, 1995; Logothetis, Pauls, & Poggio, 1995), and brain imaging data in humans showed that the ventral pathway is originally mirror-invariant, with the VWFA remaining largely so for natural objects (Dehaene et al., 2010; Pegado, Nakamura, Cohen, & Dehaene, 2011). The impact of literacy acquisition may thus be stronger on enantiomorphy than on other, non-enantiomorphic, orientation discriminations. Although our former data were coherent with this suggestion (Kolinsky et al., 2011), as illiterates' difficulties were particularly severe with enantiomorphs, literates were in fact better able than illiterates to discriminate orientation contrasts overall. It would thus be worth exploring this point more systematically. Noteworthy, in the Latin alphabet, a few plane rotation contrasts are used to differentiate between letters, and with lower case-letters only 180° rotations are pertinent (e.g., "d" vs. "p"; "u" vs. "n"). To our knowledge, no study has hitherto compared the discrimination of 180° plane rotations to enantiomorphy of geometric shapes, nor of real objects, a comparison which would add the additional benefit of controlling for the angular difference (which is the same as in the out-of-plane flip involved in enantiomorphs).

1.2. Overview of the present study

We examined these issues by testing the impact of four factors on enantiomorphy: the degree of literacy of the participants, the familiarity of the material, the strength of the association between familiar shapes and manipulation, and the nature of the task, involving either vision-for-perception or vision-for-action. To this aim, three groups of adults – unschooled illiterate and ex-illiterate, and schooled literate – participated in two experiments.

In Experiment 1, we used as vision-for-perception task an orientation-based same–different comparison task, using sequential presentation of the stimuli as most prior studies (Dehaene, Nakamura, et al., 2010; Kolinsky et al., 2011; Pegado et al., submitted for publication). We examined for the first time the degree of generalization of enantiomorphy, as consequence of literacy acquisition, by using three types of asymmetrical material: geometric shapes, graspable familiar objects, and non-graspable familiar objects. *Graspability* referred here to the fact that the orientation of the object in the picture strongly signaled the use of one particular hand to grasp it. This was the case for *graspable objects*, e.g., for a cup appearing with its handle on the right, but not for *non-graspable* objects, e.g., for a shoe (see Fig. 1A).

To test in a stringent way whether the impact of literacy during vision-for-perception is the strongest for enantiomorphic contrasts, we examined participants' performance on four trial types (see Fig. 1B). On "same"-response trials (henceforth, *same* trials), the stimuli were exact matches, with same identity and same orientation. In the three types of "different"-response trials, stimuli had different orientations. In two cases, they depicted the same object but differed either by a mirror reflection (henceforth, *mirror-image* trials) or by a plane rotation (henceforth, *plane-rotation* trials). In the third type of "different"-response trials, the stimuli differed by both identity and orientation (henceforth, *fully different* trials).

We first compared participants' performance on mirror-image and plane-rotation trials. Next, we controlled for overall differences between groups using as baseline the performance on the fully different trials. Indeed, these trials should be easy to process as they combine orientation and identity variations. Using this situation as baseline thus allowed us to estimate the relative cost of having to respond "different" when only orientation (either mirror image or plane rotation) varies, compared to the situation in which both identity and orientation vary.

In sum, in Experiment 1, we adopted a 3 (Group: illiterates; ex-illiterates; and literates) × 3 (Material: geometric shapes; graspable familiar objects; and non-graspable familiar objects) × 4 (Trial type: same; mirror-image; plane-rotation; and fully different) design.

If literacy does have a specific impact on enantiomorphy, compared to the baseline (i.e., performance on fully different trials), the illiterates would present a huger performance drop for mirror images than the literate participants (unschooled ex-illiterates and schooled literates), whereas the performance drop for plane rotations would be equivalent for the illiterate and literate groups.

If enantiomorphy generalized to any visual material, the literate groups should be as able to discriminate mirrored familiar objects as mirrored geometric shapes. In contrast, illiterates would present enantiomorphic difficulties for both materials. We should thus find a significant Group × Trial type interaction. Yet, as novel shapes (as were most of the geometrical shapes used here) seem to be coded in an orientation-specific manner, whereas familiar objects tend to benefit from viewpoint-independent, object-centered representations (Tarr & Bülthoff, 1995), illiterates' enantiomorphic difficulties might be more severe for familiar objects than for geometric shapes. In fact, for familiar objects, the relative difficulty of enantiomorphy might vary as a function of their graspability, here as a function of the fact that the orientation of the object in the picture strongly signaled (or not) the use of one particular hand to grasp it. In Experiment 1 no grasping response was required, but given that, the visuomotor information of graspable objects is activated even in such situations (Rice et al., 2007; Tucker & Ellis, 1998), illiterates might display better enantiomorphy abilities for graspable than for non-graspable objects. If this were the case, we would find a significant three-way interaction between Group, Material, and Trial type.

In Experiment 2, we aimed at using a task that would involve vision-for-action. Direct comparison with Experiment 1 would have required using a similar sequential same–different comparison task, here based on visuomotor interaction, e.g., asking participants to decide whether they would use the same or a different hand to grasp the two sequentially presented objects. However, previous neuroimaging and neuropsychological studies have shown that the time-window at which the visuomotor computations are performed is critical (Creem & Proffitt, 2001; James, Culham, Humphreys, Milner, & Goodale, 2003; see also Rossit, Fraser, Teasell, Malhotra, & Goodale, 2011): the visual information must map directly onto the response "guiding it in the 'here and now'" (Milner & Goodale, 2008, p. 778). Indeed, priming effects mediated by the dorsal stream are extremely short-lived (less than 1 s; Masson, Bub, & Breuer, 2011). When there is a delay between stimulus offset and the onset of the visuomotor action, motor programming will be predominantly driven by high-level perceptual representations created earlier by ventral stream mechanisms. Coherently, Cohen, Cross, Tunik, Grafton, and Culham (2009) showed that transcranial magnetic stimulation (*TMS*) to the lateral occipital cortex (part of the ventral stream) influenced only delayed grasping, whereas TMS to the anterior intraparietal sulcus (part of the dorsal stream) affected both immediate and delayed grasping.

In Experiment 2, we thus decided to use a *virtual grasping* task that would maximize the probability to involve vision-for-action. On each trial, participants were presented with only one picture of a familiar object and asked to decide which hand they would use to grasp it, considering that they could not change their position relative to the object (see Fig. 1C). Given that participants performed the task on each one of the stimulus presented sequentially, mirror image processing was measured indirectly. If illiterates were sensitive to enantiomorphic-related information during visuomotor processing, they should be as skillful as

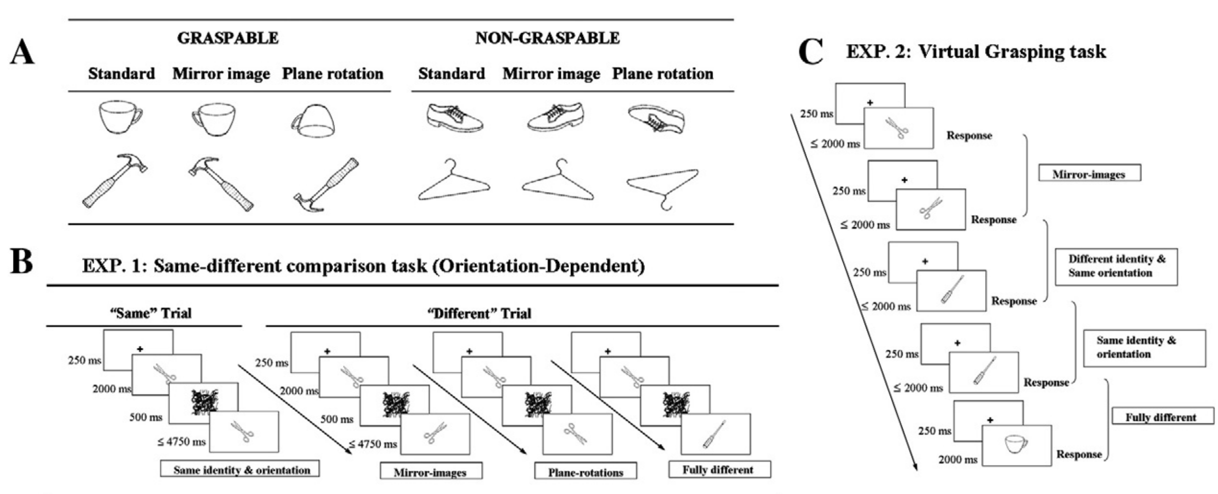

Fig. 1. Examples of the familiar objects and trial types used in the present study. A — Graspable and non-graspable objects; B — The four trial-types used in the vision-for-perception task (Experiment 1), in which participants performed an orientation-based sequential same–different comparison task. C — The sequence of trials in the vision-for-action task (Experiment 2), in which participants performed the virtual grasping task on each stimulus presented sequentially.

literates in this task, even if the current target were the mirror image of the former (see Fig. 1C). We thus predicted no group difference in such a situation.

In other words, illiterates' difficulties with enantiomorphs should be confined to vision-for-perception tasks, as in Experiment 1. The expected Group × Task interaction would also guarantee that any difference to be found on enantiomorphy between the illiterate and literate groups during vision-for-perception would not be due to other factors (e.g., general cognitive abilities) than literacy.

2. Methods

2.1. Participants

Forty-six Portuguese adults from the same socioeconomic and residential background were paid to participate in the present study. According to schooling and literacy levels, they were assigned to three groups: 17 illiterates, 14 unschooled ex-illiterates, and 15 schooled literates. Illiterates were recruited through non-governmental agencies. Ex-illiterates were engaged in or already had finished the final level of alphabetization. Literates had on average eight years of schooling (SD = 3.3).

2.1.1. Checking for task commitment

To check for task commitment, we examined Signal Detection Theory d' scores, considering as *hits* the correct “different” responses on fully different trials and as *false alarms* the incorrect “different” responses on “same” trials (i.e., in which both the orientation and the identity of the two stimuli were the same). Two illiterates and one ex-illiterate were excluded from further analyses due to their $d' \sim 0$, indicating that they were not able to perform the task (for the objects set: d' of 0.30, 0.83, and 0.89, respectively). Two literates were also excluded because one of them performed at chance on same trials (average correct: 54%), the other performed the task as being an identity-based task, i.e., with 28% average performance on mirror-image and plane-rotation trials of the geometric shapes set.

The final sample thus included 41[1] participants: 15 illiterates (11 women), aged 31 to 74 years-old (average: 58.1 years), 13 ex-illiterates (10 women), aged 19 to 71 years-old (average: 49.8 years), and 13 literates (8 women), 27 to 68 years-old (average: 50.7 years).

2.1.2. Checking for literacy and cognitive level

Participants first performed a letter recognition test and a reading test including six words and six pseudo-words. Illiterates were able to identify, on average, 8 out of the 23 letters of the Portuguese alphabet (with a range of 0 to 20 letters correctly identified), with only one of them able to read a single word of the reading test (average reading score: 0.56%). Ex-illiterates had a near-perfect letter recognition performance: they identified on average 22.6 letters, and reached at least 83.3% correct reading (average: 96.2%). Except for one participant who did not recognize one letter, all literates were perfect in both the letter recognition (average: 22.9) and the reading (average: 100%) tests. In the analyses of variance (ANOVAs) on these scores, there were significant effects of Group, $F(2, 38) = 71.70$ and $= 3034.93$, both $ps < .0001$, respectively. Post-hoc tests[2] showed that ex-illiterates and literates presented similar letter recognition performance, both differing from illiterates, $ps = .0001$. In the reading test, all groups differed from each other, all $ps < .05$.

To check for overall cognitive differences between groups, participants were also tested on the Mini-Mental State Examination (*MMSE*, Folstein, Folstein, & McHugh, 1975; Portuguese version: Guerreiro et al., 1994). This test is known to be sensitive to educational and (correlated) literacy levels (e.g., Crum, Anthony, Bassett, & Folstein, 1993); hence, we used MMSE revised scores, recalculating individual scores after discarding the three items examining reading, writing, and arithmetic abilities. This led to average scores of 23.9 (SD: 3.0), 22.7 (SD: 1.3) and 23.4 (SD: 1.8) for illiterates, ex-illiterates and schooled literates, respectively, with no significant difference between groups, $F < 1$.[3]

2.2. Material and procedure

2.2.1. Experiment 1

Participants performed the sequential orientation-based same–different comparison task on two types of asymmetric material (separated by block, in fixed order): first drawings of familiar objects (half graspable, half non-graspable, randomly intermixed within block), then geometric shapes. Procedure was the same for the two blocks (see Fig. 1B).

The objects set comprised 36 black and white drawings selected from Snodgrass and Vanderwart (1980). Their values on critical visual dimensions (Snodgrass & Vanderwart, 1980; Ventura, 2003) are presented in the Appendix A. As we were interested more precisely in knowing whether the position of the object in the picture strongly signaled the use of one particular hand, we pretested the whole set of objects on 19 Portuguese undergraduate Psychology students, who classified them using a scale from 1 (“the position of the object in the picture strongly signals the use of one particular hand”) to 5 (“to grasp the object any hand can be used”). Eighteen objects were evaluated as graspable and 18 as non-graspable, $t(34) = -13.62$, $p < .0001$. The two categories were matched on visual ambiguity, complexity, and familiarity, all $ts < 1$.

The geometric shape set, presented in Fig. 2, included nine black-line asymmetric figures created with Windows Paint.

For both material sets, three versions of each stimulus were created using irfanview software (www.irfanview.com): the standard[4], the mirror image (i.e., the lateral reflection of the standard) and the plane rotation (i.e., clock-wise rotation of the standard). The two orientation transformations had the same 180° difference from the standard version. For each standard stimulus, four pairs were thus created: one exact match pair (i.e., same trials), and three types of different orientation pairs (i.e., mirror-image trials; plane-rotation trials; and fully different trials).

Participants sat at a distance of ~70–80 cm from the LG Flatron CRT 17″ computer screen (640 × 480 pixels). Each experimental trial started with a fixation cross, presented in the center of the screen for 250 ms, after which the standard was presented during 2000 ms in the same location (occupying an area of 9.15° × 9.15). A 500 ms mask formed by random black lines separated the presentation of the standard and of the comparison stimulus, guaranteeing no involvement of iconic memory in performance. The second, comparison stimulus was on half of the trials an exact match of the standard (i.e., on “same” trials), and in the other half a different (by orientation or by orientation and identity) stimulus (see Fig. 1B). Participants performed 648 trials for the objects set: each standard occurred nine times on “same” trials, and nine times on “different” trials — three times in each one of the three possible “different” trial types. With geometric shapes, they performed 216 trials: each standard occurred 12 times on “same” trials and 12 times on “different” trials (four times in each one of the three possible “different” trials types).

[1] In Experiment 2, due to a computer error, the data of one literate were not collected. Thus, the results reported for Experiment 2 and for the comparison between experiments consider a final sample that includes 15 illiterates, 13 ex-illiterates, and 12 literates.

[2] All post-hoc tests reported in the present study are Tukey HSD test for unequal N.

[3] When the items that examine reading, writing, and arithmetic abilities were also considered in the analysis, the Group effect was significant, $F(2, 38) = 16.90$, $p < .0001$, with illiterates differing from both ex-illiterates and schooled literates, $ps < .0005$, with average scores of 23.9, 27.8 and 28.4, respectively.

[4] For the objects set, within each graspability class, half of the standard stimuli were oriented to the left and half to the right.

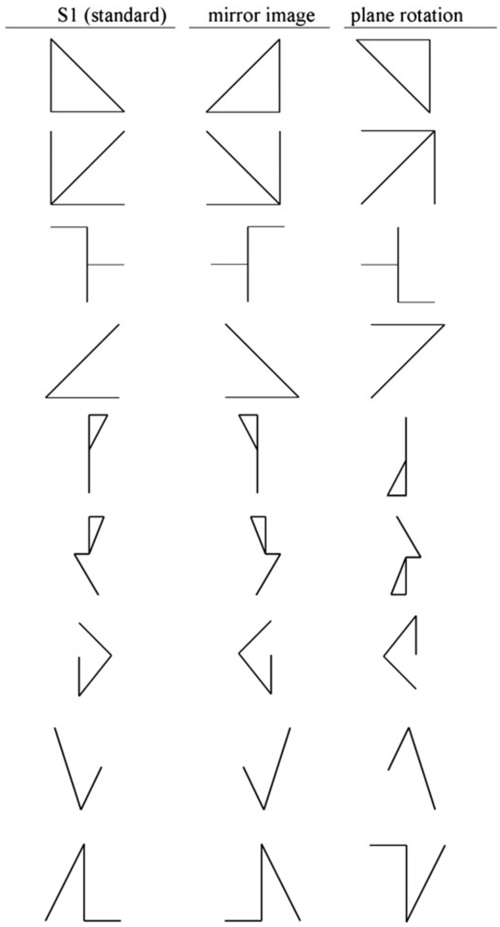

Fig. 2. Set of geometric shapes used in Experiment 1.

Stimuli presentation, timing, and data collection was controlled by E-Prime 2.0 (http://www.pstnet.com/eprime). Instructions were given orally; participants were asked to decide as accurately and quickly as possible whether the second stimulus was (or was not) an exact match of the first, using the index-fingers to press one of two buttons of the SRT-Box ("same" responses were given with the right index finger). Participants were told that they should respond "different" (using the left key, left index finger) if the second stimulus had a different orientation than the first, even if the two had the same identity. For the objects set, participants were not told about graspability. Reaction times (RTs) were measured from the onset of the second stimulus to response onset. Immediately after response, another trial began; if no response was provided the next trial began after 4750 ms.

Participants first performed six demo trials in which the stimuli were presented in the center of A4 sheets (the first, standard stimulus on paper sheets and the second, comparison stimulus on transparent sheets). In these trials (half leading to a "same" response), participants were first presented with the standard during 2 s, after which it was replaced by the comparison stimulus. Participants were asked to decide whether the latter was or was not an exact match of the first. On each trial, feedback was provided by superimposing the transparent sheet (comparison stimulus) on the paper sheet (standard), demonstrating that for same identity and different orientation trials, the second stimulus should be considered as different due to the orientation difference. Next, participants performed 12 computerized practice trials with the same procedure as experimental trials, after which they performed the two blocks of experimental trials, separated by a short break.

After Experiment 1 and a short pause, participants performed Experiment 2.

2.2.2. Experiment 2

The motor representations automatically afforded by graspable objects are determined by the current orientation as long as it is compatible with the objects' typical function (Masson et al., 2011). As this is always the case for mirror images but not for plane rotations, only the standard and mirrored versions of the familiar objects of Experiment 1 (see Section 2.2.1; Fig. 1A) were used here.

Each trial started with a fixation cross, presented in the center of the screen for 250 ms, after which a stimulus was presented at the same location for a maximum of 2000 ms (see Fig. 1C). Immediately after participants gave their response, another trial began, or if no response was provided the next trial began after 2750 ms. Participants performed 576 trials in which the two object sets (graspable and non-graspable, 288 trials each) were randomly intermixed, and in which no more than three trials in a row led to the same response or presented the same object. Participants were not told that two successive stimuli could be mirror images of each other (in one fourth of the trials; in the others, they were exact matches, or depicted different objects, either with the same orientation or with different orientations, see Fig. 1C).

On each trial, participants were asked to decide which hand they would use to grasp the object presented on the screen by pressing the right or the left button of the SRT-Box with their index fingers. Participants had thus to consider the orientation of the target object, independently of being right- or left-handed; they were told that they should imagine grasping the object presented on the screen through one single movement, without changing their position relative to the object. To clarify the instructions, four demo trials with graspable objects (not part of the experimental set) were presented, after which participants performed eight practice trials (with the same procedure as for experimental trials) with feedback on response correctness, to guarantee that they understood the task.

Prior to the experimental trials, participants were informed that for some objects there would be no straight answer (i.e., there was no obligation of using one particular hand), and hence, they should pay careful attention to the stimulus. Performance was only analyzed for the graspable set.

The whole session (Experiments 1 and 2) lasted about 2 h.

3. Results and discussion

Based on previous work with illiterate adults (e.g., Kolinsky et al., 2011), we know that these participants have difficulties with orientation-based tasks, particularly for enantiomorphs, and also at speeded responses, to which they are not used to. Thus, although RTs were collected and analyzed to guarantee that there was no trade-off between RTs and accuracy, the latter was the primary measure of interest that will be presented here. Accuracy was analyzed using the arcsine transformation of the proportion of correct responses,[5] but for the sake of clarity the results are presented in percentages.

3.1. Experiment 1: performance pattern in the vision-for-perception task

3.1.1. Accuracy results

We first examined the accuracy scores in the mixed ANOVA with Group (illiterates; ex-illiterates; and literates) as between-participants

[5] Given that proportion of correct responses follows a binomial distribution in which the variance is usually a direct function of the mean, to guarantee no violation of the normality assumption necessary for conducting ANOVAs, these data were arcsine transformed (see e.g., Howel, 2010). Still, we always checked that the same statistical results were found when ANOVAs were run over the (untransformed) proportion of correct responses.

variable, and Material (graspable objects; non-graspable objects; and geometric shapes) and Trial type (same; mirror-image; plane-rotation; and fully different) as within-participants variables.

The main effect of Material was significant, $F(2, 38) = 11.89$, $p < .00005$, $MSE = 0.025$, $\eta p^2 = .238$. Overall, graspable objects and geometrical shapes led to similar performance, $F(1, 38) = 2.31$, $p > .10$, which was significantly better than that for non-graspable objects, $F(1, 38) = 69.88$, $p < .0001$ and $= 6.89$, $p = .01$, respectively. This main effect was modulated by Trial type, $F(6, 228) = 6.93$, $p < .0001$, $MSE = 0.008$, $\eta p^2 = .154$. As illustrated in Fig. 3, except for fully different trials, $F < 1$, the main effect of Material was significant for all other trial types [$F(1, 38) = 4.04$, $p < .05$, $= 16.75$, $p < .001$ and $= 11.99$, $p < .001$ for same, mirror-image and plane-rotation trials, respectively]. No significant Group × Material interaction was found, $F < 1$.

Critically, the interaction between Group and Trial type was significant, $F(6, 114) = 3.44$, $p < .005$, $MSE = 0.022$, $\eta p^2 = .153$, and not modulated by Material, $F < 1$, as shown in Fig. 3 (main effects of Group, $F(2, 38) = 13.70$, $p < .0005$, $MSE = 0.238$, $\eta p^2 = .219$, and of Trial type, $F(3, 114) = 64.30$, $p < .0001$, $MSE = 0.022$, $\eta p^2 = .628$).

All groups exhibited the same qualitative pattern, with worst performance for mirror images compared to both plane rotations ($F(1, 38) = 62.09$, $= 33.6$, and $= 23.07$, for illiterates, ex-illiterates, and literates, respectively, all $ps < .005$) and fully different trials, $F(1, 38) = 62.75$, $= 43.13$, and $= 22.45$, for illiterates, ex-illiterates, and literates, respectively, all $ps < .005$. Nevertheless, illiterates showed the strongest performance drop for mirror-image trials relative to other trial types in comparison to the two literate groups considered jointly (as they presented similar results), $F(1, 38) = 5.46$, $p = .025$. In contrast, illiterates did not show a stronger performance drop for plane-rotation trials relative to other trial types in comparison to the two literate groups, $F < 1$.

Note, however, that post-hoc comparisons between groups for each trial type showed that illiterates presented worse performance than the literate groups for all "different" trial types, all $ps < .05$ (for same trials: illiterates vs. ex-illiterates: $p = .24$; illiterates vs. literates: $p = .44$). It thus seems that literacy impacts orientation discrimination overall. In fact, observing absolute differences between groups for the "different" trial types is not surprising, as previous work has already shown that reading is a highly demanding visual task with strong consequences on vision at both the behavioral and brain levels (Dehaene, Pegado, et al., 2010; Kolinsky et al., 2011; Szwed et al., 2012). But this result pattern argues for controlling for the overall performance difference between groups. It is only in this way that we can determine whether literacy in the Latin alphabet facilitates enantiomorphy more than the discrimination of non-enantiomorphic, plane-rotation contrasts.

3.1.2. Controlling for overall differences between groups

We estimated the performance drop of each participant for, on the one hand, mirror-image contrasts and, on the other hand, plane-rotation contrasts, using the fully different trials as baseline. We entered the proportion of correct responses into the following formula: $(x - y)/(x + y)$, where x corresponds to the proportion of correct responses on the fully different trials, and y to the proportion of correct responses on either mirror-image or plane-rotation trials. Thus, the stronger the relative

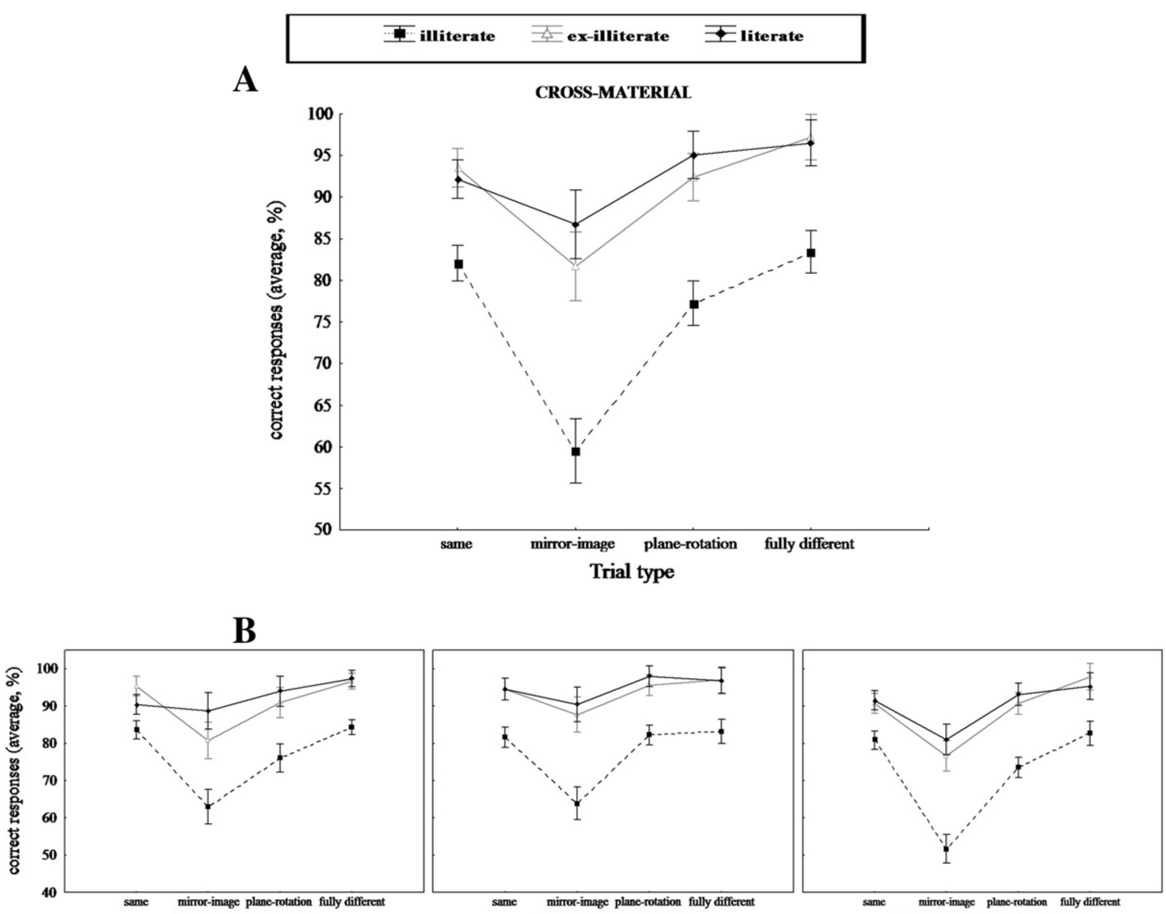

Fig. 3. Accuracy (average, %) in the vision-for-perception task (Experiment 1), separately by Group (illiterate, ex-illiterate, and literate) and Trial type (same; mirror image, plane rotation, and fully different). Error bars correspond to standard error. A: Cross-material accuracy. B: Accuracy separately by Material: geometric shapes; graspable objects; and non-graspable objects.

difficulty to discriminate the stimuli on the basis of an orientation contrast only (either mirror-image or plane-rotation) rather than on the basis of an identity *and* orientation contrast (on fully different trials), the higher the index value for either mirror images or plane rotations.

In the mixed Group × Material × Orientation (mirror-image vs. plane-rotation) ANOVA run on this index, the critical Group × Orientation interaction was significant, $F(2, 38) = 8.58$, $p < .001$, $MSE = 0.007$, $\eta p^2 = .311$. As shown in Table 1, the performance drop for plane-rotation contrasts was similar across the three groups (illiterates vs. ex-illiterates: $F < 1$; illiterates vs. literates: $F(1, 38) = 2.76$, $p > .10$; ex-illiterates vs. literates: $F = 1$). In other words, the performance drop for these contrasts was not affected by literacy. On the contrary, for mirror-image contrasts illiterates presented a stronger performance drop in comparison to both ex-illiterates, $F(1, 38) = 8.21$, $p < .01$, and literates, $F(1, 38) = 17.07$, $p < .0005$; the two literate groups did not differ from each other, $F < 1.5$.

Note, however, that, as presented in Table 1, enantiomorphic contrasts were harder than plane-rotation contrasts even for the literate groups [main effect of Orientation: $F(1, 38) = 69.91$, $p < .00001$ and simple effects of Orientation for each Group: illiterates: $t(14) = 6.19$, ex-illiterates: $t(12) = 5.26$, and literates: $t(12) = 3.72$, all $ps < .0005$].

The main effect of Material, $F(2, 76) = 10.76$, $p < .0001$, $MSE = 0.005$, $\eta p^2 = .220$, $MSE = 0.007$, $\eta p^2 = .648$, was modulated by Orientation, $F(2, 76) = 7.74$, $p < .001$, $MSE = 0.002$, $\eta p^2 = .169$. Neither the interaction between Group and Material, $F < 1$, nor the three-way interaction, $F(4, 76) = 1.96$, $p = .11$, was significant.

For plane rotations, all groups benefited from the graspability of familiar objects. Graspable objects were the easiest to discriminate, in comparison to both non-graspable objects and geometric shapes, $F(1, 38) = 22.13$, and $= 7.71$, both $ps < .01$, whereas no difference was found between the two latter materials, $F < 1$ (see Table 1).

For mirror images, discrimination was the hardest for non-graspable objects in comparison to both graspable objects and geometric shapes, $F(1, 38) = 38.19$, and $= 9.18$, both $ps < .005$. Graspable objects also tended to be easier to discriminate than geometric shapes, $F(1, 38) = 3.84$, $p = .06$.

In sum, the result pattern of Experiment 1 reinforces prior evidence (Kolinsky et al., 2011) showing that the impact of literacy on visual perception is particularly strong for enantiomorphy, which extends to familiar objects. This result pattern is also in line with the notion that plane rotations and mirror images are subserved by different mechanisms (Baylis & Driver, 2001; Gregory & McCloskey, 2010; Logothetis & Pauls, 1995; Logothetis et al., 1995; Turnbull & McCarthy, 1996; Turnbull et al., 1997).

As prior work has already suggested (e.g., Szwed et al., 2012), literacy benefits visual discrimination in many situations. Yet, what the present results clearly show is that the impact of literacy on orientation discrimination is enantiomorphic-specific. Note that both orientation contrasts here at study differed from the standard stimulus by the same 180° difference, and both are important to discriminate lowercase letters of the Latin alphabet (enantiomorphs: e.g., "b" vs "d"; plane rotations: e.g., "u" vs. "n"). Nevertheless, after controlling for the overall performance differences between groups, illiterates differed from literates only for enantiomorphs, not for plane rotations.

The results found in Experiment 1 cannot be attributed to overall cognitive differences between groups as the same statistical patterns were found in the ANOVAs aforementioned when the MMSE revised scores were entered as covariate. This conclusion was further reinforced by the results of stepwise regression analyses using as predictors the MMSE revised scores and literacy abilities (i.e., composite measure using letter knowledge and reading abilities). For mirror-images, only the literacy abilities were a reliable predictor of the performance drop, $F(2, 38) = 5.03$, $p = .01$, $R^2 = .21$, β (MMSE) = −.08, $t < 1$, β (literacy abilities) = −.46, $t = -3.16$, $p < .005$, but for plane-rotations neither factor was reliable, $F < 1$, $R^2 = .04$, β (MMSE) = .15, β (literacy abilities) = −.14, both $ts < 1$.

Whether the enantiomorphic trouble of illiterates found in Experiment 1 corresponded to a general difficulty in processing mirror images was examined in Experiment 2.

3.2. Experiment 1 vs. Experiment 2: comparison between performance in vision-for-perception and vision-for-action tasks

In order to evaluate whether illiterates differed from the two literate groups only in the vision-for-perception task (Experiment 1), we compared the overall performance of the three groups in Experiments 1 and 2. For this analysis, accuracy results were considered for familiar graspable objects only (see Fig. 4).

In the mixed Group (illiterates; ex-illiterates; and literates: between-participants factor) × Task (Experiment 1 and Experiment 2: within-participants factor) ANOVA run on the accuracy results, the main effect of Group, $F(2, 37) = 8.65$, $p < .001$, $MSE = 0.017$, $\eta p^2 = .318$, was modulated by Task, $F(2, 37) = 7.53$, $p < .005$, $MSE = 0.014$, $\eta p^2 = .289$.

As shown in Fig. 4, illiterates were the only group with better performance in the virtual grasping task (Experiment 2) than in the same–different comparison task (Experiment 1), $F(1, 37) = 12.91$, $p < .001$. The two literate groups displayed similar performance levels in both tasks (literates: $F(1, 37) = 2.39$, $p = .13$; ex-illiterates: $F < 1$). Furthermore, illiterates did not differ from the other groups in the virtual grasping task, $F < 1$; they had thus worst performance than the literate groups only in the same–different comparison task of Experiment 1, $F(2, 37) = 10.11$, $p < .0005$.

Neither overall differences in difficulty between tasks nor ceiling effects in the virtual grasping task seem to explain this interaction between Group and Task. On the one hand, no significant main effect of Task was found, $F < 1$: the two tasks presented similar overall levels of difficulty. On the other hand, although the performance level in the virtual grasping task was similar in the three groups, it was far from ceiling. Indeed, none of the participants had an accuracy of 100%, and only nine out of the 40 participants tested (two illiterates, five ex-illiterates, and

Table 1
Performance drop computed for mirror-image and plane-rotation contrasts using as baseline performance on fully different trials, separately by Group and Material.

Material	Orientation contrast	Illiterates		Ex-illiterates		Literates		Cross-groups	
Geometric shapes	Mirror-image	.162	(.03)	.106	(.04)	.049	(.02)	.106	(.02)
	Plane-rotation	.064	(.02)	.036	(.02)	.018	(.01)	.039	(.01)
Graspable objects	Mirror-image	.149	(.03)	.054	(.01)	.035	(.01)	.080	(.01)
	Plane-rotation	−.001	(.02)	.007	(.01)	−.007	(.01)	.000	(.01)
Non-graspable objects	Mirror-image	.245	(.03)	.126	(.02)	.082	(.02)	.151	(.01)
	Plane-rotation	.053	(.02)	.040	(.01)	.009	(.01)	.034	(.01)
Cross-material	Mirror-image	.185	(.02)	.095	(.02)	.056	(.05)		
	Plane-rotation	.039	(.01)	.028	(.01)	.007	(.01)		

Note: Standard error of the mean in parentheses.

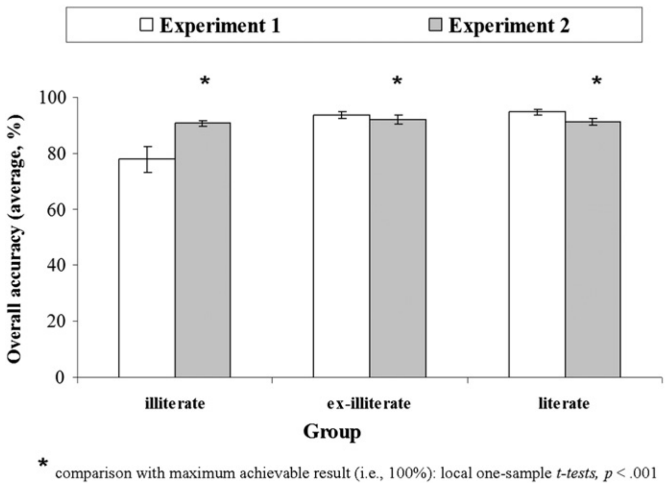

Fig. 4. Overall accuracy (average, %) in Experiment 1 (an orientation-dependent vision-for-perception task) and in Experiment 2 (a virtual-grasping vision-for-action task), separately for each Group (illiterate, ex-illiterate, and literate). Error bars correspond to standard error.

two literates) performed above 95% (see Fig. 4 for the local one-sample *t*-tests comparison with maximum achievable result, i.e., 100%[6]). Therefore, the between groups difference in the vision-for-perception task (Experiment 1) cannot be attributed mainly to overall differences in general cognitive abilities. Had it been the case, illiterates should have differed from the other groups in the virtual grasping task (Experiment 2) as well.

The results of the present experiment suggest that in a virtual grasping task, which probably triggers real-time visuomotor representations, illiterates are as sensitive as literates to enantiomorphic-related information. This stands in sharp contrast to the illiterates' difficulty with enantiomorphy found in Experiment 1, suggesting that illiterates do not have a general difficulty in processing mirror images.

4. General discussion

In the present study, we extended prior work on the impact of literacy acquisition on enantiomorphy (Danziger & Pederson, 1998; Kolinsky et al., 2011; Pederson, 2003) by examining the performance of three groups of adults differing by schooling and literacy (i.e., unschooled illiterates and ex-illiterates, plus schooled literates) in two Experiments. We delineated three approaches to test our hypotheses that the impact of literacy (in a mirrored script) (i) generalized to familiar non-linguistic objects; (ii) affected specifically enantiomorphy rather than any orientation contrast during vision-for-perception; and (iii) was specific to vision-for-perception tasks.

First, in Experiment 1 we compared participants' same–different orientation judgments for three materials: non-linguistic geometric shapes, and two types of familiar objects differing on the graspability dimension, i.e., the degree by which visuomotor information is critical for the representation of those objects. Thus, for the first time, we examined whether enantiomorphy, as consequence of literacy acquisition, would generalize to familiar non-linguistic objects. Second, as previous studies have indicated that literacy has a large impact on visual perception (e.g., Szwed et al., 2012), and hence, on the processing of various orientation contrasts (Kolinsky et al., 2011), we examined participants' performance on two types of orientation contrasts – plane rotations and mirror images, differing from the standard position by the same 180° difference – while using as baseline participants' performance on fully different trials, in which stimuli differed by both orientation and identity. Finally, by evaluating the performance of the three groups not only in a vision-for-perception task (Experiment 1) but also in a virtual grasping, vision-for-action, task (Experiment 2), we were able to examine whether the effect of literacy acquisition is confined to the former situation, predicting illiterates to be as good as literates in the vision-for-action task.

In Experiment 1, participants performed an orientation-based, sequential same–different comparison task. Prior neuroimaging and neuropsychological evidence suggests that this vision-for-perception task requires object recognition and the adoption of a viewer-independent, allocentric referential frame, probably mediated by the ventral stream (e.g., Creem & Proffitt, 2001; Goodale et al., 1994; Milner & Goodale, 1993, 2008), as well as the comparison between a current stimulus and a previously stored representation, thus mainly involving high-level perceptual representations (Cohen et al., 2009; Rossit et al., 2011). In Experiment 2, participants performed a virtual grasping task. This vision-for-action task required an on-line response to the currently presented stimulus based on an egocentric referential frame and probably on visuomotor interaction; hence, it might be mediated by the dorsal stream (e.g., Cohen et al., 2009; Creem & Proffitt, 2001; Goodale et al., 1994; Milner & Goodale, 2008; Murata et al., 2000).

The result pattern of Experiment 1 adds to prior evidence (Danziger & Pederson, 1998; Kolinsky et al., 2011; Pederson, 2003) by showing that once triggered by literacy acquisition in a script with mirrored symbols, as the Latin alphabet, enantiomorphy generalizes to familiar objects. Crucially, we have also shown that literacy does not merely enhance orientation discrimination overall, but is specifically critical to trigger enantiomorphy. Indeed, in comparison to the easiest discrimination at test (i.e., on fully different trials), the performance drop for mirror images was significantly more severe in illiterate than in literate groups, whereas for plane rotations the performance drop was similar across groups. Therefore, although both orientation contrasts are important in the Latin alphabet, the impact of literacy is particularly strong for enantiomorphy.

This result pattern does not stem from variability in more general cognitive skills between the illiterate and literate groups. In the stepwise regressions run on the performance drop for plane rotations and for mirror images, after partialling out the potential impact of general cognitive abilities (using participants' MMSE revised scores), literacy abilities (i.e., letter knowledge and reading skills) were still a reliable predictor of the enantiomorphic performance drop, which was not the case for plane rotations.

The result pattern observed in Experiment 1 is consistent with the notion that different processing mechanisms are engaged by plane rotations and mirror reflections (Baylis & Driver, 2001; Gregory & McCloskey, 2010; Logothetis & Pauls, 1995; Logothetis et al., 1995; Turnbull & McCarthy, 1996; Turnbull et al., 1997). Noteworthy, enantiomorphy continued to be harder than plane rotation discrimination for all groups, even literates. Given that enantiomorphy is learned during literacy acquisition in a script with mirrored symbols, it may remain less pregnant or less automatically evoked than the discrimination of other orientation contrasts. Thus, the original properties of the occipitotemporal region (i.e., mirror invariance vs. plane-rotation variance: Baylis & Driver, 2001; Logothetis & Pauls, 1995; Logothetis et al., 1995; Rollenhagen & Olson, 2000), although recycled for literacy acquisition (Dehaene & Cohen, 2011), may not be entirely erased in the Latin alphabet reader (see also Duñabeitia, Molinaro, & Carreiras, 2011; Perea, Moret-Tatay, & Panadero, 2011).

In Experiment 1, the type of material, as regards graspability and familiarity, also modulated enantiomorphic performance, and this effect was largely independent of the impact of literacy. Regarding familiar objects, graspability facilitated orientation judgments for all groups and for both plane rotations and mirror images. Note that

[6] Although accuracy is a binomial variable, the more trials, the more closely the sampling distribution resembles a normal curve (e.g., Lewis, Bryman, & Liao, 2004). Given that, in the present study, the distribution of accuracy results did not differ from a normal distribution, $X^2(2) = 1.53$, $p = .46$, we examined whether participants' average accuracy differed from the maximum score using one-sample local *t*-tests. Still, we also checked that the same statistical result was found with nonparametric binomial tests (binomial, all $ps \leq .001$).

visual factors as complexity and familiarity of graspable and non-graspable objects were controlled for (see Sections 2.1.2. and the Appendix A), and in the easiest discrimination at test (i.e., on fully different trials), all participants were as able to discriminate graspable as non-graspable objects. Thus, the present results are coherent with the notion that orientation signals the visuomotor properties of graspable objects, being critical to these objects but not to non-graspable ones (e.g., Murata et al., 2000; Rice et al., 2007; Tucker & Ellis, 1998; Valyear et al., 2006).

Regarding familiarity of the material, geometric shapes led to better performance than non-graspable objects, but only for enantiomorphic contrasts, not for plane rotations. This held true for all groups, including illiterates; although unfamiliarity of the material did not help them to fully overcome their difficulties with enantiomorphs, which were found for all materials. The codification of novel material using viewpoint-dependent representations (cf. Tarr & Bülthoff, 1995; Tarr & Pinker, 1989) may specifically benefit enantiomorphy in a vision-for-perception task, given that the representations involved in such a task may depend on ventral regions that are mirror invariant for familiar objects (Dehaene, Nakamura, et al., 2010; Pegado et al., 2011), but sensitive to plane rotations (Baylis & Driver, 2001; Logothetis & Pauls, 1995; Logothetis et al., 1995). Furthermore, geometric shapes are more letter-like than pictures of familiar objects; hence, the specific benefit on enantiomorphy for this material might also be related to evidence showing that the VWFA of preliterate children already responds to the presentation of letter-like symbols in comparison to faces or shoes (Cantlon, Pinel, Dehaene, & Pelphrey, 2011; but see James, 2011).

In sharp contrast to the results found in Experiment 1, in Experiment 2, illiterates were as able as literates to perform a virtual grasping task. The exclusive difference between illiterate and literate groups in the vision-for-perception task (Experiment 1) cannot be attributed to overall differences in tasks' difficulty. For the literate and ex-illiterate groups, both tasks led to similar performance levels, which although quite good, were not at ceiling. Furthermore, the fact that illiterate participants were as good as the literate groups in the vision-for-action task (Experiment 2) also ensures that the differences between groups found in Experiment 1 cannot be attributed to illiterates being either less able to sustain attention over a lengthy experimental session or cognitively less competent overall. Had it been the case, we should have found an overall difference between the illiterate and literate groups in the two experiments. Quite on the contrary, the results of the present study show that literacy triggers enantiomorphy as part of vision-for-perception. In other words, the illiterates' difficulty with enantiomorphy does not correspond to a general difficulty in processing mirror images. As long as the task relies on visuomotor operations performed on-line, illiterates behave just as literates.

Indeed, in line with what has been suggested by Tucker and Ellis (1998) in another situation that did not require an object-directed action (an upright/inverted judgment), we suggest that performance in the virtual grasping task of Experiment 2 is afforded by participants' sensitivity to the “graspable” components of the objects, which in turn afford the motor representation of those objects. In Experiment 2, mirror images processing was measured indirectly when participants performed the virtual grasping on a target stimulus that was a mirror image of the former target. Still, to perform successfully on those trials, participants must have been sensitive to enantiomorphic-related information. As illiterates succeeded quite well, our results suggest that different representations were involved in Experiment 2 vs. Experiment 1. Although further work using brain imaging would be needed to confirm this idea, it seems probable that these representations are subserved by dorsal regions (Rice et al., 2007; Valyear et al., 2006), which would be in accordance with the more general notion that imagined action (or *motor imagery*) involves mechanisms similar to those operating during the real action (Jeannerod, 1994, 1997).

The result pattern observed in Experiment 2 may however hold true only as far as the required computations are performed in real-time. Previous literature has already shown that besides the adoption of an egocentric referential frame (Milner & Goodale, 1993, 2008), the time-window at which visuomotor computations are performed is critical as regards the relative involvement of the dorsal and/or ventral streams (e.g., Creem & Proffitt, 2001; James et al., 2003; Rossit et al., 2011). It would thus be interesting to check illiterates' performance in a delayed virtual grasping task, in which they would be asked to decide whether they would use the same or a different hand to grasp the current and a previous stimulus. Given that high-level perceptual representations should be enrolled in such a task (Cohen et al., 2009; James et al., 2003), we would expect illiterates to display poor performance. Importantly, poorer performance in such a task would be expected only with sequential presentation of the stimuli but not when the task requires vision-for-perception anyway, as it is the case of the orientation-based comparison task used in Experiment 1. In other words, illiterates' enantiomorphic difficulties would depend on the vision-for-perception vs. vision-for-action nature of the task and not on the presentation mode (simultaneous vs. sequential) per se. Indeed, Kolinsky et al. (2011) have already shown that illiterates display as poor enantiomorphic performance in simultaneous as in sequential vision-for-perception tasks.

The fact that illiterates were as sensitive to enantiomorphic-related information as literates in Experiment 2 is also coherent with the idea that motor knowledge acquired through writing could contribute to the visual recognition of letters. Indeed, Longcamp et al. (2008) showed that adult learners that were taught a novel script had better enantiomorphic abilities for symbols on which they practiced handwriting than for those on which they practiced typewriting. Possibly, early on in literacy learning, the left–right discrimination of letters is guided primarily by motor actions, as in handwriting, encoded in parietal areas, part of the dorsal stream, and also in frontal motor/premotor areas (James, 2011). Sensory-motor experience may also be critical to the emergence of neural specialization for letters: four-years-old preliterates, who practiced handwriting (copying letters and words), exhibited stronger activation of the fusiform regions to letters (vs. false-fonts and geometric shapes) than children who did not performed the visuomotor training (James, 2011). Future studies should test the relationship between motor discrimination, literacy learning, and enantiomorphy.

In the vision-for-perception task of Experiment 1, literate participants were quite able of classifying enantiomorphs as being *different* stimuli. This result pattern is actually a mirror image of the literates' performance pattern found by Pegado et al. (submitted for publication) in an identity-based (i.e., orientation-independent) same–different comparison task. There, literates suffered from irrelevant enantiomorphic variations for all materials at test, whereas illiterates did not display any interference from such irrelevant variations. The present findings and those of Pegado et al. (see also Dehaene, Nakamura, et al., 2010) suggest that one of the deleterious effects of literacy learning in a script with mirrored symbols is the automatized discrimination of enantiomorphs during object recognition.

In sum, an emergent bulk of research has been devoted to the impact of literacy acquisition on visual non-linguistic object processing (e.g., Dehaene, Pegado, et al., 2010; Kolinsky et al., 2011; Pegado et al., submitted for publication; Szwed et al., 2012). The present results clearly indicate that literacy triggers enantiomorphy during object recognition of any visual category, although the original properties of the ventral stream do not seem to be entirely erased in skilled readers. Moreover, the difficulties in enantiomorphy shown by illiterates seem to pertain only to vision-for-perception tasks. In vision-for-actions tasks, requiring on-line visuomotor computations — from hand to eye, sensitivity to enantiomorphic-related information is not influenced by literacy.

Acknowledgments

Preparation of this article was supported by a FRFC grant (Convention 2.4515.12, “Cognitive and brain plasticity in learning to read:

comparing early, late, missing and failed literacy"), Belgium, and by Centro de Psicologia of Universidade do Porto, Portugal. Régine Kolinsky is Research Director of the Fonds de la Recherche Scientifique-FNRS, Belgium.

We would like to thank Sérgio Gregório, Olga Mariano, and Maria Alzinda for the assistance in contacting the individuals that participated in this study.

We would also like to thank Marcin Szwed and two other anonymous reviewers for the very relevant comments they made on a previous version of this manuscript.

Appendix A

List of the pictures of familiar objects used (mainly from Snodgrass & Vanderwart, 1980, plus from Bonin, Peereman, Malardier, Méot, & Chalard, 2003), and their values in visual ambiguity, complexity, familiarity (cf. Ventura, 2003), and graspability, as evaluated in the pre-test reported in Section 2.1.2.

[a]Graspability; G = graspable objects; NG = non-graspable objects.
*Items from Bonin et al. (2003).

Item	Graspable class[a]	Ambiguity	Complexity	Familiarity	Graspability
Ax	G	2.43	2.48	2.33	1.55
Brush	G	2.97	2.82	4.71	2.65
Clothespin	G	1.50	2.82	4.55	2.20
Coffee pot*	G	1.70	2.90	3.40	1.40
Cup	G	2.88	1.78	4.62	2.00
Fork	G	2.00	2.62	4.93	1.70
frying pan	G	2.78	2.05	4.24	1.85
Gun	G	2.00	3.53	1.79	1.25
Hammer	G	2.08	2.60	2.00	1.25
Iron	G	3.10	3.25	4.78	2.15
Kettle	G	2.30	2.40	2.86	1.75
Mug*	G	2.80	2.45	4.62	1.60
Pitcher	G	2.66	1.85	4.28	1.30
Scissors	G	1.75	2.15	4.38	1.85
Screwdriver	G	2.51	2.35	3.08	1.60
Tea pot*	G	2.31	2.78	2.90	1.85
tennis racket	G	2.25	2.55	3.17	1.65
watering can	G	1.63	2.78	3.07	1.95
Average (SD)	G	2.31 (0.49)	2.56 (0.45)	3.65 (1.03)	1.75 (0.36)
Baby carriage	NG	2.43	3.42	2.56	3.85
Boot	NG	1.94	2.45	4.24	3.90
Chair	NG	2.61	2.05	4.81	4.25
Flag	NG	2.18	1.88	2.82	2.70
Glasses	NG	2.59	2.85	4.33	3.45
Hanger	NG	1.98	1.20	4.14	3.55
Hat	NG	2.55	2.35	2.78	3.30
Kite	NG	1.66	2.85	2.71	4.20
Rolling pin	NG	2.09	1.52	3.14	4.10
Screw	NG	2.61	3.25	3.61	3.00
Shirt	NG	2.78	3.08	4.56	4.40
Shoe	NG	2.29	3.38	4.78	4.15
Sock	NG	2.35	1.62	4.86	4.10
Suitcase	NG	2.53	3.60	3.93	3.25
Truck	NG	2.47	2.75	3.25	4.00
Umbrella	NG	2.08	3.00	3.89	3.40
Watch	NG	2.20	3.4	4.67	3.30
Wheelbarrow*	NG	2.43	3.42	3.15	4.30
Average (SD)	NG	2.32 (0.29)	2.67 (0.75)	3.79 (0.80)	3.73 (0.50)

References

Baylis, G. C., & Driver, J. (2001). Shape-coding in IT cells generalizes over contrast and mirror reversal, but not figure-ground reversal. *Nature Neurosciences*, *4*, 937–942. http://dx.doi.org/10.1038/nn0901-937.

Biederman, I., & Gerhardstein, P. C. (1993). Recognizing depth rotated objects : Evidence and conditions for three-dimensional viewpoint invariance. *Journal of Experimental Psychology. Human Perception and Performance*, *19*, 1162–1182.

Bonin, P., Peereman, R., Malardier, N., Méot, A., & Chalard, M. (2003). A new set of 299 pictures for psycholinguistic studies: French norms for name agreement, image agreement, conceptual familiarity, visual complexity, age of acquisition, and naming latencies. *Behavior Research Methods, Instruments, & Computers*, *35*, 158–167.

Cantlon, J. F., Pinel, P., Dehaene, S., & Pelphrey, K. A. (2011). Cortical representations of symbols, objects, and faces are pruned back during early childhood. *Cerebral Cortex*, *21*, 191–199. http://dx.doi.org/10.1093/cercor/bhq078.

Cohen, N. R., Cross, E. S., Tunik, E., Grafton, S. T., & Culham, J. C. (2009). Ventral and dorsal stream contributions to the online control of immediate and delayed grasping: A TMS approach. *Neuropsychologia*, *47*, 1553–1562. http://dx.doi.org/10.1016/j.neuropsychologia.2008.12.034.

Cohen, L., Dehaene, S., Naccache, L., Lehéricy, S., Dehaene-Lambertz, G., Hénaff, M. A., et al. (2000). The visual word form area: Spatial and temporal characterization of an initial stage of reading in normal and posterior split-brain patients. *Brain*, *123*, 291–307.

Corballis, M. C., & Beale, I. L. (1976). *The psychology of left and right.* Hillsdale, NJ: Erlbaum.

Creem, S. H., & Proffitt, D. R. (2001). Defining the cortical visual systems: "What", "where", and "how". *Acta Psychologica*, *107*, 43–68.

Crum, R. M., Anthony, J. C., Bassett, S. S., & Folstein, M. F. (1993). Population-based norms for the mini-mental-state-examination by age and educational-level. *Journal of the American Medical Association*, *269*, 2386–2391.

Danziger, E., & Pederson, E. (1998). Through the looking-glass: Literacy, writing systems, and mirror-image discrimination. *Written Language and Literacy*, *1*, 153–164.

Dehaene, S., & Cohen, L. (2011). The unique role of the visual word form area in reading. *Trends in Cognitive Sciences*, *15*, 254–262. http://dx.doi.org/10.1016/j.tics.2011.04.003.

Dehaene, S., Nakamura, K., Jobert, A., Kuroki, C., Ogawa, S., & Cohen, L. (2010). Why do children make mirror errors in reading? Neural correlates of mirror invariance in the visual word form area. *NeuroImage*, *49*(2), 1837–1848. http://dx.doi.org/10.1016/.neuroimage2009.09.024.

Dehaene, S., Pegado, F., Braga, L. W., Ventura, P., Nunes, G., Jobert, A., et al. (2010). How learning to read changes the cortical networks for vision and language. *Science*, *330*, 1359-1354. http://dx.doi.org/10.1126/science.1194140.

Duñabeitia, J. A., Molinaro, N., & Carreiras, M. (2011). Through the looking-glass: Mirror reading. *NeuroImage*, *54*, 3004–3009. http://dx.doi.org/10.1016/j.neuroimage.2010.10.079.

Folstein, M. F., Folstein, S., & McHugh, P. R. (1975). 'Mini-mental state': A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12*, 189–198.

Gibson, E. J. (1969). *Principles of perceptual learning and development.* New York, NY: Appleton-Century-Crofts.

Goodale, M. A., Jakobson, L. S., & Keillor, J. M. (1994). Differences in the visual control of pantomimed and natural grasping movements. *Neuropsychologia*, *32*, 1159–1178. http://dx.doi.org/10.1016/0028-3932(94)90100-7.

Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neurosciences*, *15*, 20–25. http://dx.doi.org/10.1016/0166-2236(92)90344-8.

Gregory, E., & McCloskey, M. (2010). Mirror-image confusions: Implications for representation and processing of objects orientation. *Cognition*, *116*, 110–129. http://dx.doi.org/10.1016/j.cognition.2010.04.005.

Gross, C. G., & Bornstein, M. H. (1978). Left and right in science and art. *Leonardo*, *11*, 29–38.

Guerreiro, M., Silva, A. P., Botelho, M., Leitão, O., Castro-Caldas, A., & Garcia, C. (1994). Adaptação portuguesa da tradução do Mini Mental State Examination (MMSE) [Adaptation to the Portuguese population of the translation of the Mini Mental State Examination (MMSE)]. *Revista Portuguesa de Neurologia*, *1*, 9–10.

Howel, D. C. (2010). *Statistical methods for psychology* (7th ed.). USA: Cengage Wadsworth.

James, K. H. (2011). Sensori-motor experience leads to changes in visual processing in the developing brain. *Developmental Science*, *13*, 279–288. http://dx.doi.org/10.1111/j.1467-7687.2009.00883.x.

James, T. W., Culham, J., Humphreys, G. H., Milner, A. D., & Goodale, M. A. (2003). Ventral occipital lesions impair object recognition but not object-directed grasping: an fMRI study. *Brain*, *126*, 2463–2475. http://dx.doi.org/10.1093/brain/awg248.

Jeannerod, M. (1994). The representing brain. Neural correlates of motor intention and imagery. *The Behavioral and Brain Sciences*, *17*, 187–245.

Jeannerod, M. (1997). *The cognitive neuroscience of action.* Oxford: Blackwell.

Kolinsky, R., Verhaeghe, A., Fernandes, T., Mengarda, E. J., Grimm-Cabral, L., & Morais, J. (2011). Enantiomorphy through the looking-glass: Literacy effects on mirror-image discrimination. *Journal of Experimental Psychology. General*, *140*(2), 210–238. http://dx.doi.org/10.1037/a0022168.

Lewis, M. S., Bryman, A., & Liao, T. F. (2004). *The Sage Encyclopedia of social science research methods.* Sage Publications.

Logothetis, N. K., & Pauls, J. (1995). Psychophysical and physiological evidence for viewer-centered object representations in the primate. *Cerebral Cortex*, *5*, 270–288.

Logothetis, N. K., Pauls, J., & Poggio, T. (1995). Shape representation in the inferior temporal cortex of monkeys. *Current Biology*, *5*, 552–563.

Longcamp, M., Boucard, C., Gilhodes, J. -C., Anton, J. -L.-., Roth, M., Nazarian, B., et al. (2008). Learning through hand- or typewriting influences visual recognition of new graphic shapes: Behavioral and functional imaging evidence. *Journal of Cognitive Neuroscience*, *20*, 802–815. http://dx.doi.org/10.1162/jocn.2008.20504.

Masson, M. E. J., Bub, D. N., & Breuer, A. T. (2011). Priming of reach and grasp actions by handled objects. *Journal of Experimental Psychology. Human Perception and Performance*, *37*, 1470–1484. http://dx.doi.org/10.1037/a0023509.

Milner, A. D., & Goodale, M. A. (1993). Visual pathways to perception and action. *Progress in Brain Research*, *95*, 317–337.

Milner, A. D., & Goodale, M. A. (2008). Two visual systems reviewed. *Neuropsychologia*, *46*, 774–785. http://dx.doi.org/10.1016/j.neuropsychologia.2007.10.005.

Murata, A., Gallese, V., Luppino, G., Kaseda, M., & Sakata, H. (2000). Selectivity for the shape, size, and orientation of objects for grasping in neurons of monkey parietal area AIP. *Journal of Neurophysiology*, *83*, 2580–2601.

Pederson, E. (2003). Mirror-image discrimination among nonliterates, monoliterate, and biliterate Tamil subjects. *Written Language & Literacy*, *6*, 71–91. http://dx.doi.org/10.1075/wll.6.1.04ped.

Pegado, F., Nakamura, K., Braga, L., Ventura, P., Nunes, G., Jobert, A., Morais, J., Cohen, L., Kolinsky, R., & Dehaene, S. (submitted for publication). Literacy breaks mirror invariance for visual stimuli: A behavioral study with adult illiterates.

Pegado, F., Nakamura, K., Cohen, L., & Dehaene, S. (2011). Breaking the symmetry: Mirror discrimination for single letters but not for pictures in the Visual Word Form Area. *NeuroImage*, *55*(2), 742–749. http://dx.doi.org/10.1016/j.neuroimage.2010.11.043.

Perea, M., Moret-Tatay, C., & Panadero, V. (2011). Suppression of mirror generalization for reversible letters: Evidence from masked priming. *Journal of Memory and Language*, *3*, 237–246. http://dx.doi.org/10.1016/j.jml.2011.04.005.

Rice, N. J., Valyear, K. F., Goodale, M. A., Milner, A. D., & Culham, J. C. (2007). Orientation sensitivity to graspable objects: An fMRI adaptation study. *NeuroImage*, *36*, T87–T93. http://dx.doi.org/10.1016/j.neuroimage.2007.03.032.

Rollenhagen, J. E., & Olson, C. R. (2000). Mirror-Image Confusion in Single Neurons of the Macaque Inferotemporal Cortex. *Science*, *287*(5457), 1506–1508. http://dx.doi.org/10.1126/science.287.5457.1506.

Rossit, S., Fraser, J. A., Teasell, R., Malhotra, P. A., & Goodale, M. A. (2011). Impaired delayed but preserved immediate grasping in a neglect patient with parieto-occipital lesions. *Neuropsychologia*, *49*, 2498–2504. http://dx.doi.org/10.1016/j.neuropsychologia.2011.04.030.

Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology: Human Learning and Memory*, *6*(2), 174–215.

Szwed, M., Ventura, P., Querido, L., Cohen, L., & Dehaene, S. (2012). Reading acquisition enhances an early visual process of contour integration. *Developmental Science*, *15*, 139–149. http://dx.doi.org/10.1111/j.1467-7687.2011.01102.x.

Tarr, M. J., & Bülthoff, H. H. (1995). Is human object recognition better described by geon structural descriptions or by multiple views? Comment on Biederman and Gerhardstein (1993). *Journal of Experimental Psychology. Human Perception and Performance*, *21*, 1494–1505.

Tarr, M. J., & Pinker, S. (1989). Mental rotation and orientation-dependent in shape recognition. *Cognitive Psychology*, *21*, 233–282.

Tucker, M., & Ellis, R. (1998). On the relations between seen objects and components of potential actions. *Journal of Experimental Psychology. Human Perception and Performance*, *24*, 830–846.

Turnbull, O. H., Becshin, E., & DellaSala, S. (1997). Agnosia for object orientation: Implications for theories of object recognition. *Neuropsychologia*, *35*, 153–163.

Turnbull, O. H., & McCarthy, R. A. (1996). When is a view unusual? A single case study of orientation-dependent visual agnosia. *Brain Research Bulletin*, *40*, 497–502.

Valyear, K. F., Culham, J. C., Sharif, N., Westwood, D., & Goodale, M. A. (2006). A double dissociation between sensitivity to changes in object identity and object orientation in the ventral and dorsal visual streams: A human fMRI study. *Neuropsychologia*, *44*, 218–228. http://dx.doi.org/10.1016/j.neuropsychologia.2005.05.004.

Ventura, P. (2003). Normas para figuras do corpus de Snodgrass e Vanderwart (1980) [Norms for the pictures of the database of Snodgrass and Vanderwart (1980)]. *Laboratório de Psicologia*, *1*, 5–19.