Into the looking glass: Literacy acquisition and mirror invariance in preschool and first-grade children

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Learning to read is a gateway to culture and education, and, most impressively, it profoundly changes the brain and mind. Literacy acquisition leads to the emergence of a neural network in the ventral occipitotemporal cortex tuned to the processing of written strings, reproducible across literate people, independently of script (e.g., in Japanese and French readers; Dehaene, Nakamura, et al., 2010; e.g., for kana and kanji in Japanese readers; Nakamura, Dehaene, Jobert, Le Bihan, & Kouider, 2005) and age of acquisition (i.e., in childhood for *early literate* adults, or in adulthood for *late literate* adults; Dehaene, Pegado, et al., 2010). Most impressively, learning to read also impacts on evolutionarily older systems, including visual object recognition (e.g., Dehaene, Nakamura, et al., 2010; Dehaene, Pegado, et al., 2010; Pegado, Nakamura, et al., 2014; Pegado, Nakamura, Cohen, & Dehaene, 2011). This agrees with the *neuronal recycling hypothesis* (Dehaene, 2009), which holds that the ventral occipitotemporal regions, originally devoted to object recognition, were partially recycled to accommodate literacy, with spillover effects on the older function.

In fact, probably as a consequence of the intensive perceptual training that it requires, literacy acquisition alters early visual responses in the occipital cortex, including in areas involved in very early processing (i.e, in V1; e.g., Dehaene, Pegado, et al., 2010; Pegado, Comerlato, et al., 2014). The impact of literacy can thus be found on several visual tasks outside the written domain. For instance, visual integration is enhanced in readers, as shown by early and late literate adults' superior capacity (compared to illiterates) in connecting local elements into an overall shape (Szwed, Ventura, Querido, Cohen, & Dehaene, 2012). The visual properties of the script itself have also a moderator role (for a recent review, see Zhou, McBride-Chang, & Wong, 2014). For instance, Chinese and Korean children learning to read visually complex and demanding scripts outperform Israeli and Spanish children on visual nonlinguistic spatial skills (McBride-Chang et al., 2011; Experiment 1), and the importance of reading to spatial skills is stronger than the other way around, as shown in a one-year longitudinal study with Chinese children (McBride-Chang et al., 2011; Experiment 2).

Learning to read in scripts such as the Latin alphabet also requires quite specific adaptations, especially when considering original properties of the visual system that may oppose to literacy acquisition. One such property is mirror-image generalization or *mirror invariance*: lateral mirror images (180º flip outside the image plane, e.g., ⌉ and ⌈) are processed as equivalent percepts by humans and other animals (e.g., Bornstein, Gross, & Wolf, 1978; Dehaene, Nakamura, et al., 2010; Logothetis, Pauls, & Poggio, 1995; Pegado et al., 2011; Tarr & Pinker, 1989). Yet, to learn a script with mirrored symbols, one must discriminate mirror images, which collides with mirror invariance.

Besides the Latin alphabet (which is used in more than 400 languages; e.g., d and b), other scripts such as the Japanese hiragana (e.g., ち and さ) and the Cyrillic alphabet (e.g., ɛ and З) also include mirrored or quasi-mirrored symbols. In any of these scripts mirrored symbols are just a small proportion but this is sufficient to trigger the ability to discriminate them, which transfers to nonlinguistic categories (e.g., Dehaene, Nakamura, et al., 2010; Kolinsky et al., 2011; Pegado et al., 2011), either novel (i.e., blob-like and geometric shapes) or familiar (e.g., pictures of tools or cloths). In contrast to readers of the Latin alphabet, illiterate adults present poor mirror discrimination (Fernandes & Kolinsky, 2013; Kolinsky et al., 2011), and readers of Tamil, a script with no mirrored symbols, have the same difficulties as illiterates (Danziger & Pederson, 1998; Pederson, 2003). Therefore, it is not learning to read in general that causes people to become able to discriminate mirror images. The trigger is learning a script with mirrored symbols.

Noteworthy, Pegado, Nakamura, et al. (2014; see also Kolinsky & Fernandes, 2014) recently showed that mirror discrimination also extends to situations where orientation processing is irrelevant and even harmful to the task at hand. In a same-different, identity-based and orientation-independent task, requiring a *same* response to both exact matches (henceforth, *identical pairs*) and mirrored pairs of the same object, only illiterate adults had as good performance for mirrored as for identical pairs. In contrast, both early and late literate adults in the Latin alphabet showed a *mirror cost,* i.e., worse performance for mirrored than identical pairs of linguistic (i.e., pseudowords) and nonlinguistic materials (i.e., false-font strings, composed of letter-like characters; pictures of objects and faces). Thus, with literacy acquisition, mirror discrimination seems to become automatic during visual object recognition, as readers of the Latin alphabet are unable to ignore mirror-image differences even when this hinders performance. The impact of literacy on automatic orientation processing could also explain the weaker priming effect for targets preceded by mirrored than by identical primes in short-term priming studies with adult readers (e.g., Dehaene, Nakamura, et al., 2010; Pegado et al., 2011).

Although this bulk of research has shown that learning a script with mirrored symbols impacts on sensitivity to mirror images, to the best of our knowledge no study has hitherto examined when, during literacy acquisition, mirror discrimination becomes automatic. Examining this question in children differing on reading skills (preschoolers with no reading skills vs. beginning readers at the end of the first grade) was the main aim of the present study. We used single letters and geometric shapes in order to investigate the effects of literacy acquisition on linguistic and nonlinguistic material.

Mirror discrimination probably develops and becomes automatic earlier for letters and for nonlinguistic stimuli visually similar to letters, such as geometric shapes, than for other nonlinguistic categories. Indeed, even before children are able to read, their letter knowledge already predicts attention to text (as measured through eye movements; Evans, Saint-Aubin, & Landry, 2009) and stronger responsiveness of the left occipitotemporal region to letters than to other visual categories (Cantlon, Pinel, Dehaene, & Pelphrey, 2011). Consistently, illiterate adults who are unable to decode but have high letter knowledge process letters differently than non-letters (Fernandes, Vale, Martins, Morais, & Kolinsky, 2014). Regarding mirror-image processing, Kolinsky and Fernandes (2014) recently showed that, whereas for pictures of familiar objects illiterate adults did not present any mirror cost on identity-based judgments (as in Pegado, Nakamura, et al., 2014), for geometric shapes they did present a mirror cost. This result agrees with the *shape bias hypothesis* (Hannagan, Amedi, Cohen, Dehaene-Lambertz, & Dehaene, 2015), according to which the specific tuning of ventral occipitotemporal neurons to shape features like those of letters is responsible (at least partially) for the highly reproducible location of the brain regions devoted to letter and visual word recognition. Under this view, the closer the features of nonlinguistic stimuli to those of letters, the earlier the consequences of literacy on visual (nonlinguistic) processing. Noteworthy, rudimentary reading seems enough, as late literate adults present the same mirror costs as early literates on both linguistic and nonlinguistic materials (Kolinsky & Fernandes, 2014; Pegado, Nakamura, et al., 2014).

However, late literate adults are not comparable to young children. Note that even *explicit* mirror discrimination (i.e., when orientation is critical to the task) seems to develop slowly in childhood. Children often present mirror errors in reading and writing during the first two years of literacy instruction (Cornell, 1985). Compared with fluent adult readers, first-grade children fixate more and for longer time on distractors differing from the target-word on two mirrored letters (e.g., *meter*, letters underlined were mirrored in the distractor) than on control distractors (e.g., matar; Duñabeitia, Dimitropoulou, Estévez, & Carreiras, 2013). For nonlinguistic material, in contrast to literate adults, 7-8 year-old children present similar short-term priming effects when pictures of familiar objects (e.g., animals) are preceded by mirrored and by identical primes (Wakui et al., 2013).

We thus decided to investigate the impact of learning to read on both explicit and implicit (i.e., automatic) mirror-image processing of letters and of geometric shapes, using a within-participants design. Furthermore, it is still unclear whether the impact of literacy on orientation processing is restricted to / or at least stronger for mirror images than for other orientation contrasts. Thus, we contrasted the processing of mirror images with that of rotations in the image plane (henceforth, *plane rotations*; e.g., 180º clockwise rotation: ⌉ and ⌊), because as highlighted by Gibson, Pick, Osser, and Gibson (1962) both distinguish letters of the Latin alphabet (e.g., d – b, and d – p). Given that letters are a category of expertise for readers (McCandliss, Cohen, & Dehaene, 2003), then through perceptual learning, dimensions that maximally distinguish letters, like orientation, would become enhanced (e.g., Folstein, Palmeri, & Gauthier, 2013). Literacy should thus impact on both mirror-image and plane-rotation processing. Yet, the neuronal recycling hypothesis predicts that this impact should be stronger for the former contrast (Dehaene, 2009) because the visual system is originally sensitive to plane rotations but not to mirror images (e.g., Logothetis et al., 1995). Consistently, both 4-6 year-old children and illiterate adults find it harder to explicitly discriminate mirror images than plane rotations of nonlinguistic objects (Fernandes & Kolinsky, 2013; Gregory, Landau, & McCloskey, 2011). Whether a similar pattern would be found on automatic orientation processing is not clear. In Pegado, Nakamura, et al. (2014), mirror images were the only orientation contrast examined. In Kolinsky and Fernandes (2014), whereas for identity-based judgments of familiar objects illiterate adults presented no orientation costs, for geometric shapes, both illiterate and literate adults presented stronger interference for rotated than mirrored pairs.

Therefore, to examine explicit vs. implicit, automatic processing of orientation, children performed two same-different tasks, on which they decided in each trial whether the second stimulus (S2) was the same or not as the first one (S1). As illustrated in Figure 1, the two tasks were performed separately on geometric shapes and single letters, and had the same four trial types: *fully different* trials (on which S2 differed from S1 on shape and on orientation; e.g., b – u); identical trials (S2 had the same shape and same orientation as S1; e.g., b – b); mirrored trials (S2 was a mirror image of S1; e.g., b – d); and rotated trials (S2 was a plane rotation of S1; e.g., b – q). The mirror-image and plane-rotation contrasts differed from the standard stimulus (S1) by the same 180º difference and preserved all object-based properties (global shape, parts, and relation between parts). Thus, any difference in performance between mirrored and rotated trials would not be due to low-level differences. The two tasks examined both mirror-image and plane-rotation processing, and differed only on the matching criterion; orientation was either irrelevant or critical for successful performance.

In the *shape-based* task, children were asked to classify a stimulus pair as *same* if S2 had the same shape as S1; orientation was thus irrelevant to the task (not only identical but also mirrored and rotated pairs should be classified as *same*). Automatic orientation processing was assessed by using the performance on identical pairs as baseline, given that orientation processing would lead to an *orientation cost* in mirrored or rotated trials compared to identical trials. In contrast, in the *orientation-based* task, orientation was the critical dimension: children were asked to classify a stimulus pair as *same* only if S2 was identical to S1 – same shape and same orientation –, and to classify as *different* both the *fully different* pairs and the mirrored and rotated pairs. Explicit orientation processing was assessed by examining the *performance drop* on trials on which only orientation varied (mirrored and rotated trials) relative to fully different trials.

-------------------- Figure 1 about here ------------------

Given the original property of mirror invariance of the ventral visual system (Dehaene, 2009; Logothetis et al., 1995; Tarr & Pinker, 1989), we expected preschoolers to be better able to tolerate, i.e., to classify as *same*, the mirrored pairs in the shape-based task than to discriminate them in the orientation-based task, whereas they would be as able to tolerate as to discriminate plane rotations. Indeed, in the shape-based task, preschoolers would exhibit no mirror cost at all. Conversely, in the orientation-based task, they would present the worst performance for mirrored pairs, even when compared with rotated pairs. This pattern of results was expected for both materials.

If mirror discrimination transferred to nonlinguistic categories early on in reading acquisition, first graders would present good mirror discrimination of both letters and geometric shapes in the orientation-based task. If it became automatic, they would also present a mirror cost for both materials in shape-based judgments. Given the importance of plane-rotation contrasts in letter discrimination, we expected first graders to be less able to tolerate plane rotations in the shape-based task than to discriminate them in the orientation-based task.

Therefore, the strongest difference between preschoolers and first graders was expected for the mirrored pairs. Note that by using the two normalized indexes (i.e., the orientation cost and the performance drop) we ensured that any difficulty to be found on explicit mirror discrimination by preschoolers could not be due to overall differences in performance between groups.

We also examined the mirror cost for *reversible* letters (i.e., differing only by orientation; e.g., u – n) and *non-reversible* ones, for which orientation contrasts do not map onto different representations (e.g., e – ə). As mirror discrimination is most relevant to reversible letters (Perea, Moret-Tatay, & Panadero, 2011), the orientation cost on shape-based judgments of first graders should be stronger for these letters, but no difference was expected for preschoolers due to their limited letter knowledge.

Finally, to assess whether literacy related-skills (i.e., letter knowledge in preschoolers, reading skills and phonological awareness in first graders) were associated with mirror discrimination or orientation processing in general, we conducted correlation analyses in each group for each material.

Method

Participants

Twenty-eight preliterate preschoolers (17 males; M_{age} = 65.9 months, SD = 3.2) and 24 first graders (7 males; M_{age} = 82.7 months, SD = 3.6), all Portuguese native speakers, from schools of Lisbon and Évora, Portugal, with no known history of developmental and/or neurological disorders, participated voluntarily in compliance with Declaration of Helsinki. Data was collected between March – June 2011, and March – June 2013. Due to the end of the school year, six preschoolers did not perform the orientation-based task for geometric shapes and three did not perform it for letters. These children were excluded, as well as those who performed at the chance level on the fully different and identical trials, which led to same responses in the two tasks (for geometric shapes: two preschoolers and one first grader; for letters: two other preschoolers and the same first grader). The final sample thus included 20 preschoolers for geometric shapes and 23 for letters, plus 23 first graders tested on both materials.

Table 1 presents children's results in five domains: nonverbal IQ (Colored Progressive Matrices of Raven, Portuguese version; Simões, 2000); visuospatial working memory (Corsi block test, WMS-III; Wechsler, 1997); phonological awareness (i.e., same-different matching task on the target-unit – the first phoneme, the rhyme, or the syllable - of two words; 16 trials per unit preceded by 6 practice trials); letter knowledge (naming and recognition of lower- and upper-case letters of the Portuguese alphabet); and reading skills for first graders only, i.e., reading fluency of isolated items (3DM Battery, Portuguese version; Reis, Faisca, Castro, & Petersson, 2013) and reading comprehension (Lobrot L3 test, Portuguese adaptation; Sucena & Castro, 2008).

The phonological awareness task was examined using *Signal Detection Theory* (SDT) *d'* scores (Macmillan & Creelman, 2005). The *reading index* was the summed result across the 3DM subtests and the Lobrot L3 test, given the high correlations between them, $r(21)$s > .85, ps < .001.

In the Portuguese educational system, literacy instruction starts only at Grade 1. There are no official directives concerning literacy-related activities in preschool years, and hence, usually no (or only few) instruction on letter knowledge is given, explaining the low letter knowledge of these preschoolers (see Table 1), and the independence between their letter knowledge and phonological awareness, $r(18) = -.26$, $p = .13$. In contrast, for first graders, phonological awareness was significantly associated with reading skills, $r(21) = .59$, $p < .005$. In both groups, visuospatial abilities, i.e., working memory and nonverbal IQ were significantly associated with each other: for preschoolers, $r(18) = .46$, $p = .015$, and first graders, $r(21) = .40$, $p = .03$.

----------------------- Table 1 about here --------------------

Material

Two types of asymmetrical black-line material were used: nine geometric shapes and eight letters (see Figure 1). The geometric shapes were those used by Fernandes and Kolinsky (2013) except for two stimuli which were replaced by those presented in Figure 1A. As shown in Figure 1B, half of the letters were non-reversible and the others were reversible (for b and p both orientation-contrasts corresponded to real letters but not for m and u).

For each material, three versions were created with irfanview (www.irfanview.com): the standard, its mirror image (180º lateral reflection) and its plane rotation (180º clockwise rotation). For each standard stimulus, four pairs were prepared to create the four trial types (S1 was the standard): identical trials (S2 was the same as S1); mirrored trials (S2 was the mirror image of S1); rotated trials (S2 was the plane rotation of S1); and fully different trials (S2 was a different standard stimulus).

Procedure

Children were tested in a quiet room of their school. They performed the two same-different tasks for the two materials in four sessions. The shape-based task was performed first to ensure that any orientation cost to be found would not be due to prior performance of the orientation-based task. Sequence of events in experimental trials was the same for each task and material (see Figure 1A), and was controlled by E-Prime 2.0 (www.pstnet.com/eprime). Children sat at a distance of ~70 cm of the computer screen (resolution: 640 x 480 pixels; refresh rate: 60 Hz) and were asked to perform a same-different judgment on S2 in each trial (in each task, half of the trials were expected to lead to a *same*-response). Instructions were given orally with six demo-trials using animals as stimuli. Next, to ensure that children understood the task, they performed 12 practice trials (six with animals, six with the experimental material; half trials leading to a *same*-response), with feedback on response accuracy.

In the shape-based task, on each trial children were asked to decide as accurately and quickly as possible whether S2 had the same shape as S1, independently of orientation, by pressing one of the two keys of the response box (*same* response given with the right index finger). It was emphasized that stimuli's name was irrelevant to the task; S2 should be classified based on shape and not on name. Note that at least for letters, especially for reversible ones, an identity-based criterion (same identity, same name) would induce an incorrect response (e.g., d and b are different letters, with different names, but have the same shape). In the orientation-based task, children were asked to decide whether S2 was an exact match of S1. They should respond *different* (using the left key, left index finger) if S2 had a different orientation than S1 even if they had the same shape. Accuracy and RTs (measured from S2 onset to response onset) were collected in each trial.

Children performed 108 trials for geometric shapes in each task (i.e., shape-based task: 54 fully different, 18 identical, 18 mirrored, and 18 rotated trials; orientation-based task: 54 identical, 18 fully different, 18 mirrored, and 18 rotated trials). For letters, they performed 96 trials per task (For each letter type: in the shape-based task, 24 fully different, 8 identical, 8 mirrored, and 8 rotated trials; in the orientation-based task, 24 identical, 8 fully different, 8 mirrored, and 8 rotated trials).

Results

The mean accuracy and correct RTs (after the trimming of outliers 2.5 SD above or below the grand mean RT for each participant by material and task; < 3% data excluded) were examined separately for each material, with group (preschoolers, first graders; between-participants), task (shape- vs. orientation-based) and trial type (fully different, identical, mirrored, rotated) as factors, plus letter type (reversible vs. non-reversible) for the analyses run on letters. We also checked that a similar pattern of statistical significance was found when analyses were run on SDT *d'* scores adapted for same-different designs (i.e., hits correspond to proportion of correct responses in different-response trials, and false alarms correspond to the proportion of incorrect responses in same-response trials; cf. Macmillan & Creelman, 2005), with group, task, and *condition* (fully-different; mirrored; rotated) as factors, plus the letter-type factor in the analyses run on letters.

Geometric shapes

The three-way interaction between all factors at test was significant on both accuracy, $F(3,123) = 3.72$, $p = .013$, $\eta p^2 = .08$ (*d*' scores, $F(2, 82) = 3.97$, $p = .022$, $\eta p^2 = .09$), and RTs, $F(3,123) = 2.94$, $p = .036$, $\eta p^2 = .07$. In line with our predictions, as shown in Figure 2 (see also Table 2), whereas preschoolers were immune to mirror-image differences, first graders were sensitive to them even if harmful for performance. Specifically, preschoolers were perfectly able of tolerating (i.e., responding *same* to) the mirrored pairs in the shape-based task (Figure 2A) and had the strongest difficulty in discriminating them in the orientation-based task (Figure 2B), whereas first graders presented a mirror cost on shape-based judgments and were quite able of explicitly discriminating the mirrored pairs.

-------------------- Figure 2 about here -------------------

Shape-based task.

In the shape-based, orientation-independent task (Figure 2A), preschoolers had similar overall performance level as first graders on both accuracy, $F(1, 41) = 2.02$, $p = .16$ (*d'* scores, $F < 1$), and RTs, $F = 1$; we thus compared directly their performance. Notably, it was only for mirrored trials that first graders were significantly slower than preschoolers by 118 ms on average, $t(41) = 1.65$, $p = .05$ (accuracy, $t(41) = 1.40$, $p = .10$; *d'* scores, $t < 1$), other *t*s < 1. Furthermore, whereas first graders showed a significant mirror cost, with slower performance on mirrored than on identical trials, $F(1, 22) = 10.05$, $p = .004$ (accuracy, $F < 1$), preschoolers did not show any mirror cost (accuracy and RTs: *F*s < 1). For plane rotations, no difference was found between groups, *t*s < 1, as both presented a rotation cost, with worse and slower performance on rotated than on identical trials: preschoolers, $F(1, 19) = 10.85$, and = 39.36, respectively, both *p*s < .005; first graders, $F(1, 22) = 9.34$, and = 19.84, respectively, both *p*s < .010. On *d'* scores, whereas preschoolers were not affected by orientation, presenting similar *d'* scores for mirrored, rotated, and fully different conditions, *F*s ≤ 1, first graders were affected by orientation, $F(2, 44) = 6.20$, $p = .004$, with higher *d'* scores in the fully different (which did not differ from the mirrored condition, $F < 1$), than in the rotated condition, $F(1, 22) = 9.09$, $p = .006$ (see Table 2).

-------------------- Table 2 about here -------------------

Orientation-based task.

As illustrated in Figure 2B, preschoolers had a specific difficulty in discriminating mirrored pairs, presenting the worst and slowest performance for these trials compared with either fully different trials, $F(1, 19) = 23.15$, (*d'* scores, $F(1, 19) = 14.47$), and $F(1, 19) = 16.93$, respectively, *p*s ≤.001, or rotated trials, $F(1, 19) = 4.73$ (*d' scores*, $F(1, 19) = 16.11$) and $F(1, 19) = = 4.55$, respectively, *p*s < .05. Preschoolers were also less accurate and slower on rotated than on fully different trials, $F(1, 19) = 16.91$ (*d'* scores, $F(1, 19) = 4.40$) and = 7.05, respectively, *p*s ≤ .05. Furthermore, on mirrored trials, preschoolers were also worse than first graders, $t(41) = 5.97$, (*d'* scores, $t(41) = 10.44$), *p*s < .001, but not slower, $t = -1.20$, $p > .10$.

Although first graders were still less accurate and slower in discriminating mirror images than plane rotations, $F(1, 22) = 14.18$, (*d' scores*, $F(1, 22) = 19.65$), and $F(1, 22) = 4.97$, respectively, *p*s < .05, they were quite able of discriminating any orientation contrast, with average accuracy above 80% (see Figure 2B). Also, they were as accurate on rotated as on fully different pairs, $F < 1$, (*d'* scores, $F(1, 22) = 2.42$, $p = .13$; see Table 2), albeit slower for the former pairs, $F(1, 22) = 17.84$, $p < .001$.

In contrast to what happened in the shape-based task, in the orientation-based task first graders were overall more accurate than preschoolers, $F(1, 41) = 37.84$, (d' scores, $F(1, 41) = 122.11$), $ps < .001$, but not faster, $F < 1$. As shown in Figure 2B, first graders were especially better than preschoolers for mirror images (Group x Trial type: accuracy, $F(3, 123) = 7.94$, $p < .001$; RTs, $F < 1$; d' scores, Group x Condition, $F(2, 82) = 3.00$, $p = .05$;).

To ensure that this result was not merely due to the overall difference between groups, we next used a normalized index to compare preschoolers with first graders on their performance drop for mirrored and rotated trials relative to fully different trials ($[(x-y)/(x+y)]*100$, where x is the proportion of correct responses on fully different trials, and y is the proportion of correct responses on either mirrored or rotated trials, cf. Fernandes & Kolinsky, 2013). The higher the performance drop, the stronger the relative difficulty to discriminate the pair on the basis of only orientation (on mirrored or rotated trials) rather than on the basis of both shape and orientation (on fully different trials). For mirror images, the performance drop was significantly stronger in preschoolers than in first graders ($M = 11.89$, $SEM = 4.19$ vs. $M = 6.06\%$, $SEM = 2.19$, respectively), $F(1, 41) = 6.74$, $p = .013$; for plane rotations, the difference between groups did not reach the conventional level of significance, preschoolers only tended to present a larger performance drop ($M = 4.31$, $SEM = 2.76$ vs. $M = -1.37\%$, $SEM = 1.46$, respectively), $F(1, 41) = 3.57$, $p = .07$.

Comparison between the two tasks and the two groups.

The comparison between tasks revealed that preschoolers found it harder to explicitly discriminate (in the orientation-based task) than to tolerate (in the shape-based task) the mirrored pairs: accuracy, d' scores, and RTs, $F(1, 19) = 14.90$, $= 14.11$, and $= 20.78$, respectively, all $ps \leq .001$. For the other trial types (including the rotated trials), they were as fast and as accurate (and had similar d' scores) on shape- as on orientation-based judgments, all $Fs < 1$ (see Figure 2). Yet, the association between performance in the two tasks was not significant, for mirrored trials (accuracy: $r(18) = -.22$, $p = .18$; RTs: $r(18) = .35$, $p = .12$), for rotated trials (accuracy and RTs: $r(18) = .05$, and $= .13$, $ps > .25$), or across trials (accuracy: $r(18) = .26$, $p = .13$; RTs, $r(18) = .30$, $p = .10$; one-tailed t-tests).

The result pattern of first graders differed from that of preschoolers in three ways. First graders were as accurate and fast in discriminating as in tolerating the mirrored pairs, both $Fs < 1.25$, Yet, the association between the two tasks for these trials did not reach statistical significance: accuracy, $r(21)$

= -.13, p = .28; RTs, $r(21)$ = .32, p = .07. Moreover, on *d'* scores, they were even better on orientation-based than on shape-based judgments in the mirrored condition, $F(1, 22) = 36.57$, $p < .001$. Second, a similar advantage for the orientation- over the shape-based task was observed for the other trial types, especially for rotated pairs. On average, they were 24% more accurate in discriminating than in tolerating these pairs, $F(1, 22) = 44.13$, $p < .001$, and their average *d'* score for these pairs in the orientation-based task was almost the double of that in the shape-based task, $F(1, 22) = 153.78$, $p < .001$ (see Table 2). Finally, the association between the two tasks was significant for rotated trials, on RTs, $r(21) = .50$, $p = .008$ (not on accuracy, $r = .09$), and across trials, accuracy and RTs, $rs(21) > .50$.

-------------------- Figure 3 about here -------------------

Letters

In the ANOVAS run on accuracy and RTs, the Group x Trial type x Letter type interaction was significant, $F(3, 132) = 4.79$, $p = .003$, $\eta p^2 = .10$, and $F(3, 132) = 2.63$, $p = .050$, $\eta p^2 = .056$ (see Figure 3). Similarly, on *d'* scores, the Group x Condition x Letter type interaction was also significant, $F(2, 88) = 5.72$, $p = .02$, $\eta p^2 = .115$. Indeed, preschoolers were not affected by letter type at all (neither the main effect of letter type nor any interaction with other variables was significant on accuracy, *d'* scores, and RTs, all Fs < 1.62, $ps > .21$). In contrast, first graders' performance was affected by Letter type x Trial type (accuracy, $F(3, 66) = 13.81$, $p < .001$, $\eta p^2 = .39$, and RTs, $F(3, 66) = 5.33$, $p = .002$, $\eta p^2 = .19$; and on *d*' scores by Letter type x Condition, $F(2, 44) = 3.08$, $p = .05$, $\eta p^2 = .122$) and by Letter type x Task (accuracy, $F(1, 22) = 47.03$, $p < .001$, $\eta p^2 = .68$, *d'* scores, $F(1, 22) = 6.70$, $p = .017$, $\eta p^2 =.233$, and RTs, $F(1, 22) = 5.20$, $p = .032$, $\eta p^2 = .19$). Actually, the impact of letter type on first-graders' accuracy was quite specific: it was modulated by task and trial type (Letter type x Task x Trial type; accuracy, $F(3, 66) = 9.53$, $p < .001$, $\eta p^2 = .30$; *d'* scores, $F = 1.38$, and RTs, $F < 1$). As aforementioned, for preschoolers, performance was not affected by letter type but it was modulated by task and trial type, on accuracy, $F(3, 66) = 5.61$, $p = .002$, $\eta p^2 = .20$, and RTs, $F(3, 66) = 3.89$, $p = .01$, $\eta p^2 = .15$ (similarly, on *d'* scores, the Task x Condition interaction was significant, $F(2, 44) = 9.89$, $p < .001$, $\eta p^2 = .31$; see Table 3). Therefore, we further examined the preschoolers' results in each task across letter type, whereas for first graders the impact of letter type was also considered.

-------------------- Table 3 about here -------------------

Shape-based task.

In contrast to what happened for geometric shapes, for letters first graders presented an overall advantage over preschoolers in the shape-based task (see Figure 3A), on accuracy, $F(1, 44) = 9.63$, $p = .003$ (*d'* scores, $F(1, 44) = 19.80$, $p < .001$), but not on RTs, $F = 1.25$ (the only significant effect on RTs was the main effect of trial type, $F(3, 132) = 11.32$, $p < .001$). This advantage was modulated by letter and trial type, $F(3, 132) = 9.16$, $p < .001$ (*d'* scores: Letter x Condition, $F(2, 88) = 2.44$, $p = .09$).

Nevertheless, both groups exhibited the same qualitative impact of trial type on their performance. As shown in Figure 3A, preschoolers presented a rotation cost on shape-based judgments of letters: worse and slower performance on rotated trials ($M = 59.5\%$, $SEM = 3.8$; $M = 1125$ ms, $SEM = 62$) than on identical trials ($M = 71.5\%$, $SEM = 3.4$; $M = 1003$ ms, $SEM = 49$), $F(1, 22) = 6.85$ and $= 11.96$, respectively, $ps \leq .016$. Similarly, they had lower *d'* scores on the rotated than on the fully different condition (see Table 3), $F(1, 22) = 4.91$, $p = .03$.

Contrary to what happened for geometric shapes, preschoolers also presented a mirror cost for letters, with significantly worse performance on mirrored trials ($M = 62.4\%$, $SEM = 2.5$; $M = 1082$ ms, $SEM = 61$) than on identical trials: accuracy, $F(1, 22) = 6.10$, $p = .022$; RTs, $F(1, 22) = 3.39$, $p = .079$. A mirror cost was also found on *d'* scores, $F(1, 22) = 4.91$, $p = .03$ (see Table 3).

Similarly, first-graders presented both rotation and mirror costs on shape-based judgments of letters: for reversible letters, a rotation cost, accuracy, $F(1, 22) = 50.63$, RTs, $F(1, 22) = 9.71$, both $ps \leq .005$, and a mirror cost, accuracy, $F(1,22) = 31.79$, $p < .001$, RTs, $F = 1.14$ (the same costs were found on *d'* scores, $F(2, 44) = 8.55$, $p < .001$, with lower performance in the mirrored and in the rotated condition than in the fully different one, $F(1, 22) = 10.82$, and $= 16.92$, respectively, both $ps < .005$); for non-reversible letters, the rotation and mirror costs were significant on RTs, $F(1, 22) = 16.16$, and $= 11.99$, respectively, both $ps < .001$, but not on accuracy or *d'* scores, $Fs < 1$ (see Table 3).

More important, first-graders' shape-based judgments were modulated by letter and trial type on accuracy, $F(3, 66) = 17.38$, $p < .001$ (RTs: $F(3, 66) = 1.55$, $p = .207$; Letter x Condition, on *d'* scores, $F(2, 44) = 5.07$, $p = .01$), because their orientation costs were stronger for reversible than for non-reversible letters. They were less accurate on shape-based judgments of reversible than non-reversible letters for mirrored pairs $F(1, 22) = 13.53$, $p = .001$ (*d'* scores, $F(1, 22) = 5.96$, $p = .023$) and rotated pairs, $F(1, 22) = 62.86$ (*d'* scores, $F(1, 22) = 18.63$), *ps* < .001, but not for identical trials nor fully different trials, *F*s < 1. Therefore, first graders found it harder to classify as *same* the pairs, either mirrored or rotated, that map onto different letter representations (e.g., d – b, or d – p) than those that do not (e.g., e – ə).

In order to directly compare the orientation cost of the two groups in the shape-based task, we adopted the orientation cost index used by Pegado, Nakamura, et al. (2014; Kolinsky & Fernandes, 2014), i.e., $[(x\text{-}z)/(x+z)]*100$, where x is the proportion of correct responses on fully different trials and z is the accuracy on identical trials: the higher the orientation cost, the stronger the interference due to an orientation transformation on shape-based judgments. This orientation cost was significantly modulated by group, letter type, and orientation contrast, $F(1, 44) = 5.92$, $p = .019$, $\eta p^2 = .12$. For non-reversible letters, the orientation cost of first graders was similar to that of preschoolers (M =1.34%, SEM = 3.24 vs. 8.72%, SEM = 4.35, respectively), $F(1, 44) = 2.60$, $p = .12$, and was not modulated by orientation contrast, $F(1, 44) = 2.34$, $p = .132$. In contrast, for reversible letters, first graders presented stronger orientation costs than preschoolers for both mirror images (M = 19.46%, SEM = 3.56 vs. M = 5.72%, SEM = 2.26, respectively), $F(1, 44) = 5.40$, $p = .025$, and plane rotations (M = 42.77%, SEM = 6.92 vs. M = 10.79%, SEM = 5.83, respectively), $F(1, 44) = 12.48$, $p < .001$.

Orientation-based task.

Although preschoolers were somewhat sensitive to mirror-image differences in the shape-based task, they still presented a specific difficulty in discriminating mirrored letters. Their orientation-based judgments were the worst for the mirrored pairs (M = 50.2%, SEM = 4.1; M = 1147 ms, SEM = 59; for *d'* scores, see Table 3) relative to fully different pairs (M = 78.2%, SEM = 2.8; M = 1022 ms, SEM = 37), accuracy, *d'* scores and RTs, $F(1, 22) = 30.79$, = 25.72 and = 8.87, respectively, all *ps* < .01, and to rotated pairs (M = 68.7%, SEM = 3.3; M = 1175 ms, SEM = 42), accuracy and *d'* scores, $F(1, 22)$ = 19.23 and = 16.59, *ps* < .001 (on RTs, $F < 1$), which also differed from each other on accuracy, $F(1, 22) = 5.95$, $p = .02$, (*d'* scores: = 6.88, $p = .016$), and RTs, $F(1, 22) = 23.78$, $p < .001$ (see Figure 3B).

Contrary to what happened for shape-based judgments, first-graders' orientation-based judgments were not affected (either on accuracy, on *d*' scores, or RTs) by letter type, all *F*s < 1.25.

Although they had an overall advantage over preschoolers in the orientation-based task, on accuracy and *d'* scores, $F(1, 44) = 58.90$, and = 39.49, respectively, both *ps* < .001 (RTs: $F < 1$), discrimination of mirrored pairs continued to be harder than discrimination of rotated pairs, for both reversible letters, on accuracy and *d'* scores, $F(1, 22) = 4.34$, and = 4.60, respectively, both *p*s < .05 (RTs, $F < 1$), and non-reversible letters, on accuracy, *d'* scores, and RTs, $F(1, 22) = 9.65$, = 13.25, and = 14.45, respectively, all *p*s ≤ .005 (see Figure 3B and Table 3).

To directly compare the two groups, we next examined the performance drop index previously considered for geometric shapes. The pattern of results was similar to that reported for geometric shapes. The performance drop on mirrored trials was stronger for preschoolers than for first graders ($M = 23.85\%$, $SEM = 3.54$ vs. $M = 8.20\%$, $SEM = 2.10$, respectively), $F(1, 44) = 9.68$, $p =. 003$, but on rotated trials, preschoolers and first graders presented similar performance drops ($M = 7.48\%$, $SEM = 2.70$, $SEM = 2.70$ vs. $M = 2.06\%$, $SEM = 1.98$, respectively), $F(1, 44) = 1.92$, $p = .17$.

Comparison between the two tasks and the two groups.

As already reported for geometric shapes, preschoolers had more difficulty in discriminating (in the orientation-based task; Figure 3B) than in tolerating (in the shape-based task; Figure 3A) mirrored letters, on accuracy, $F(1, 22) = 5.81$, $p = .025$ (and on *d'* scores, $F(1, 22) = 7.87$, $p = .01$; RTs, $F < 1$). Note, however, that for the other trial types (including rotated trials), preschoolers were as able to perform orientation- as shape-based judgments, on accuracy *F*s(1, 22) ≤ 2.94 (*d'* scores: *F*s(1, 22) < 1.07, *ps* > .30), and on RTs, *F*s ≤ 2.63, all *ps* ≥ .10. Yet, no association was found (on accuracy or RTs) between tasks, for mirrored or rotated pairs, or across trials, all *r*(s21)s < .25, *p*s > .25.

For first-graders, discrimination of mirror images continued to be harder than discrimination of plane rotations for both reversible letters, accuracy, $F(1, 22) = 4.34$, $p = .049$ (*d'* scores:= 4.70, $p = .041$), RTs, $F < 1$, and non-reversible letters, accuracy, *d'* scores, and RTs, $F(1,22) = 9.65$, = 13.25, and = 14.45, respectively, *p*s ≤ .005. Indeed, for non-reversible letters, first graders were still slower in discriminating than in tolerating mirror images, $F(1, 22) = 7.46$, $p = .012$ (on accuracy, $F < 1$; *d'* scores, $F(1, 22) = 4.27$, $p = .051$); this was not the case for plane rotations, all *F*s ≤ 1. In contrast, for reversible letters, they were actually more accurate in discriminating than in tolerating both the mirrored and rotated pairs, $F(1, 22) = 9.76$, and = 62.94, respectively, *ps* ≤ .005 (*d'* scores, $F = 1$, and

F(1, 22) = 13.06, p = .001, respectively; RTs, both Fs < 1.5). Moreover, the association between tasks was significant for mirrored and rotated trials, on RTs, both rs(21) > .64, ps < .001 (accuracy, rs < .01), and across trials, accuracy and RTs, r(21) = .59, and = .85, respectively, both ps ≤ .001.

In line with what was found for geometric shapes, for letters the performance drop on mirrored trials was stronger for preschoolers than for first graders (M = 23.85%, SEM = 3.54 vs. M = 8.20%, SEM = 2.10, respectively), F(1, 44) = 9.68, p =. 003, but on rotated trials the two groups did not differ (M = 7.48%, SEM = 2.70, SEM = 2.70 vs. M = 2.06%, SEM = 1.98, respectively), F = 1.92, p = .17.

Correlation analyses

We next examined, at the individual level, whether orientation processing was associated with literacy-related skills (i.e., preschoolers' letter knowledge and first graders' reading skills, as well as phonological awareness) rather than with visuospatial abilities, by considering the correlation coefficients between these cognitive domains and the orientation cost (in the shape-based task) and performance drop (in the orientation-based task) for mirror and rotation contrasts, separately for each material. The correlation coefficients presented in Table 4 refer to accuracy, which was a more reliable measure of preschoolers' orientation-based performance than RTs (but these correlations coefficients were also checked; see Table 4, p-values reported correspond to one-tailed t-tests; RTs indexes were multiplied by -1 so that the correlation pattern for RTs and accuracy would be in the same direction).

-------------------- Table 4 about here -------------------

Geometric Shapes

In preschoolers, sensitivity to mirror images was significantly associated with letter knowledge: the better their letter knowledge, the stronger the mirror cost in shape-based judgments, and the smaller the performance drop for mirrored pairs in orientation-based judgments (the latter was also associated with phonological awareness; see Table 4). No significant association was found between sensitivity to plane-rotation contrasts and any cognitive ability examined.

For first graders, mirror discrimination was associated with reading skills and phonological awareness (which were associated with each other, see Method): the better their literacy-related skills, the smaller the performance drop (on both accuracy and RTs) for mirrored pairs in the orientation-based task. In contrast to what was found for preschoolers, the performance drop for rotated pairs was also associated with literacy-related skills (but only when computed on RTs) and also with nonverbal IQ of first graders. For the shape-based task, only one association was significant: the better the first-graders' phonological awareness, the stronger the rotation cost on shape-based judgments. Although in the same direction, the association between phonological awareness and the mirror cost computed on RTs was unreliable, $r(21) = .27$, $p = .10$.

Letters

Preschoolers' sensitivity to mirror images was significantly associated with letter knowledge: the better their letter knowledge, the stronger the mirror cost in shape-based judgments, and the smaller the performance drop for mirrored pairs in orientation-based judgments (see Table 4). Letter knowledge was also correlated with sensitivity to plane rotations (for the indexes on accuracy only).

Unexpectedly, preschoolers' phonological awareness was negatively correlated with the orientation costs, which might be related to preschoolers' adoption of phonological labels to identify each letter-shape in an orientation-invariant manner, due to their limited letter knowledge.

For first-graders, mirror discrimination was specifically associated with reading skills: the better their reading skills, the stronger the mirror cost (on RTs) on shape-based judgments, and the lower their performance drop (on both accuracy and RTs) on orientation-based judgments of mirrored letters.

For both first graders and preschoolers, the better their visuospatial abilities (i.e., nonverbal IQ and visuospatial working memory), the smaller their performance drop (in the orientation-based task) and the smaller the orientation cost (in the shape-based task). This association was specific to plane rotations for preschoolers, whereas for first graders it was significant for both orientation contrasts.

Discussion

An emergent bulk of research has been showing that learning to read leads to deep neurocognitive changes outside the written domain, including on nonlinguistic visual object processing (e.g., Dehaene, Pegado, et al., 2010; Fernandes & Kolinsky, 2013; Kolinsky et al., 2011; McBride-Chang et al., 2011; Pegado, Comerlato, et al., 2014; Pegado, Nakamura, et al., 2014; Szwed et al., 2012). In this context, the present study targeted two open issues on the early influences of learning a script with mirrored symbols.

First, it was hitherto unknown when, during reading development, the spillover effect of literacy on object recognition and orientation processing would emerge. More specifically, it was thus far unclear when, in the course of literacy acquisition, mirror discrimination, as a consequence of learning a script with mirrored symbols, would become automatic. To investigate this question, two groups of 5-7 year-old children, differing on reading skills – preliterate preschoolers and first graders – performed two same-different matching tasks on which orientation was either critical or irrelevant to successful performance, i.e., orientation-based vs. shape-based (orientation-independent) tasks, respectively. To our knowledge, this is the first study to adopt a within-participants design in order to examine in a fine-grained manner whether the impact of literacy would be similar on explicit vs. implicit, automatic processing of orientation. Each task was performed on two categories matched in visual complexity: single letters and geometric shapes. Taking into account the shape bias hypothesis (Hannagan et al., 2015), geometric shapes were the nonlinguistic category selected given the proximity of their features to those of letters. We thus expected that if changes in visual processing started to emerge early on in literacy acquisition, even if insipient ones, then by using this material we would be able to grasp them. Furthermore, we conducted correlation analyses for each group on each material to examine at the individual level whether explicit or automatic orientation processing was associated with literacy-related skills.

Second, it was still unclear whether the impact of learning a script with mirrored symbols was specific to mirror image processing or whether it would generalize to other orientation contrasts that are relevant for letters, like plane rotations (e.g., d – p; Gibson et al., 1962). To study this point, the same four trial types were used in both tasks: fully different (with different shape and orientation), identical, mirrored, and rotated pairs. We thus directly compared explicit vs. automatic processing of mirror images vs. plane rotations, two orientation contrasts that are relevant to letters and differ from the standard view by the same angular difference while preserving all object-based properties.

The present study represents one of the first demonstrations of early changes in the mirror-generalization system due to literacy acquisition, and provided four original contributions on the impact that learning a script with mirrored symbols has outside the written domain.

First, we presented the first evidence of an absolute and specific mirror cost on visual nonlinguistic object recognition. For geometric shapes, a nonlinguistic material novel for both preschoolers and first graders, the two groups were overall equally able to perform shape-based judgments. Most interestingly, the groups differed only on mirrored pairs: whereas preschoolers were immune to irrelevant mirror-image differences, first graders exhibited such strong mirror cost that they were even slower than preschoolers. We thus found an absolute mirror cost on shape-based judgments of nonlinguistic objects, a consequence of literacy acquisition predicted by the neuronal recycling hypothesis (Dehaene, 2009). In the first study to show a mirror cost in literate adults, no other orientation-contrast was examined and the mirror cost was only relative, as illiterate adults were overall slower and more error-prone than the literate groups (Pegado, Nakamura, et al., 2014). In Kolinsky and Fernandes (2014), only literate adults (and not illiterates) were affected by mirror and rotation contrasts of familiar objects, and for geometric shapes, all participants, whatever their literacy level, were sensitive to the irrelevant orientation contrasts, at least on response latencies and mostly for plane rotations. Yet again illiterate adults were overall slower and more error-prone than literates.

Thus, the present study is the first to show that the impact of learning to read on automatic orientation processing (i.e., when this dimension is irrelevant to the task) is already noticeable in beginning readers at the end of the first grade. Additionally, both groups exhibited a rotation cost on shape-based judgments of geometric shapes, which agrees with previous findings on the plane-rotation sensitivity of the ventral visual system (Logotethis et al., 1995; Tarr & Pinker, 1989).

In line with the mirror invariance found in shape-based judgments of geometric shapes by preschoolers, the strongest difficulty of these children in orientation-based judgments was for the mirrored pairs. This result agrees with prior findings on illiterate adults and preliterate children (e.g., Casey, 1984; Danzinger & Pederson, 1998; Gibson et al., 1962; Fernandes & Kolinsky, 2013; Kolinsky et al., 2011; Nelson & Peoples, 1975; Pederson, 2003), which argues for the robustness of this effect.

Second, by examining explicit vs. implicit orientation processing in a within-participants design, the present study is the first to conclusively show that preliterates' specific difficulty with mirror discrimination cannot be attributed to a general difficulty with orientation processing or because orientation is a dimension less salient than shape. On the one hand, if preschoolers had a general difficulty with orientation, then plane-rotation discrimination should have been as hard as mirror discrimination. On the contrary, they were quite able of discriminating rotated pairs, and when compared to first graders using the normalized index, the two groups presented a similar performance drop for rotated pairs. On the other hand, if orientation was a dimension less salient than shape, preschoolers should have been worse on orientation-based than on shape-based judgments of rotated pairs. Quite the opposite, they were as able to explicitly discriminate plane-rotation contrasts as to tolerate them. Additionally, they presented the same level of interference from the irrelevant dimension of rotated pairs in each task (i.e., orientation in the shape-based task, and shape in the orientation-based task). To put it differently, preschoolers were equally sensitive to the two incongruent dimensions – orientation and shape – as they were as able to attend to shape as to orientation of rotated pairs. Consequently, their difficulty with mirror discrimination cannot be due to low sensitivity to orientation in general; it seems rather grounded on the original mirror invariance property of the ventral visual system (Dehaene, 2009; Logothetis et al., 1995).

During literacy acquisition, beginning readers become as able to attend to orientation as to shape of mirrored pairs of nonlinguistic objects, as shown by first graders' similar performance in the two experimental tasks for these pairs. In fact, learning to read seems to enhance the relevance of orientation, which becomes a critical dimension of visual objects, as shown by the overall advantage of first graders over preschoolers in the orientation-based task. This advantage does not seem to be due to a generic age effect, as no overall difference between groups was found on shape-based judgments of geometric shapes. In fact, the orientation-based task used here required both shape and orientation processing (only exact matches, i.e., identical pairs, had to be considered as *same*), which conjunction is essential in letter and visual word recognition, and hence, the advantage of first graders is not surprising. Perceptual expertise with a visual category leads to enhancement of the relevant dimensions (e.g., Dehaene, Pegado, et al., 2010; Folstein et al., 2013; McCandliss et al., 2003). Thus, when learning to read, children learn to attend to critical reading-related cues, such as orientation, which was not relevant to perceptual experience before this cultural activity took place (e.g., Casey, 1986; Gibson et al., 1962; Kolinsky et al., 2011; Nelson & Peoples, 1975). Therefore, in contrast to what was found when automatic orientation processing was involved (in the shape-based task), literacy acquisition had a general positive impact on explicit orientation processing, at least for mirror images and plane rotations, which are relevant in the Latin alphabet (Gibson et al., 1962).

Consequently, the third main contribution of the present study is to demonstrate that the expression of the visual consequences of literacy depends on the type of processing at stake. Whereas this impact was mirror-specific when the task required automatic orientation processing, it was instead general when explicit orientation processing was required. This pattern of results agrees with prior studies showing that, even when the same material and procedure is adopted, different tasks tap into different processes underpinned by different neural substrates. Whereas parietal regions, part of the dorsal stream, are important for explicit orientation processing, regions of the ventral visual stream are mainly important for processing objects' shape and identity (e.g., Gauthier et al., 2002; Harris, Benito, Ruzzoli, & Miniussi, 2008). This distinction could also explain why no significant association was found between performance in the two experimental tasks for preschoolers on either letters or geometric shapes, whereas for first graders the association was reliable. Additionally, it was only for first graders that performance in the two experimental tasks was associated with visuospatial abilities known to be related with dorsal stream functioning (e.g., Chinello, Cattani, Bonfiglioli, Dehaene, & Piazza, 2013). It thus seems that literacy acquisition enhances the cross-talk between the two visual streams. In this vein, Chinello et al. (2013) recently examined the behavioral performance of kindergarteners (from 3 to 6 years old) and adults in an extensive set of functions related to the dorsal vs. ventral streams (e.g., visuospatial memory and grip aperture during grasping vs. face and object recognition, respectively) and found that it was only for adults, not for children, that visuospatial memory (assessed with the Corsi blocks test) was associated with object recognition.

Perceptual expertise with letters also explains the remarkable advantage of first graders on both shape- and orientation-based judgments of letters after only ~8 months of reading instruction. On the downside, it also explains first graders' worse performance on shape-based judgments of mirrored and rotated pairs of reversible compared to non-reversible letters. Experts usually show less flexibility in selectively ignoring the dimensions relevant to their category of expertise (e.g., Folstein et al., 2013), which explains orientation interference on letter recognition by adult readers (e.g., Corballis & Nagourney, 1978; Jolicoeur & Landau, 1984; Pegado, Nakamura, et al., 2014; Pegado et al., 2011) and the orientation costs found here on shape-based judgments of letters by first graders. In the present study the orientation cost for reversible letters was so strong that it cancelled out the advantage of first graders over preschoolers on shape-based judgments.

Noteworthy, using the masked priming paradigm, Perea et al. (2011) showed that mirrored versions of reversible letters (e.g., ibea, mirrored letter underlined) significantly inhibited the recognition of target-words (i.e. IDEA). Based on the present results, it remains to be confirmed whether the mirror interference reported by Perea et al. (2011) is exclusive for mirror images. It could rather be due to activation of an existing letter representation that is incompatible with the target word, and hence, the same interference would be expected for rotated versions of reversible letters (e.g., if ipea preceded the target IDEA). Future research should examine this prediction.

The correlation analyses also showed that first graders' explicit orientation processing of both linguistic and nonlinguistic material was associated with reading skills, suggesting that mirror discrimination was not yet fully accomplished, and might continue to develop after the first grade (Cornell, 1985). For first graders mirror discrimination continued to be harder than plane-rotation discrimination for both geometric shapes (i.e., average accuracy of 80.0% for mirrored pairs vs. 91.0% for rotated pairs, see Figure 2), and letters (with slower performance on mirrored than rotated pairs); and this continues to be the case in adults, even after years of reading practice (Fernandes & Kolinsky, 2013; Gregory et al., 2011; Kolinsky et al., 2011). Thus, mirror discrimination is triggered by learning a script with mirrored symbols but it is not a dichotomous phenomenon fully determined by literacy: The original mirror invariance property of the visual recognition system is not fully erased (Dehaene, 2009), and could instead be inhibited during recognition of visual objects, including of letters (e.g., Duñabeitia, Molinaro, & Carreiras, 2011; Perea et al., 2011).

Neuropsychological, fMRI, and transcranial magnetic stimulation studies have shown that mirror discrimination of linguistic and nonlinguistic objects has different neurocognitive loci. For linguistic material mirror discrimination is underpinned by ventral occipitotemporal regions, which are mirror invariant for pictures of familiar objects (e.g., Dehaene, Nakamura, et al., 2010; Nakamura, Makuuchi, & Nakajima, 2014; Pegado et al., 2011; Vinckier et al., 2006). What is however unclear is the temporal locus and the cognitive mechanism responsible for mirror discrimination. Although beyond the scope of the present work, this is still hotly debated, and two accounts have been proposed. According to one account, mirror discrimination occurs due to inhibition of mirror invariance at a late, possibly attention-dependent, stage of visual processing (Duñabeitia et al., 2013; Duñabeitia et al., 2011; Perea et al., 2011). The other account proposes that mirror discrimination becomes part of visual processing from an early time window (i.e., 100-148 ms after stimulus onset; Pegado, Comerlato, et al., 2014), and evidence in favor of both has been on the table.

These mixed results could be due to the adoption of different paradigms, tasks and materials, because different experimental conditions tap into different phases of visual processing. In fact, this could also be the reason for the discrepancy between the mirror cost that we found for shape-based judgments of geometric shapes by first graders and the mirror invariance found by Wakui et al. (2013) for short-term priming of familiar objects by children. The later paradigm may tap into an earlier processing stage than the same-different task used in the present study (for discussions see e.g., Kolinsky et al., 2011; Nakamura et al., 2005). Low-level differences between materials could also explain this discrepancy. According to the shape bias hypothesis (Hannagan et al., 2015), the degree of similarity to letters should influence the magnitude of the spillover effect of literacy on visual recognition of other categories. This prediction is consistent with the observation of orientation costs in identity-based judgments of illiterate adults for geometric shapes but not for pictures of familiar objects (Kolinsky & Fernandes, 2014). Thus, the absence of a mirror cost on shape-based judgments of geometric shapes by the preschoolers examined here might seem at odds with the former results.

This apparent contradiction is solved when considering the fourth contribution of the present study, which is to show that some crude sensitivity to mirror-image differences is promoted by familiarity with letters, which is then refined during formal literacy instruction. Indeed, the mirror-specific impact of literacy on visual (nonlinguistic) object recognition begins to emerge, though crudely, before literacy instruction, allied with letter knowledge. Although as a group preschoolers did not present a mirror cost on their shape-based judgments of geometric shapes, the correlation analyses revealed that letter knowledge was specifically associated with sensitivity to mirror-image differences: the higher preschoolers' letter knowledge, the stronger the mirror cost on shape-based judgments and the smaller the performance drop on orientation-based judgments of mirrored geometric shapes. The discrepancy between the present results and those of Kolinsky and Fernandes (2014) is thus probably due to differences on experience with letters between preliterate children and illiterate adults, given that the latter group has a long life-experience in a literate world (Fernandes et al., 2014).

The fact that preliterate children already present some sensitivity to mirror images agrees with prior findings suggesting an early impact of the visual properties of the script to be learned on nonlinguistic visual processing (e.g., McBride-Chang et al., 2011; Zhou et al., 2014). The present pattern of results adds to these evidence by showing that such specific impact of literacy as the one on mirror-image processing starts to emerge with letter knowledge before children are able to decode.

This association also explains why preschoolers already present a mirror cost in shape-based judgments of letters, which was also associated with their letter knowledge. This result is consistent with former observations that preschoolers who are able to correctly write their names without mirrored errors are also able to discriminate mirrored pairs of geometric shapes (Casey, 1984, 1986). It might seem at odds with the original mirror invariance of the ventral visual system (e.g., Dehaene, 2009; Logothetis et al., 1995), but prior studies have shown that the emergence of letter-specialized processing begins before formal literacy instruction in both preliterate children and illiterate adults (e.g., Cantlon et al., 2011; Fernandes et al., 2014).

In addition to these theoretical implications, the present study can also contribute to the growing interest from multiple developmental perspectives on children's print awareness and on its unique contribution to reading acquisition. Indeed, in parent-child conversations more visual attributes are used to describe letters than pictures, and not only the parents but also the children emphasize letters' visual properties (Robins, Treiman, Rosales, & Otake, 2012), as if (at least implicitly) they recognize the importance of visual features on letter learning and subsequent reading development. The engagement in these conversations, especially about the child's initial, were associated with better reading outcomes even after other factors, such as vocabulary, were controlled for (Treiman et al., 2015). More important, even before children know what letters represent (i.e., the letter-sound correspondence), they are already sensitive to letters' visual statistical patterns (Pollo, Kessler, & Treiman, 2009; Treiman, Cohen, Mulqueeny, Kessler, & Schechtman, 2007; Treiman & Kessler, 2011). Preschoolers are better at copying and writing letters with the most frequent arrangement of visual features in the Latin alphabet, i.e., letters with a hasta on the left and a coda on the right (e.g., b and F) than letters with the opposite arrangement (Pollo et al., 2009), and hence, make more mirrored errors on letters of the latter type (e.g., writing b instead of d; Treiman & Kessler, 2011).

The present study adds to this literature, showing that mirror discrimination, which is a necessary condition for mastering the Latin alphabet, can be promoted by literacy-related activities about letter forms, and this could happen at home during parent-children interactions or at the kindergarten. Additionally, our results show that training orientation discrimination in general is not the best practice; preschoolers do not have difficulties with discrimination of plane-rotations, and this ability is not related to mirror discrimination abilities. It is letter knowledge and familiarity with letter forms that are the key. Thus, our work is part of an emergent bulk of research showing that literacy has a visual facet, crucial for learning to read, to which letter knowledge strongly contributes.

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Table 1

Age and average performance in the ancillary tests.

	Preschoolers (n = 23)	First graders (n = 23)
Age (in months)	66.04 (3.34) [64.60, 67.49]	82.65 (3.64) [81.08, 84.22]
Nonverbal IQ: Raven (correct out of 36)[a]	17.70 (2.99) [16.40, 18.99]	26.74 (5.37) [24.41, 29.06]
Visuospatial working memory: Corsi blocks[b]	6.61 (2.71) [5.44, 7.78]	13.17 (2.39) [12.14, 14.20]
Phonological awareness: *d'* score	1.51 (1.40) [0.91, 2.12]	5.19 (0.92) [4.79, 5.58]
Letter knowledge [c]	24.65 (13.67) [18.74, 30.56]	65.26 (7.45) [62.04, 68.48]
Reading performance		
3DM[d] - high frequency words		17.13 (11.22) [12.28, 21.98]
3DM - low frequency words		10.87 (7.40) [7.67, 14.07]
3DM - pseudowords		11.52 (6.29) [8.80, 14.24]
Lobrot L3[e]		9.39 (6.45) [6.60, 12.18]
Reading index (summed score)		48.91 (29.85) [36.00, 61.82]

Note. SD in parenthesis; 95% CI in brackets.
[a] Total of correct responses in the Colored Progressive Matrices of Raven. [b] Number of trials correctly performed in forward and in backward sequence. [c] Total of correct responses out of 68 items, i.e., 2 (naming and recognition tasks) x 22 upper-case letters of the Portuguese alphabet (excluding letters H, K, W, Y), plus 2 (naming and recognition tasks) x 12 lower-case letters (i.e., b, d, p, q, f, g, r, s, i, o, m, x). [d] Number of items read correctly per list in 30 s. [e]Silent reading test with 5-min time-limit, on which participants select the word that correctly completes each sentence (out of five possible words). Performance computed as number of items correctly completed (total of 36 sentences).

Table 2

Mean d' scores of preschoolers and first graders for geometric shapes in the three conditions at test (mirrored, rotated, and fully different) in the shape-based and orientation-based tasks.

	Preschoolers			**First graders**		
	mirrored	**rotated**	**fully different**	**mirrored**	**rotated**	**fully different**
Shape-based	2.96 (.23)	2.75 (.18)	2.81 (.19)	3.10 (.21)	2.69 (.17)	3.09 (.18)
Orientation-based	2.07 (.18)	2.68 (.19)	3.01 (.24)	4.61 (.17)	5.49 (.18)	5.13 (.22)

Note. SEM in parenthesis.

Table 3

Mean d' scores of preschoolers and first graders for the two letter types and across letter-type in the three conditions at test in the experimental tasks.

	Reversible letters			**Non-reversible letters**			**Across letter type**		
	mirrored	**rotated**	**fully different**	**mirrored**	**rotated**	**fully different**	**mirrored**	**rotated**	**fully different**
				Preschoolers					
Shape-based	2.58 (.20)	2.57 (.16)	3.03 (.28)	2.57 (.23)	2.40 (.24)	2.77 (.23)	2.57 (.17)	2.48 (.17)	2.90 (.25)
Orientation-based	1.77 (.26)	2.59 (.19)	3.40 (.27)	1.77 (.29)	2.77 (.31)	3.12 (.28)	1.77 (.24)	2.68 (.21)	3.26 (.23)
				First graders					
Shape-based	3.36 (.29)	3.02 (.25)	4.16 (.29)	4.27 (.30)	4.39 (.33)	4.30 (.30)	3.81 (.23)	3.70 (.25)	4.23 (.25)
Orientation-based	3.65 (.26)	4.46 (.33)	4.86 (.28)	4.63 (.28)	3.52 (.24)	4.56 (.32)	3.58 (.18)	4.51 (.28)	4.75 (.25)

Note. SEM in parenthesis.

Table 4

Correlation matrix (correlation coefficients) between the ancillary cognitive abilities and the orientation cost and performance drop.

	Geometric shapes				Letters			
Cognitive abilities	**Orientation cost (shape-based task)**		**Performance drop (orientation-based task)**		**Orientation cost (shape-based task)**		**Performance drop (orientation-based task)**	
	mirror	**rotation**	**mirror**	**rotation**	**mirror**	**rotation**	**mirror**	**rotation**
Preschoolers								
Nonverbal IQ (Raven)	-.150	-.268	.016	.161	.095	**-.360***	-.149	-.045●
Visuospatial working memory (Corsi blocks)	.068	-.270	.291	.209	-.015	**-.372***	-.047	-.078●
Phonological awareness	-.111	.177	**-.522****	-.153	**-.438***	**-.378***	-.267	-.104
Letter knowledge	**.481***	-.128	-.349†	.140	**.474**●**	**.451****	**-.332*●**	**-.397***
First graders								
Nonverbal IQ (Raven)	-.262	-.261	-.088	-.325†	**-.341***	**-.476****	-.216●	-.308†●
Visuospatial working memory (Corsi blocks)	.008	-.137	-.053	-.151	.103	.100	-.065●	-.103●
Phonological awareness (ALEPE)	-.025	.339†	**-.355*●**	.241●	-.038●	.177	.163	.170
Reading index (3DM & Lobrot L3)	.178	.272	**-.402*●**	.127●	.280●	.043	-.338†●	-.178

Note. Significant results ($p < .05$, one-tailed) are in bold, marginal results are underlined.
● Significant association (at least, $|r| > .29$, $p < .05$) for the indexes computed on RTs.
†$p < .10$. *$p < .05$. **$p \leq .01$.

Figure captions

Figure 1. Experimental material. (A) Sequence of events in each experimental trial and illustration of the four trial types. The presentation of S1 and S2 was separated by a mask to ensure no involvement of iconic memory in performance. S2 was presented until response or for the maximum of 2.5 s if no response was given, after which another trial began. The two geometric shapes presented as S2 in the fully different and identical trials are the new figures used in this study (see text). (B) The two letter types (reversible and non-reversible) organized by the four trial types.

Figure 2. Mean performance – accuracy on the top, RTs on the bottom – of preschoolers (in blue) and first graders (in red) for geometric shapes. (A) Performance in the shape-based task. (B) Performance in the orientation-based task. Error bars represent the *SEM* in each condition.

Figure 3. Mean performance – accuracy on the top, RTs on the bottom – for reversible letters (in black) and non-reversible letters (in gray) by preschoolers and first graders in the experimental tasks. (A) Performance in the shape-based task. (B) Performance in the orientation-based task. Error bars represent the *SEM* in each condition.

Figure 1

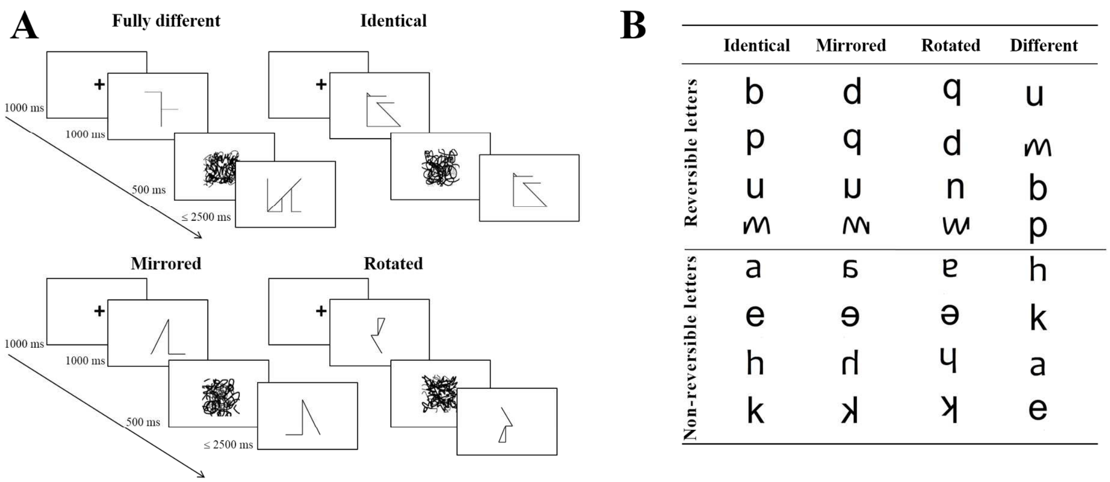

A
Fully different
Identical
Mirrored
Rotated
1000 ms
1000 ms
500 ms
≤ 2500 ms
B
Identical
Mirrored
Rotated
Different
Reversible letters
Non-reversible letters

Figure 2

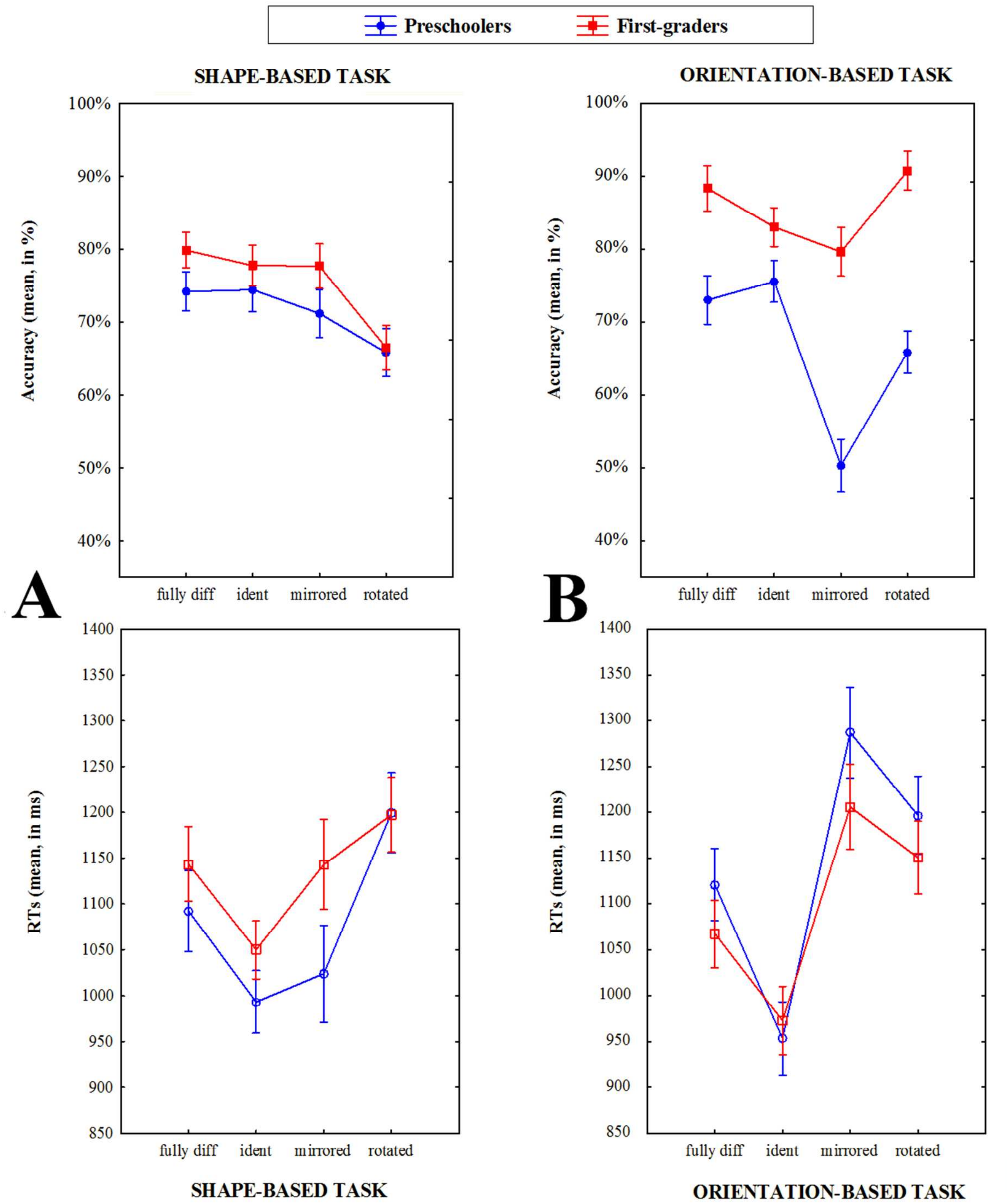
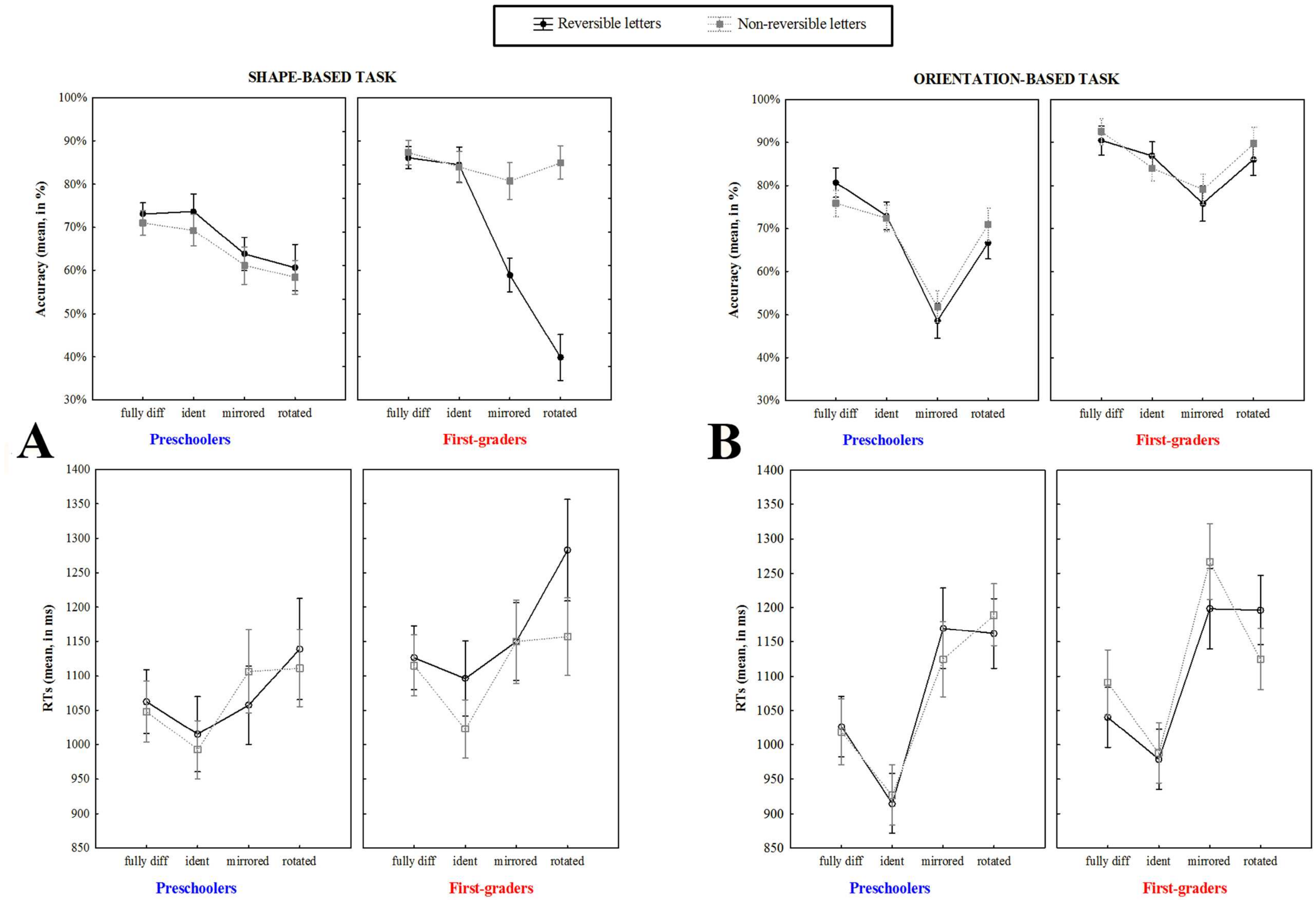

Preschoolers
First-graders
SHAPE-BASED TASK
ORIENTATION-BASED TASK
Accuracy (mean, in %)
100%
90%
80%
70%
60%
50%
40%
fully diff
ident
mirrored
rotated
A
B
RTs (mean, in ms)
1400
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
SHAPE-BASED TASK
ORIENTATION-BASED TASK

Figure 3


Reversible letters
Non-reversible letters
SHAPE-BASED TASK
ORIENTATION-BASED TASK
Accuracy (mean, in %)
100%
90%
80%
70%
60%
50%
40%
30%
fully diff
ident
mirrored
rotated
Preschoolers
First-graders
A
B
RTs (mean, in ms)
1400
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850

Into the looking glass:

Literacy acquisition and mirror invariance in preschool and first-grade children

Abstract

Since when, during reading development, does literacy impact object recognition and orientation processing? Is it specific to mirror images? To answer these questions, forty-six 5-7-year-old preschoolers and first graders performed two same-different tasks tapping explicit (orientation-based) vs. automatic (shape-based) orientation processing of geometric shapes and letters. On orientation-based judgments, first graders outperformed preschoolers who had the strongest difficulty with mirrored pairs. On shape-based judgments, first graders were slower for mirrored than identical pairs, and even slower than preschoolers. This mirror cost emerged with letter knowledge. Only first graders presented worse shape-based judgments for mirrored and rotated pairs of reversible (e.g., b–d; b–q) than non-reversible (e.g., e–ə) letters, indicating readers' difficulty in ignoring orientation-contrasts relevant to letters.

Keywords: object orientation processing; mirror invariance; literacy acquisition.

Learning to read is a gateway to culture and education, and, most impressively, it profoundly changes the brain and mind. Literacy acquisition leads to the emergence of a neural network in the ventral occipitotemporal cortex tuned to the processing of written strings, reproducible across literate people, independently of script (e.g., in Japanese and French readers; Dehaene, Nakamura, et al., 2010; e.g., for kana and kanji in Japanese readers; Nakamura, Dehaene, Jobert, Le Bihan, & Kouider, 2005) and age of acquisition (i.e., in childhood for *early literate* adults, or in adulthood for *late literate* adults; Dehaene, Pegado, et al., 2010). Most impressively, learning to read also impacts on evolutionarily older systems, including visual object recognition (e.g., Dehaene, Nakamura, et al., 2010; Dehaene, Pegado, et al., 2010; Pegado, Nakamura, et al., 2014; Pegado, Nakamura, Cohen, & Dehaene, 2011). This agrees with the *neuronal recycling hypothesis* (Dehaene, 2009), which holds that the ventral occipitotemporal regions, originally devoted to object recognition, were partially recycled to accommodate literacy, with spillover effects on the older function.

In fact, probably as a consequence of the intensive perceptual training that it requires, literacy acquisition alters early visual responses in the occipital cortex, including in areas involved in very early processing (i.e, in V1; e.g., Dehaene, Pegado, et al., 2010; Pegado, Comerlato, et al., 2014). The impact of literacy can thus be found on several visual tasks outside the written domain. For instance, visual integration is enhanced in readers, as shown by early and late literate adults' superior capacity (compared to illiterates) in connecting local elements into an overall shape (Szwed, Ventura, Querido, Cohen, & Dehaene, 2012). The visual properties of the script itself have also a moderator role (for a recent review, see Zhou, McBride-Chang, & Wong, 2014). For instance, Chinese and Korean children learning to read visually complex and demanding scripts outperform Israeli and Spanish children on visual nonlinguistic spatial skills (McBride-Chang et al., 2011; Experiment 1), and the importance of reading to spatial skills is stronger than the other way around, as shown in a one-year longitudinal study with Chinese children (McBride-Chang et al., 2011; Experiment 2).

Learning to read in scripts such as the Latin alphabet also requires quite specific adaptations, especially when considering original properties of the visual system that may oppose to literacy acquisition. One such property is mirror-image generalization or *mirror invariance*: lateral mirror images (180º flip outside the image plane, e.g., ⌉ and ⌈) are processed as equivalent percepts by humans and other animals (e.g., Bornstein, Gross, & Wolf, 1978; Dehaene, Nakamura, et al., 2010; Logothetis, Pauls, & Poggio, 1995; Pegado et al., 2011; Tarr & Pinker, 1989). Yet, to learn a script with mirrored symbols, one must discriminate mirror images, which collides with mirror invariance.

Besides the Latin alphabet (which is used in more than 400 languages; e.g., b and d), other scripts such as the Japanese hiragana (e.g., ち and さ) and the Cyrillic alphabet (e.g., Є and З) also include mirrored or quasi-mirrored symbols. In any of these scripts mirrored symbols are just a small proportion but this is sufficient to trigger the ability to discriminate them, which transfers to nonlinguistic categories (e.g., Dehaene, Nakamura, et al., 2010; Kolinsky et al., 2011; Pegado et al., 2011), either novel (i.e., blob-like and geometric shapes) or familiar (e.g., pictures of tools or cloths). In contrast to readers of the Latin alphabet, illiterate adults present poor mirror discrimination (Fernandes & Kolinsky, 2013; Kolinsky et al., 2011), and readers of Tamil, a script with no mirrored symbols, have the same difficulties as illiterates (Danziger & Pederson, 1998; Pederson, 2003). Therefore, it is not learning to read in general that causes people to become able to discriminate mirror images. The trigger is learning a script with mirrored symbols.

Noteworthy, Pegado, Nakamura, et al. (2014; see also Kolinsky & Fernandes, 2014) recently showed that mirror discrimination also extends to situations where orientation processing is irrelevant and even harmful to the task at hand. In a same-different, identity-based and orientation-independent task, requiring a *same* response to both exact matches (henceforth, *identical pairs*) and mirrored pairs of the same object, only illiterate adults had as good performance for mirrored as for identical pairs. In contrast, both early and late literate adults in the Latin alphabet showed a *mirror cost,* i.e., worse performance for mirrored than identical pairs of linguistic (i.e., pseudowords) and nonlinguistic materials (i.e., false-font strings, composed of letter-like characters; pictures of objects and faces). Thus, with literacy acquisition, mirror discrimination seems to become automatic during visual object recognition, as readers of the Latin alphabet are unable to ignore mirror-image differences even when this hinders performance. The impact of literacy on automatic orientation processing could also explain the weaker priming effect for targets preceded by mirrored than by identical primes in short-term priming studies with adult readers (e.g., Dehaene, Nakamura, et al., 2010; Pegado et al., 2011).

Although this bulk of research has shown that learning a script with mirrored symbols impacts on sensitivity to mirror images, to the best of our knowledge no study has hitherto examined when, during literacy acquisition, mirror discrimination becomes automatic. Examining this question in children differing on reading skills (preschoolers with no reading skills vs. beginning readers at the end of the first grade) was the main aim of the present study. We used single letters and geometric shapes in order to investigate the effects of literacy acquisition on linguistic and nonlinguistic material.

Mirror discrimination probably develops and becomes automatic earlier for letters and for nonlinguistic stimuli visually similar to letters, such as geometric shapes, than for other nonlinguistic categories. Indeed, even before children are able to read, their letter knowledge already predicts attention to text (as measured through eye movements; Evans, Saint-Aubin, & Landry, 2009) and stronger responsiveness of the left occipitotemporal region to letters than to other visual categories (Cantlon, Pinel, Dehaene, & Pelphrey, 2011). Consistently, illiterate adults who are unable to decode but have high letter knowledge process letters differently than non-letters (Fernandes, Vale, Martins, Morais, & Kolinsky, 2014). Regarding mirror-image processing, Kolinsky and Fernandes (2014) recently showed that, whereas for pictures of familiar objects illiterate adults did not present any mirror cost on identity-based judgments (as in Pegado, Nakamura, et al., 2014), for geometric shapes they did present a mirror cost. This result agrees with the *shape bias hypothesis* (Hannagan, Amedi, Cohen, Dehaene-Lambertz, & Dehaene, 2015), according to which the specific tuning of ventral occipitotemporal neurons to shape features like those of letters is responsible (at least partially) for the highly reproducible location of the brain regions devoted to letter and visual word recognition. Under this view, the closer the features of nonlinguistic stimuli to those of letters, the earlier the consequences of literacy on visual (nonlinguistic) processing. Noteworthy, rudimentary reading seems enough, as late literate adults present the same mirror costs as early literates on both linguistic and nonlinguistic materials (Kolinsky & Fernandes, 2014; Pegado, Nakamura, et al., 2014).

However, late literate adults are not comparable to young children. Note that even *explicit* mirror discrimination (i.e., when orientation is critical to the task) seems to develop slowly in childhood. Children often present mirror errors in reading and writing during the first two years of literacy instruction (Cornell, 1985). Compared with fluent adult readers, first-grade children fixate more and for longer time on distractors differing from the target-word on two mirrored letters (e.g., *meter*, letters underlined were mirrored in the distractor) than on control distractors (e.g., matar; Duñabeitia, Dimitropoulou, Estévez, & Carreiras, 2013). For nonlinguistic material, in contrast to literate adults, 7-8 year-old children present similar short-term priming effects when pictures of familiar objects (e.g., animals) are preceded by mirrored and by identical primes (Wakui et al., 2013).

We thus decided to investigate the impact of learning to read on both explicit and implicit (i.e., automatic) mirror-image processing of letters and of geometric shapes, using a within-participants design. Furthermore, it is still unclear whether the impact of literacy on orientation processing is restricted to / or at least stronger for mirror images than for other orientation contrasts. Thus, we contrasted the processing of mirror images with that of rotations in the image plane (henceforth, *plane rotations*; e.g., 180º clockwise rotation: ⌉ and ⌊), because as highlighted by Gibson, Pick, Osser, and Gibson (1962) both distinguish letters of the Latin alphabet (e.g., d – b, and d – p). Given that letters are a category of expertise for readers (McCandliss, Cohen, & Dehaene, 2003), then through perceptual learning, dimensions that maximally distinguish letters, like orientation, would become enhanced (e.g., Folstein, Palmeri, & Gauthier, 2013). Literacy should thus impact on both mirror-image and plane-rotation processing. Yet, the neuronal recycling hypothesis predicts that this impact should be stronger for the former contrast (Dehaene, 2009) because the visual system is originally sensitive to plane rotations but not to mirror images (e.g., Logothetis et al., 1995). Consistently, both 4-6 year-old children and illiterate adults find it harder to explicitly discriminate mirror images than plane rotations of nonlinguistic objects (Fernandes & Kolinsky, 2013; Gregory, Landau, & McCloskey, 2011). Whether a similar pattern would be found on automatic orientation processing is not clear. In Pegado, Nakamura, et al. (2014), mirror images were the only orientation contrast examined. In Kolinsky and Fernandes (2014), whereas for identity-based judgments of familiar objects illiterate adults presented no orientation costs, for geometric shapes, both illiterate and literate adults presented stronger interference for rotated than mirrored pairs.

Therefore, to examine explicit vs. implicit, automatic processing of orientation, children performed two same-different tasks, on which they decided in each trial whether the second stimulus (S2) was the same or not as the first one (S1). As illustrated in Figure 1, the two tasks were performed separately on geometric shapes and single letters, and had the same four trial types: *fully different* trials (on which S2 differed from S1 on shape and on orientation; e.g., b – u); identical trials (S2 had the same shape and same orientation as S1; e.g., b – b); mirrored trials (S2 was a mirror image of S1; e.g., b – d); and rotated trials (S2 was a plane rotation of S1; e.g., b – q). The mirror-image and plane-rotation contrasts differed from the standard stimulus (S1) by the same 180º difference and preserved all object-based properties (global shape, parts, and relation between parts). Thus, any difference in performance between mirrored and rotated trials would not be due to low-level differences. The two tasks examined both mirror-image and plane-rotation processing, and differed only on the matching criterion; orientation was either irrelevant or critical for successful performance.

In the *shape-based* task, children were asked to classify a stimulus pair as *same* if S2 had the same shape as S1; orientation was thus irrelevant to the task (not only identical but also mirrored and rotated pairs should be classified as *same*). Automatic orientation processing was assessed by using the performance on identical pairs as baseline, given that orientation processing would lead to an *orientation cost* in mirrored or rotated trials compared to identical trials. In contrast, in the *orientation-based* task, orientation was the critical dimension: children were asked to classify a stimulus pair as *same* only if S2 was identical to S1 – same shape and same orientation –, and to classify as *different* both the *fully different* pairs and the mirrored and rotated pairs. Explicit orientation processing was assessed by examining the *performance drop* on trials on which only orientation varied (mirrored and rotated trials) relative to fully different trials.

-------------------- Figure 1 about here -------------------

Given the original property of mirror invariance of the ventral visual system (Dehaene, 2009; Logothetis et al., 1995; Tarr & Pinker, 1989), we expected preschoolers to be better able to tolerate, i.e., to classify as *same*, the mirrored pairs in the shape-based task than to discriminate them in the orientation-based task, whereas they would be as able to tolerate as to discriminate plane rotations. Indeed, in the shape-based task, preschoolers would exhibit no mirror cost at all. Conversely, in the orientation-based task, they would present the worst performance for mirrored pairs, even when compared with rotated pairs. This pattern of results was expected for both materials.

If mirror discrimination transferred to nonlinguistic categories early on in reading acquisition, first graders would present good mirror discrimination of both letters and geometric shapes in the orientation-based task. If it became automatic, they would also present a mirror cost for both materials in shape-based judgments. Given the importance of plane-rotation contrasts in letter discrimination, we expected first graders to be less able to tolerate plane rotations in the shape-based task than to discriminate them in the orientation-based task.

Therefore, the strongest difference between preschoolers and first graders was expected for the mirrored pairs. Note that by using the two normalized indexes (i.e., the orientation cost and the performance drop) we ensured that any difficulty to be found on explicit mirror discrimination by preschoolers could not be due to overall differences in performance between groups.

We also examined the mirror cost for *reversible* letters (i.e., differing only by orientation; e.g., u – n) and *non-reversible* ones, for which orientation contrasts do not map onto different representations (e.g., e – ə). As mirror discrimination is most relevant to reversible letters (Perea, Moret-Tatay, & Panadero, 2011), the orientation cost on shape-based judgments of first graders should be stronger for these letters, but no difference was expected for preschoolers due to their limited letter knowledge.

Finally, to assess whether literacy related-skills (i.e., letter knowledge in preschoolers, reading skills and phonological awareness in first graders) were associated with mirror discrimination or orientation processing in general, we conducted correlation analyses in each group for each material.

Method

Participants

Twenty-eight preliterate preschoolers (17 males; M_{age} = 65.9 months, SD = 3.2) and 24 first graders (7 males; M_{age} = 82.7 months, SD = 3.6), all Portuguese native speakers, from schools of Lisbon and Évora, Portugal, with no known history of developmental and/or neurological disorders, participated voluntarily in compliance with Declaration of Helsinki. Data was collected between March – June 2011, and March – June 2013. Due to the end of the school year, six preschoolers did not perform the orientation-based task for geometric shapes and three did not perform it for letters. These children were excluded, as well as those who performed at the chance level on the fully different and identical trials, which led to same responses in the two tasks (for geometric shapes: two preschoolers and one first grader; for letters: two other preschoolers and the same first grader). The final sample thus included 20 preschoolers for geometric shapes and 23 for letters, plus 23 first graders tested on both materials.

Table 1 presents children's results in five domains: nonverbal IQ (Colored Progressive Matrices of Raven, Portuguese version; Simões, 2000); visuospatial working memory (Corsi block test, WMS-III; Wechsler, 1997); phonological awareness (i.e., same-different matching task on the target-unit – the first phoneme, the rhyme, or the syllable - of two words; 16 trials per unit preceded by 6 practice trials); letter knowledge (naming and recognition of lower- and upper-case letters of the Portuguese alphabet); and reading skills for first graders only, i.e., reading fluency of isolated items (3DM Battery, Portuguese version; Reis, Faisca, Castro, & Petersson, 2013) and reading comprehension (Lobrot L3 test, Portuguese adaptation; Sucena & Castro, 2008).

The phonological awareness task was examined using *Signal Detection Theory* (SDT) *d'* scores (Macmillan & Creelman, 2005). The *reading index* was the summed result across the 3DM subtests and the Lobrot L3 test, given the high correlations between them, $r(21)$s > .85, ps < .001.

In the Portuguese educational system, literacy instruction starts only at Grade 1. There are no official directives concerning literacy-related activities in preschool years, and hence, usually no (or only few) instruction on letter knowledge is given, explaining the low letter knowledge of these preschoolers (see Table 1), and the independence between their letter knowledge and phonological awareness, $r(18) = -.26$, $p = .13$. In contrast, for first graders, phonological awareness was significantly associated with reading skills, $r(21) = .59$, $p < .005$. In both groups, visuospatial abilities, i.e., working memory and nonverbal IQ were significantly associated with each other: for preschoolers, $r(18) = .46$, $p = .015$, and first graders, $r(21) = .40$, $p = .03$.

----------------------- Table 1 about here --------------------

Material

Two types of asymmetrical black-line material were used: nine geometric shapes and eight letters (see Figure 1). The geometric shapes were those used by Fernandes and Kolinsky (2013) except for two stimuli which were replaced by those presented in Figure 1A. As shown in Figure 1B, half of the letters were non-reversible and the others were reversible (for b and p both orientation-contrasts corresponded to real letters but not for m and u).

For each material, three versions were created with irfanview (www.irfanview.com): the standard, its mirror image (180º lateral reflection) and its plane rotation (180º clockwise rotation). For each standard stimulus, four pairs were prepared to create the four trial types (S1 was the standard): identical trials (S2 was the same as S1); mirrored trials (S2 was the mirror image of S1); rotated trials (S2 was the plane rotation of S1); and fully different trials (S2 was a different standard stimulus).

Procedure

Children were tested in a quiet room of their school. They performed the two same-different tasks for the two materials in four sessions. The shape-based task was performed first to ensure that any orientation cost to be found would not be due to prior performance of the orientation-based task. Sequence of events in experimental trials was the same for each task and material (see Figure 1A), and was controlled by E-Prime 2.0 (www.pstnet.com/eprime). Children sat at a distance of ~70 cm of the computer screen (resolution: 640 x 480 pixels; refresh rate: 60 Hz) and were asked to perform a same-different judgment on S2 in each trial (in each task, half of the trials were expected to lead to a *same*-response). Instructions were given orally with six demo-trials using animals as stimuli. Next, to ensure that children understood the task, they performed 12 practice trials (six with animals, six with the experimental material; half trials leading to a *same*-response), with feedback on response accuracy.

In the shape-based task, on each trial children were asked to decide as accurately and quickly as possible whether S2 had the same shape as S1, independently of orientation, by pressing one of the two keys of the response box (*same* response given with the right index finger). It was emphasized that stimuli's name was irrelevant to the task; S2 should be classified based on shape and not on name. Note that at least for letters, especially for reversible ones, an identity-based criterion (same identity, same name) would induce an incorrect response (e.g., d and b are different letters, with different names, but have the same shape). In the orientation-based task, children were asked to decide whether S2 was an exact match of S1. They should respond *different* (using the left key, left index finger) if S2 had a different orientation than S1 even if they had the same shape. Accuracy and RTs (measured from S2 onset to response onset) were collected in each trial.

Children performed 108 trials for geometric shapes in each task (i.e., shape-based task: 54 fully different, 18 identical, 18 mirrored, and 18 rotated trials; orientation-based task: 54 identical, 18 fully different, 18 mirrored, and 18 rotated trials). For letters, they performed 96 trials per task (For each letter type: in the shape-based task, 24 fully different, 8 identical, 8 mirrored, and 8 rotated trials; in the orientation-based task, 24 identical, 8 fully different, 8 mirrored, and 8 rotated trials).

Results

The mean accuracy and correct RTs (after the trimming of outliers 2.5 SD above or below the grand mean RT for each participant by material and task; < 3% data excluded) were examined separately for each material, with group (preschoolers, first graders; between-participants), task (shape- vs. orientation-based) and trial type (fully different, identical, mirrored, rotated) as factors, plus letter type (reversible vs. non-reversible) for the analyses run on letters. We also checked that a similar pattern of statistical significance was found when analyses were run on SDT *d'* scores adapted for same-different designs (i.e., hits correspond to proportion of correct responses in different-response trials, and false alarms correspond to the proportion of incorrect responses in same-response trials; cf. Macmillan & Creelman, 2005), with group, task, and *condition* (fully-different; mirrored; rotated) as factors, plus the letter-type factor in the analyses run on letters.

Geometric shapes

The three-way interaction between all factors at test was significant on both accuracy, $F(3,123) = 3.72$, $p = .013$, $\eta p^2 = .08$ (*d*' scores, $F(2, 82) = 3.97$, $p = .022$, $\eta p^2 = .09$), and RTs, $F(3,123) = 2.94$, $p = .036$, $\eta p^2 = .07$. In line with our predictions, as shown in Figure 2 (see also Table 2), whereas preschoolers were immune to mirror-image differences, first graders were sensitive to them even if harmful for performance. Specifically, preschoolers were perfectly able of tolerating (i.e., responding *same* to) the mirrored pairs in the shape-based task (Figure 2A) and had the strongest difficulty in discriminating them in the orientation-based task (Figure 2B), whereas first graders presented a mirror cost on shape-based judgments and were quite able of explicitly discriminating the mirrored pairs.

-------------------- Figure 2 about here -------------------

Shape-based task.

In the shape-based, orientation-independent task (Figure 2A), preschoolers had similar overall performance level as first graders on both accuracy, $F(1, 41) = 2.02$, $p = .16$ (*d'* scores, $F < 1$), and RTs, $F = 1$; we thus compared directly their performance. Notably, it was only for mirrored trials that first graders were significantly slower than preschoolers by 118 ms on average, $t(41) = 1.65$, $p = .05$ (accuracy, $t(41) = 1.40$, $p = .10$; *d'* scores, $t < 1$), other *t*s < 1. Furthermore, whereas first graders showed a significant mirror cost, with slower performance on mirrored than on identical trials, $F(1, 22) = 10.05$, $p = .004$ (accuracy, $F < 1$), preschoolers did not show any mirror cost (accuracy and RTs: *F*s < 1). For plane rotations, no difference was found between groups, *t*s < 1, as both presented a rotation cost, with worse and slower performance on rotated than on identical trials: preschoolers, $F(1, 19) = 10.85$, and = 39.36, respectively, both *p*s < .005; first graders, $F(1, 22) = 9.34$, and = 19.84, respectively, both *p*s < .010. On *d'* scores, whereas preschoolers were not affected by orientation, presenting similar *d'* scores for mirrored, rotated, and fully different conditions, *F*s ≤ 1, first graders were affected by orientation, $F(2, 44) = 6.20$, $p = .004$, with higher *d'* scores in the fully different (which did not differ from the mirrored condition, $F < 1$), than in the rotated condition, $F(1, 22) = 9.09$, $p = .006$ (see Table 2).

-------------------- Table 2 about here -------------------

Orientation-based task.

As illustrated in Figure 2B, preschoolers had a specific difficulty in discriminating mirrored pairs, presenting the worst and slowest performance for these trials compared with either fully different trials, $F(1, 19) = 23.15$, (*d'* scores, $F(1, 19) = 14.47$), and $F(1, 19) = 16.93$, respectively, *p*s ≤.001, or rotated trials, $F(1, 19) = 4.73$ (*d' scores*, $F(1, 19) = 16.11$) and $F(1, 19) = = 4.55$, respectively, *p*s < .05. Preschoolers were also less accurate and slower on rotated than on fully different trials, $F(1, 19) = 16.91$ (*d'* scores, $F(1, 19) = 4.40$) and = 7.05, respectively, *p*s ≤ .05. Furthermore, on mirrored trials, preschoolers were also worse than first graders, $t(41) = 5.97$, (*d'* scores, $t(41) = 10.44$), *ps* < .001, but not slower, $t = -1.20$, $p > .10$.

Although first graders were still less accurate and slower in discriminating mirror images than plane rotations, $F(1, 22) = 14.18$, (*d' scores,* $F(1, 22) = 19.65$), and $F(1, 22) = 4.97$, respectively, *ps* < .05, they were quite able of discriminating any orientation contrast, with average accuracy above 80% (see Figure 2B). Also, they were as accurate on rotated as on fully different pairs, $F < 1$, (*d'* scores, $F(1, 22) = 2.42$, $p = .13$; see Table 2), albeit slower for the former pairs, $F(1, 22) = 17.84$, $p < .001$.

In contrast to what happened in the shape-based task, in the orientation-based task first graders were overall more accurate than preschoolers, $F(1, 41) = 37.84$, (*d'* scores, $F(1, 41) = 122.11$), $ps < .001$, but not faster, $F < 1$. As shown in Figure 2B, first graders were especially better than preschoolers for mirror images (Group x Trial type: accuracy, $F(3, 123) = 7.94$, $p < .001$; RTs, $F < 1$; *d'* scores, $F(2, 82) = 3.00$, $p = .05$).

To ensure that this result was not merely due to the overall difference between groups, we next used a normalized index to compare preschoolers with first graders on their performance drop for mirrored and rotated trials relative to fully different trials ($[(x-y)/(x+y)]*100$, where x is the proportion of correct responses on fully different trials, and y is the proportion of correct responses on either mirrored or rotated trials, cf. Fernandes & Kolinsky, 2013). The higher the performance drop, the stronger the relative difficulty to discriminate the pair on the basis of only orientation (on mirrored or rotated trials) rather than on the basis of both shape and orientation (on fully different trials). For mirror images, the performance drop was significantly stronger in preschoolers than in first graders ($M = 11.89$, $SEM = 4.19$ vs. $M = 6.06\%$, $SEM = 2.19$, respectively), $F(1, 41) = 6.74$, $p = .013$; for plane rotations, the difference between groups did not reach the conventional level of significance, preschoolers only tended to present a larger performance drop ($M = 4.31$, $SEM = 2.76$ vs. $M = -1.37\%$, $SEM = 1.46$, respectively), $F(1, 41) = 3.57$, $p = .07$.

Comparison between the two tasks and the two groups.

The comparison between tasks revealed that preschoolers found it harder to explicitly discriminate (in the orientation-based task) than to tolerate (in the shape-based task) the mirrored pairs: accuracy, *d'* scores, and RTs, $F(1, 19) = 14.90$, $= 14.11$, and $= 20.78$, respectively, all $ps \leq .001$. For the other trial types (including the rotated trials), they were as fast and as accurate (and had similar *d'* scores) on shape- as on orientation-based judgments, all Fs < 1 (see Figure 2). Yet, the association between performance in the two tasks was not significant, for mirrored trials (accuracy: $r(18) = -.22$, $p = .18$; RTs: $r(18) = .35$, $p = .12$), for rotated trials (accuracy and RTs: $r(18) = .05$, and $= .13$, $ps > .25$), or across trials (accuracy: $r(18) = .26$, $p = .13$; RTs, $r(18) = .30$, $p = .10$; one-tailed *t*-tests).

The result pattern of first graders differed from that of preschoolers in three ways. First graders were as accurate and fast in discriminating as in tolerating the mirrored pairs, both Fs < 1.25, Yet, the association between the two tasks for these trials did not reach statistical significance: accuracy, $r(21)$

$= -.13$, $p = .28$; RTs, $r(21) = .32$, $p = .07$. Moreover, on *d'* scores, they were even better on orientation-based than on shape-based judgments in the mirrored condition, $F(1, 22) = 36.57$, $p < .001$. Second, a similar advantage for the orientation- over the shape-based task was observed for the other trial types, especially for rotated pairs. On average, they were 24% more accurate in discriminating than in tolerating these pairs, $F(1, 22) = 44.13$, $p < .001$, and their average *d'* score for these pairs in the orientation-based task was almost the double of that in the shape-based task, $F(1, 22) = 153.78$, $p < .001$ (see Table 2). Finally, the association between the two tasks was significant for rotated trials, on RTs, $r(21) = .50$, $p = .008$ (not on accuracy, $r = .09$), and across trials, accuracy and RTs, $rs(21) > .50$.

-------------------- Figure 3 about here ------------------

Letters

In the ANOVAS run on accuracy and RTs, the Group x Trial type x Letter type interaction was significant, $F(3, 132) = 4.79$, $p = .003$, $\eta p^2 = .10$, and $F(3, 132) = 2.63$, $p = .050$, $\eta p^2 = .056$ (see Figure 3). Similarly, on *d'* scores, the Group x Condition x Letter type interaction was also significant, $F(2, 88) = 5.72$, $p = .02$, $\eta p^2 = .115$. Indeed, preschoolers were not affected by letter type at all (neither the main effect of letter type nor any interaction with other variables was significant on accuracy, *d'* scores, and RTs, all *F*s < 1.62, *p*s > .21). In contrast, first graders' performance was affected by Letter type x Trial type (accuracy, $F(3, 66) = 13.81$, $p < .001$, $\eta p^2 = .39$, and RTs, $F(3, 66) = 5.33$, $p = .002$, $\eta p^2 = .19$; and on *d*' scores by Letter type x Condition, $F(2, 44) = 3.08$, $p = .05$, $\eta p^2 = .122$) and by Letter type x Task (accuracy, $F(1, 22) = 47.03$, $p < .001$, $\eta p^2 = .68$, *d'* scores, $F(1, 22) = 6.70$, $p = .017$, $\eta p^2 =.233$, and RTs, $F(1, 22) = 5.20$, $p = .032$, $\eta p^2 = .19$). Actually, the impact of letter type on first-graders' accuracy was quite specific: it was modulated by task and trial type (Letter type x Task x Trial type; accuracy, $F(3, 66) = 9.53$, $p < .001$, $\eta p^2 = .30$; *d'* scores, $F = 1.38$, and RTs, $F < 1$). As aforementioned, for preschoolers, performance was not affected by letter type but it was modulated by task and trial type, on accuracy, $F(3, 66) = 5.61$, $p = .002$, $\eta p^2 = .20$, and RTs, $F(3, 66) = 3.89$, $p = .01$, $\eta p^2 = .15$ (similarly, on *d'* scores, the Task x Condition interaction was significant, $F(2, 44) = 9.89$, $p < .001$, $\eta p^2 = .31$; see Table 3). Therefore, we further examined the preschoolers' results in each task across letter type, whereas for first graders the impact of letter type was also considered.

-------------------- Table 3 about here -------------------

Shape-based task.

In contrast to what happened for geometric shapes, for letters first graders presented an overall advantage over preschoolers in the shape-based task (see Figure 3A), on accuracy, $F(1, 44) = 9.63$, $p = .003$ (d' scores, $F(1, 44) = 19.80$, $p < .001$), but not on RTs, $F = 1.25$ (the only significant effect on RTs was the main effect of trial type, $F(3, 132) = 11.32$, $p < .001$). This advantage was modulated by letter and trial type, $F(3, 132) = 9.16$, $p < .001$ (d' scores: Letter x Condition, $F(2, 88) = 2.44$, $p = .09$).

Nevertheless, both groups exhibited the same qualitative impact of trial type on their performance. As shown in Figure 3A, preschoolers presented a rotation cost on shape-based judgments of letters: worse and slower performance on rotated trials ($M = 59.5\%$, $SEM = 3.8$; $M = 1125$ ms, $SEM = 62$) than on identical trials ($M = 71.5\%$, $SEM = 3.4$; $M = 1003$ ms, $SEM = 49$), $F(1, 22) = 6.85$ and $= 11.96$, respectively, $ps \leq .016$. Similarly, they had lower d' scores on the rotated than on the fully different condition (see Table 3), $F(1, 22) = 4.91$, $p = .03$.

Contrary to what happened for geometric shapes, preschoolers also presented a mirror cost for letters, with significantly worse performance on mirrored trials ($M = 62.4\%$, $SEM = 2.5$; $M = 1082$ ms, $SEM = 61$) than on identical trials: accuracy, $F(1, 22) = 6.10$, $p = .022$; RTs, $F(1, 22) = 3.39$, $p = .079$. A mirror cost was also found on d' scores, $F(1, 22) = 4.91$, $p = .03$ (see Table 3).

Similarly, first-graders presented both rotation and mirror costs on shape-based judgments of letters: for reversible letters, a rotation cost, accuracy, $F(1, 22) = 50.63$, RTs, $F(1, 22) = 9.71$, both $ps \leq .005$, and a mirror cost, accuracy, $F(1,22) = 31.79$, $p < .001$, RTs, $F = 1.14$ (the same costs were found on d' scores, $F(2, 44) = 8.55$, $p < .001$, with lower performance in the mirrored and in the rotated condition than in the fully different one, $F(1, 22) = 10.82$, and $= 16.92$, respectively, both $ps < .005$); for non-reversible letters, the rotation and mirror costs were significant on RTs, $F(1, 22) = 16.16$, and $= 11.99$, respectively, both $ps < .001$, but not on accuracy or d' scores, $Fs < 1$ (see Table 3).

More important, first-graders' shape-based judgments were modulated by letter and trial type on accuracy, $F(3, 66) = 17.38$, $p < .001$ (RTs: $F(3, 66) = 1.55$, $p = .207$; Letter x Condition, on d' scores, $F(2, 44) = 5.07$, $p = .01$), because their orientation costs were stronger for reversible than for non-reversible letters. They were less accurate on shape-based judgments of reversible than non-reversible letters for mirrored pairs $F(1, 22) = 13.53$, $p = .001$ (*d’* scores, $F(1, 22) = 5.96$, $p = .023$) and rotated pairs, $F(1, 22) = 62.86$ (*d’* scores, $F(1, 22) = 18.63$), *ps* < .001, but not for identical trials nor fully different trials, *F*s < 1. Therefore, first graders found it harder to classify as *same* the pairs, either mirrored or rotated, that map onto different letter representations (e.g., d – b, or d – p) than those that do not (e.g., e – ə).

In order to directly compare the orientation cost of the two groups in the shape-based task, we adopted the orientation cost index used by Pegado, Nakamura, et al. (2014; Kolinsky & Fernandes, 2014), i.e., $[(x\text{-}z)/(x+z)]*100$, where x is the proportion of correct responses on fully different trials and z is the accuracy on identical trials: the higher the orientation cost, the stronger the interference due to an orientation transformation on shape-based judgments. This orientation cost was significantly modulated by group, letter type, and orientation contrast, $F(1, 44) = 5.92$, $p = .019$, $\eta p^2 = .12$. For non-reversible letters, the orientation cost of first graders was similar to that of preschoolers (*M* =1.34%, *SEM* = 3.24 vs. 8.72%, *SEM* = 4.35, respectively), $F(1, 44) = 2.60$, $p = .12$, and was not modulated by orientation contrast, $F(1, 44) = 2.34$, $p = .132$. In contrast, for reversible letters, first graders presented stronger orientation costs than preschoolers for both mirror images (*M* = 19.46%, *SEM* = 3.56 vs. *M* = 5.72%, *SEM* = 2.26, respectively), $F(1, 44) = 5.40$, $p = .025$, and plane rotations (*M* = 42.77%, *SEM* = 6.92 vs. *M* = 10.79%, *SEM* = 5.83, respectively), $F(1, 44) = 12.48$, $p < .001$.

Orientation-based task.

Although preschoolers were somewhat sensitive to mirror-image differences in the shape-based task, they still presented a specific difficulty in discriminating mirrored letters. Their orientation-based judgments were the worst for the mirrored pairs (*M* = 50.2%, *SEM* = 4.1; *M* = 1147 ms, *SEM* = 59; for *d’* scores, see Table 3) relative to fully different pairs (*M* = 78.2%, *SEM* = 2.8; *M* = 1022 ms, *SEM* = 37), accuracy, *d’* scores and RTs, $F(1, 22) = 30.79$, = 25.72 and = 8.87, respectively, all *ps* < .01, and to rotated pairs (*M* = 68.7%, *SEM* = 3.3; *M* = 1175 ms, *SEM* = 42), accuracy and *d’* scores, $F(1, 22) = 19.23$ and = 16.59, *ps* < .001 (on RTs, *F* < 1), which also differed from each other on accuracy, $F(1, 22) = 5.95$, $p = .02$, (*d’* scores: = 6.88, $p = .016$), and RTs, $F(1, 22) = 23.78$, $p < .001$ (see Figure 3B).

Contrary to what happened for shape-based judgments, first-graders’ orientation-based judgments were not affected (either on accuracy, on *d*’ scores, or RTs) by letter type, all *F*s < 1.25.

Although they had an overall advantage over preschoolers in the orientation-based task, on accuracy and *d'* scores, $F(1, 44) = 58.90$, and $= 39.49$, respectively, both *p*s $< .001$ (RTs: $F < 1$), discrimination of mirrored pairs continued to be harder than discrimination of rotated pairs, for both reversible letters, on accuracy and *d'* scores, $F(1, 22) = 4.34$, and $= 4.60$, respectively, both *p*s $< .05$ (RTs, $F < 1$), and non-reversible letters, on accuracy, *d'* scores, and RTs, $F(1, 22) = 9.65$, $= 13.25$, and $= 14.45$, respectively, all *p*s $\leq .005$ (see Figure 3B and Table 3).

To directly compare the two groups, we next examined the performance drop index previously considered for geometric shapes. The pattern of results was similar to that reported for geometric shapes. The performance drop on mirrored trials was stronger for preschoolers than for first graders ($M = 23.85\%$, $SEM = 3.54$ vs. $M = 8.20\%$, $SEM = 2.10$, respectively), $F(1, 44) = 9.68$, $p =. 003$, but on rotated trials, preschoolers and first graders presented similar performance drops ($M = 7.48\%$, $SEM = 2.70$, $SEM = 2.70$ vs. $M = 2.06\%$, $SEM = 1.98$, respectively), $F(1, 44) = 1.92$, $p = .17$.

Comparison between the two tasks and the two groups.

As already reported for geometric shapes, preschoolers had more difficulty in discriminating (in the orientation-based task; Figure 3B) than in tolerating (in the shape-based task; Figure 3A) mirrored letters, on accuracy, $F(1, 22) = 5.81$, $p = .025$ (and on *d'* scores, $F(1, 22) = 7.87$, $p = .01$; RTs, $F < 1$). Note, however, that for the other trial types (including rotated trials), preschoolers were as able to perform orientation- as shape-based judgments, on accuracy *F*s$(1, 22) \leq 2.94$ (*d'* scores: *F*s$(1, 22) < 1.07$, *p*s $> .30$), and on RTs, *F*s ≤ 2.63, all *p*s $\geq .10$. Yet, no association was found (on accuracy or RTs) between tasks, for mirrored or rotated pairs, or across trials, all *r*(s21)s $< .25$, *p*s $> .25$.

For first-graders, discrimination of mirror images continued to be harder than discrimination of plane rotations for both reversible letters, accuracy, $F(1, 22) = 4.34$, $p = .049$ (*d'* scores:$= 4.70$, $p = .041$), RTs, $F < 1$, and non-reversible letters, accuracy, *d'* scores, and RTs, $F(1,22) = 9.65$, $= 13.25$, and $= 14.45$, respectively, *p*s $\leq .005$. Indeed, for non-reversible letters, first graders were still slower in discriminating than in tolerating mirror images, $F(1, 22) = 7.46$, $p = .012$ (on accuracy, $F < 1$; *d'* scores, $F(1, 22) = 4.27$, $p = .051$); this was not the case for plane rotations, all *F*s ≤ 1. In contrast, for reversible letters, they were actually more accurate in discriminating than in tolerating both the mirrored and rotated pairs, $F(1, 22) = 9.76$, and $= 62.94$, respectively, *p*s $\leq .005$ (*d'* scores, $F = 1$, and

$F(1, 22) = 13.06$, $p = .001$, respectively; RTs, both Fs < 1.5). Moreover, the association between tasks was significant for mirrored and rotated trials, on RTs, both rs(21) > .64, ps < .001 (accuracy, rs < .01), and across trials, accuracy and RTs, $r(21) = .59$, and = .85, respectively, both ps ≤ .001.

In line with what was found for geometric shapes, for letters the performance drop on mirrored trials was stronger for preschoolers than for first graders (M = 23.85%, SEM = 3.54 vs. M = 8.20%, SEM = 2.10, respectively), $F(1, 44) = 9.68$, p =. 003, but on rotated trials the two groups did not differ (M = 7.48%, SEM = 2.70, SEM = 2.70 vs. M = 2.06%, SEM = 1.98, respectively), $F = 1.92$, $p = .17$.

Correlation analyses

We next examined, at the individual level, whether orientation processing was associated with literacy-related skills (i.e., preschoolers' letter knowledge and first graders' reading skills, as well as phonological awareness) rather than with visuospatial abilities, by considering the correlation coefficients between these cognitive domains and the orientation cost (in the shape-based task) and performance drop (in the orientation-based task) for mirror and rotation contrasts, separately for each material. The correlation coefficients presented in Table 4 refer to accuracy, which was a more reliable measure of preschoolers' orientation-based performance than RTs (but these correlations coefficients were also checked; see Table 4, p-values reported correspond to one-tailed t-tests; RTs indexes were multiplied by -1 so that the correlation pattern for RTs and accuracy would be in the same direction).

-------------------- Table 4 about here -------------------

Geometric Shapes

In preschoolers, sensitivity to mirror images was significantly associated with letter knowledge: the better their letter knowledge, the stronger the mirror cost in shape-based judgments, and the smaller the performance drop for mirrored pairs in orientation-based judgments (the latter was also associated with phonological awareness; see Table 4). No significant association was found between sensitivity to plane-rotation contrasts and any cognitive ability examined.

For first graders, mirror discrimination was associated with reading skills and phonological awareness (which were associated with each other, see Method): the better their literacy-related skills, the smaller the performance drop (on both accuracy and RTs) for mirrored pairs in the orientation-based task. In contrast to what was found for preschoolers, the performance drop for rotated pairs was also associated with literacy-related skills (but only when computed on RTs) and also with nonverbal IQ of first graders. For the shape-based task, only one association was significant: the better the first-graders' phonological awareness, the stronger the rotation cost on shape-based judgments. Although in the same direction, the association between phonological awareness and the mirror cost computed on RTs was unreliable, $r(21) = .27$, $p = .10$.

Letters

Preschoolers' sensitivity to mirror images was significantly associated with letter knowledge: the better their letter knowledge, the stronger the mirror cost in shape-based judgments, and the smaller the performance drop for mirrored pairs in orientation-based judgments (see Table 4). Letter knowledge was also correlated with sensitivity to plane rotations (for the indexes on accuracy only).

Unexpectedly, preschoolers' phonological awareness was negatively correlated with the orientation costs, which might be related to preschoolers' adoption of phonological labels to identify each letter-shape in an orientation-invariant manner, due to their limited letter knowledge.

For first-graders, mirror discrimination was specifically associated with reading skills: the better their reading skills, the stronger the mirror cost (on RTs) on shape-based judgments, and the lower their performance drop (on both accuracy and RTs) on orientation-based judgments of mirrored letters.

For both first graders and preschoolers, the better their visuospatial abilities (i.e., nonverbal IQ and visuospatial working memory), the smaller their performance drop (in the orientation-based task) and the smaller the orientation cost (in the shape-based task). This association was specific to plane rotations for preschoolers, whereas for first graders it was significant for both orientation contrasts.

Discussion

An emergent bulk of research has been showing that learning to read leads to deep neurocognitive changes outside the written domain, including on nonlinguistic visual object processing (e.g., Dehaene, Pegado, et al., 2010; Fernandes & Kolinsky, 2013; Kolinsky et al., 2011; McBride-Chang et al., 2011; Pegado, Comerlato, et al., 2014; Pegado, Nakamura, et al., 2014; Szwed et al., 2012). In this context, the present study targeted two open issues on the early influences of learning a script with mirrored symbols.

First, it was hitherto unknown when, during reading development, the spillover effect of literacy on object recognition and orientation processing would emerge. More specifically, it was thus far unclear when, in the course of literacy acquisition, mirror discrimination, as a consequence of learning a script with mirrored symbols, would become automatic. To investigate this question, two groups of 5-7 year-old children, differing on reading skills – preliterate preschoolers and first graders – performed two same-different matching tasks on which orientation was either critical or irrelevant to successful performance, i.e., orientation-based vs. shape-based (orientation-independent) tasks, respectively. To our knowledge, this is the first study to adopt a within-participants design in order to examine in a fine-grained manner whether the impact of literacy would be similar on explicit vs. implicit, automatic processing of orientation. Each task was performed on two categories matched in visual complexity: single letters and geometric shapes. Taking into account the shape bias hypothesis (Hannagan et al., 2015), geometric shapes were the nonlinguistic category selected given the proximity of their features to those of letters. We thus expected that if changes in visual processing started to emerge early on in literacy acquisition, even if insipient ones, then by using this material we would be able to grasp them. Furthermore, we conducted correlation analyses for each group on each material to examine at the individual level whether explicit or automatic orientation processing was associated with literacy-related skills.

Second, it was still unclear whether the impact of learning a script with mirrored symbols was specific to mirror image processing or whether it would generalize to other orientation contrasts that are relevant for letters, like plane rotations (e.g., d – p; Gibson et al., 1962). To study this point, the same four trial types were used in both tasks: fully different (with different shape and orientation), identical, mirrored, and rotated pairs. We thus directly compared explicit vs. automatic processing of mirror images vs. plane rotations, two orientation contrasts that are relevant to letters and differ from the standard view by the same angular difference while preserving all object-based properties.

The present study represents one of the first demonstrations of early changes in the mirror-generalization system due to literacy acquisition, and provided four original contributions on the impact that learning a script with mirrored symbols has outside the written domain.

First, we presented the first evidence of an absolute and specific mirror cost on visual nonlinguistic object recognition. For geometric shapes, a nonlinguistic material novel for both preschoolers and first graders, the two groups were overall equally able to perform shape-based judgments. Most interestingly, the groups differed only on mirrored pairs: whereas preschoolers were immune to irrelevant mirror-image differences, first graders exhibited such strong mirror cost that they were even slower than preschoolers. We thus found an absolute mirror cost on shape-based judgments of nonlinguistic objects, a consequence of literacy acquisition predicted by the neuronal recycling hypothesis (Dehaene, 2009). In the first study to show a mirror cost in literate adults, no other orientation-contrast was examined and the mirror cost was only relative, as illiterate adults were overall slower and more error-prone than the literate groups (Pegado, Nakamura, et al., 2014). In Kolinsky and Fernandes (2014), only literate adults (and not illiterates) were affected by mirror and rotation contrasts of familiar objects, and for geometric shapes, all participants, whatever their literacy level, were sensitive to the irrelevant orientation contrasts, at least on response latencies and mostly for plane rotations. Yet again illiterate adults were overall slower and more error-prone than literates.

Thus, the present study is the first to show that the impact of learning to read on automatic orientation processing (i.e., when this dimension is irrelevant to the task) is already noticeable in beginning readers at the end of the first grade. Additionally, both groups exhibited a rotation cost on shape-based judgments of geometric shapes, which agrees with previous findings on the plane-rotation sensitivity of the ventral visual system (Logotethis et al., 1995; Tarr & Pinker, 1989).

In line with the mirror invariance found in shape-based judgments of geometric shapes by preschoolers, the strongest difficulty of these children in orientation-based judgments was for the mirrored pairs. This result agrees with prior findings on illiterate adults and preliterate children (e.g., Casey, 1984; Danzinger & Pederson, 1998; Gibson et al., 1962; Fernandes & Kolinsky, 2013; Kolinsky et al., 2011; Nelson & Peoples, 1975; Pederson, 2003), which argues for the robustness of this effect.

Second, by examining explicit vs. implicit orientation processing in a within-participants design, the present study is the first to conclusively show that preliterates' specific difficulty with mirror discrimination cannot be attributed to a general difficulty with orientation processing or because orientation is a dimension less salient than shape. On the one hand, if preschoolers had a general difficulty with orientation, then plane-rotation discrimination should have been as hard as mirror discrimination. On the contrary, they were quite able of discriminating rotated pairs, and when compared to first graders using the normalized index, the two groups presented a similar performance drop for rotated pairs. On the other hand, if orientation was a dimension less salient than shape, preschoolers should have been worse on orientation-based than on shape-based judgments of rotated pairs. Quite the opposite, they were as able to explicitly discriminate plane-rotation contrasts as to tolerate them. Additionally, they presented the same level of interference from the irrelevant dimension of rotated pairs in each task (i.e., orientation in the shape-based task, and shape in the orientation-based task). To put it differently, preschoolers were equally sensitive to the two incongruent dimensions – orientation and shape – as they were as able to attend to shape as to orientation of rotated pairs. Consequently, their difficulty with mirror discrimination cannot be due to low sensitivity to orientation in general; it seems rather grounded on the original mirror invariance property of the ventral visual system (Dehaene, 2009; Logothetis et al., 1995).

During literacy acquisition, beginning readers become as able to attend to orientation as to shape of mirrored pairs of nonlinguistic objects, as shown by first graders' similar performance in the two experimental tasks for these pairs. In fact, learning to read seems to enhance the relevance of orientation, which becomes a critical dimension of visual objects, as shown by the overall advantage of first graders over preschoolers in the orientation-based task. This advantage does not seem to be due to a generic age effect, as no overall difference between groups was found on shape-based judgments of geometric shapes. In fact, the orientation-based task used here required both shape and orientation processing (only exact matches, i.e., identical pairs, had to be considered as *same*), which conjunction is essential in letter and visual word recognition, and hence, the advantage of first graders is not surprising. Perceptual expertise with a visual category leads to enhancement of the relevant dimensions (e.g., Dehaene, Pegado, et al., 2010; Folstein et al., 2013; McCandliss et al., 2003). Thus, when learning to read, children learn to attend to critical reading-related cues, such as orientation, which was not relevant to perceptual experience before this cultural activity took place (e.g., Casey, 1986; Gibson et al., 1962; Kolinsky et al., 2011; Nelson & Peoples, 1975). Therefore, in contrast to what was found when automatic orientation processing was involved (in the shape-based task), literacy acquisition had a general positive impact on explicit orientation processing, at least for mirror images and plane rotations, which are relevant in the Latin alphabet (Gibson et al., 1962).

Consequently, the third main contribution of the present study is to demonstrate that the expression of the visual consequences of literacy depends on the type of processing at stake. Whereas this impact was mirror-specific when the task required automatic orientation processing, it was instead general when explicit orientation processing was required. This pattern of results agrees with prior studies showing that, even when the same material and procedure is adopted, different tasks tap into different processes underpinned by different neural substrates. Whereas parietal regions, part of the dorsal stream, are important for explicit orientation processing, regions of the ventral visual stream are mainly important for processing objects' shape and identity (e.g., Gauthier et al., 2002; Harris, Benito, Ruzzoli, & Miniussi, 2008). This distinction could also explain why no significant association was found between performance in the two experimental tasks for preschoolers on either letters or geometric shapes, whereas for first graders the association was reliable. Additionally, it was only for first graders that performance in the two experimental tasks was associated with visuospatial abilities known to be related with dorsal stream functioning (e.g., Chinello, Cattani, Bonfiglioli, Dehaene, & Piazza, 2013). It thus seems that literacy acquisition enhances the cross-talk between the two visual streams. In this vein, Chinello et al. (2013) recently examined the behavioral performance of kindergarteners (from 3 to 6 years old) and adults in an extensive set of functions related to the dorsal vs. ventral streams (e.g., visuospatial memory and grip aperture during grasping vs. face and object recognition, respectively) and found that it was only for adults, not for children, that visuospatial memory (assessed with the Corsi blocks test) was associated with object recognition.

Perceptual expertise with letters also explains the remarkable advantage of first graders on both shape- and orientation-based judgments of letters after only ~8 months of reading instruction. On the downside, it also explains first graders' worse performance on shape-based judgments of mirrored and rotated pairs of reversible compared to non-reversible letters. Experts usually show less flexibility in selectively ignoring the dimensions relevant to their category of expertise (e.g., Folstein et al., 2013), which explains orientation interference on letter recognition by adult readers (e.g., Corballis & Nagourney, 1978; Jolicoeur & Landau, 1984; Pegado, Nakamura, et al., 2014; Pegado et al., 2011) and the orientation costs found here on shape-based judgments of letters by first graders. In the present study the orientation cost for reversible letters was so strong that it cancelled out the advantage of first graders over preschoolers on shape-based judgments.

Noteworthy, using the masked priming paradigm, Perea et al. (2011) showed that mirrored versions of reversible letters (e.g., ibea, mirrored letter underlined) significantly inhibited the recognition of target-words (i.e. IDEA). Based on the present results, it remains to be confirmed whether the mirror interference reported by Perea et al. (2011) is exclusive for mirror images. It could rather be due to activation of an existing letter representation that is incompatible with the target word, and hence, the same interference would be expected for rotated versions of reversible letters (e.g., if ipea preceded the target IDEA). Future research should examine this prediction.

The correlation analyses also showed that first graders' explicit orientation processing of both linguistic and nonlinguistic material was associated with reading skills, suggesting that mirror discrimination was not yet fully accomplished, and might continue to develop after the first grade (Cornell, 1985). For first graders mirror discrimination continued to be harder than plane-rotation discrimination for both geometric shapes (i.e., average accuracy of 80.0% for mirrored pairs vs. 91.0% for rotated pairs, see Figure 2), and letters (with slower performance on mirrored than rotated pairs); and this continues to be the case in adults, even after years of reading practice (Fernandes & Kolinsky, 2013; Gregory et al., 2011; Kolinsky et al., 2011). Thus, mirror discrimination is triggered by learning a script with mirrored symbols but it is not a dichotomous phenomenon fully determined by literacy: The original mirror invariance property of the visual recognition system is not fully erased (Dehaene, 2009), and could instead be inhibited during recognition of visual objects, including of letters (e.g., Duñabeitia, Molinaro, & Carreiras, 2011; Perea et al., 2011).

Neuropsychological, fMRI, and transcranial magnetic stimulation studies have shown that mirror discrimination of linguistic and nonlinguistic objects has different neurocognitive loci. For linguistic material mirror discrimination is underpinned by ventral occipitotemporal regions, which are mirror invariant for pictures of familiar objects (e.g., Dehaene, Nakamura, et al., 2010; Nakamura, Makuuchi, & Nakajima, 2014; Pegado et al., 2011; Vinckier et al., 2006). What is however unclear is the temporal locus and the cognitive mechanism responsible for mirror discrimination. Although beyond the scope of the present work, this is still hotly debated, and two accounts have been proposed. According to one account, mirror discrimination occurs due to inhibition of mirror invariance at a late, possibly attention-dependent, stage of visual processing (Duñabeitia et al., 2013; Duñabeitia et al., 2011; Perea et al., 2011). The other account proposes that mirror discrimination becomes part of visual processing from an early time window (i.e., 100-148 ms after stimulus onset; Pegado, Comerlato, et al., 2014), and evidence in favor of both has been on the table.

These mixed results could be due to the adoption of different paradigms, tasks and materials, because different experimental conditions tap into different phases of visual processing. In fact, this could also be the reason for the discrepancy between the mirror cost that we found for shape-based judgments of geometric shapes by first graders and the mirror invariance found by Wakui et al. (2013) for short-term priming of familiar objects by children. The later paradigm may tap into an earlier processing stage than the same-different task used in the present study (for discussions see e.g., Kolinsky et al., 2011; Nakamura et al., 2005). Low-level differences between materials could also explain this discrepancy. According to the shape bias hypothesis (Hannagan et al., 2015), the degree of similarity to letters should influence the magnitude of the spillover effect of literacy on visual recognition of other categories. This prediction is consistent with the observation of orientation costs in identity-based judgments of illiterate adults for geometric shapes but not for pictures of familiar objects (Kolinsky & Fernandes, 2014). Thus, the absence of a mirror cost on shape-based judgments of geometric shapes by the preschoolers examined here might seem at odds with the former results.

This apparent contradiction is solved when considering the fourth contribution of the present study, which is to show that some crude sensitivity to mirror-image differences is promoted by familiarity with letters, which is then refined during formal literacy instruction. Indeed, the mirror-specific impact of literacy on visual (nonlinguistic) object recognition begins to emerge, though crudely, before literacy instruction, allied with letter knowledge. Although as a group preschoolers did not present a mirror cost on their shape-based judgments of geometric shapes, the correlation analyses revealed that letter knowledge was specifically associated with sensitivity to mirror-image differences: the higher preschoolers' letter knowledge, the stronger the mirror cost on shape-based judgments and the smaller the performance drop on orientation-based judgments of mirrored geometric shapes. The discrepancy between the present results and those of Kolinsky and Fernandes (2014) is thus probably due to differences on experience with letters between preliterate children and illiterate adults, given that the latter group has a long life-experience in a literate world (Fernandes et al., 2014).

The fact that preliterate children already present some sensitivity to mirror images agrees with prior findings suggesting an early impact of the visual properties of the script to be learned on nonlinguistic visual processing (e.g., McBride-Chang et al., 2011; Zhou et al., 2014). The present pattern of results adds to these evidence by showing that such specific impact of literacy as the one on mirror-image processing starts to emerge with letter knowledge before children are able to decode.

This association also explains why preschoolers already present a mirror cost in shape-based judgments of letters, which was also associated with their letter knowledge. This result is consistent with former observations that preschoolers who are able to correctly write their names without mirrored errors are also able to discriminate mirrored pairs of geometric shapes (Casey, 1984, 1986). It might seem at odds with the original mirror invariance of the ventral visual system (e.g., Dehaene, 2009; Logothetis et al., 1995), but prior studies have shown that the emergence of letter-specialized processing begins before formal literacy instruction in both preliterate children and illiterate adults (e.g., Cantlon et al., 2011; Fernandes et al., 2014).

In addition to these theoretical implications, the present study can also contribute to the growing interest from multiple developmental perspectives on children's print awareness and on its unique contribution to reading acquisition. Indeed, in parent-child conversations more visual attributes are used to describe letters than pictures, and not only the parents but also the children emphasize letters' visual properties (Robins, Treiman, Rosales, & Otake, 2012), as if (at least implicitly) they recognize the importance of visual features on letter learning and subsequent reading development. The engagement in these conversations, especially about the child's initial, were associated with better reading outcomes even after other factors, such as vocabulary, were controlled for (Treiman et al., 2015). More important, even before children know what letters represent (i.e., the letter-sound correspondence), they are already sensitive to letters' visual statistical patterns (Pollo, Kessler, & Treiman, 2009; Treiman, Cohen, Mulqueeny, Kessler, & Schechtman, 2007; Treiman & Kessler, 2011). Preschoolers are better at copying and writing letters with the most frequent arrangement of visual features in the Latin alphabet, i.e., letters with a hasta on the left and a coda on the right (e.g., b and F) than letters with the opposite arrangement (Pollo et al., 2009), and hence, make more mirrored errors on letters of the latter type (e.g., writing b instead of d; Treiman & Kessler, 2011).

The present study adds to this literature, showing that mirror discrimination, which is a necessary condition for mastering the Latin alphabet, can be promoted by literacy-related activities about letter forms, and this could happen at home during parent-children interactions or at the kindergarten. Additionally, our results show that training orientation discrimination in general is not the best practice; preschoolers do not have difficulties with discrimination of plane-rotations, and this ability is not related to mirror discrimination abilities. It is letter knowledge and familiarity with letter forms that are the key. Thus, our work is part of an emergent bulk of research showing that literacy has a visual facet, crucial for learning to read, to which letter knowledge strongly contributes.

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Table 1

Age and average performance in the ancillary tests.

	Preschoolers (n = 23)	First graders (n = 23)
Age (in months)	66.04 (3.34)	82.65 (3.64)
	[64.60, 67.49]	[81.08, 84.22]
Nonverbal IQ: Raven (correct out of 36)[a]	17.70 (2.99)	26.74 (5.37)
	[16.40, 18.99]	[24.41, 29.06]
Visuospatial working memory: Corsi blocks[b]	6.61 (2.71)	13.17 (2.39)
	[5.44, 7.78]	[12.14, 14.20]
Phonological awareness: *d'* score	1.51 (1.40)	5.19 (0.92)
	[0.91, 2.12]	[4.79, 5.58]
Letter knowledge [c]	24.65 (13.67)	65.26 (7.45)
	[18.74, 30.56]	[62.04, 68.48]
Reading performance		
3DM[d] - high frequency words		17.13 (11.22)
		[12.28, 21.98]
3DM - low frequency words		10.87 (7.40)
		[7.67, 14.07]
3DM - pseudowords		11.52 (6.29)
		[8.80, 14.24]
Lobrot L3[e]		9.39 (6.45)
		[6.60, 12.18]
Reading index (summed score)		48.91 (29.85)
		[36.00, 61.82]

Note. SD in parenthesis; 95% CI in brackets.
[a] Total of correct responses in the Colored Progressive Matrices of Raven. [b] Number of trials correctly performed in forward and in backward sequence. [c] Total of correct responses out of 68 items, i.e., 2 (naming and recognition tasks) x 22 upper-case letters of the Portuguese alphabet (excluding letters H, K, W, Y), plus 2 (naming and recognition tasks) x 12 lower-case letters (i.e., b, d, p, q, f, g, r, s, i, o, m, x). [d] Number of items read correctly per list in 30 s. [e] Silent reading test with 5-min time-limit, on which participants select the word that correctly completes each sentence (out of five possible words). Performance computed as number of items correctly completed (total of 36 sentences).

Table 2

Mean d' scores of preschoolers and first graders for geometric shapes in the three conditions at test (mirrored, rotated, and fully different) in the shape-based and orientation-based tasks.

	Preschoolers			**First graders**		
	mirrored	**rotated**	**fully different**	**mirrored**	**rotated**	**fully different**
Shape-based	2.96 (.23)	2.75 (.18)	2.81 (.19)	3.10 (.21)	2.69 (.17)	3.09 (.18)
Orientation-based	2.07 (.18)	2.68 (.19)	3.01 (.24)	4.61 (.17)	5.49 (.18)	5.13 (.22)

Note. SEM in parenthesis.

Table 3

Mean d' scores of preschoolers and first graders for the two letter types and across letter-type in the three conditions at test in the experimental tasks.

	Reversible letters			Non-reversible letters			Across letter type		
	mirrored	**rotated**	**fully different**	**mirrored**	**rotated**	**fully different**	**mirrored**	**rotated**	**fully different**
				Preschoolers					
Shape-based	2.58 (.20)	2.57 (.16)	3.03 (.28)	2.57 (.23)	2.40 (.24)	2.77 (.23)	2.57 (.17)	2.48 (.17)	2.90 (.25)
Orientation-based	1.77 (.26)	2.59 (.19)	3.40 (.27)	1.77 (.29)	2.77 (.31)	3.12 (.28)	1.77 (.24)	2.68 (.21)	3.26 (.23)
				First graders					
Shape-based	3.36 (.29)	3.02 (.25)	4.16 (.29)	4.27 (.30)	4.39 (.33)	4.30 (.30)	3.81 (.23)	3.70 (.25)	4.23 (.25)
Orientation-based	3.65 (.26)	4.46 (.33)	4.86 (.28)	4.63 (.28)	3.52 (.24)	4.56 (.32)	3.58 (.18)	4.51 (.28)	4.75 (.25)

Note. SEM in parenthesis.

Table 4

Correlation matrix (correlation coefficients) between the ancillary cognitive abilities and the orientation cost and performance drop.

Cognitive abilities	Geometric shapes: Orientation cost (shape-based task) mirror	Geometric shapes: Orientation cost (shape-based task) rotation	Geometric shapes: Performance drop (orientation-based task) mirror	Geometric shapes: Performance drop (orientation-based task) rotation	Letters: Orientation cost (shape-based task) mirror	Letters: Orientation cost (shape-based task) rotation	Letters: Performance drop (orientation-based task) mirror	Letters: Performance drop (orientation-based task) rotation
Preschoolers								
Nonverbal IQ (Raven)	-.150	-.268	.016	.161	.095	**-.360***	-.149	-.045●
Visuospatial working memory (Corsi blocks)	.068	-.270	.291	.209	-.015	**-.372***	-.047	-.078●
Phonological awareness	-.111	.177	**-.522****	-.153	**-.438***	**-.378***	-.267	-.104
Letter knowledge	**.481***	-.128	-.349†	.140	**.474**●**	**.451****	**-.332*●**	**-.397***
First graders								
Nonverbal IQ (Raven)	-.262	-.261	-.088	-.325†	**-.341***	**-.476****	-.216●	-.308†●
Visuospatial working memory (Corsi blocks)	.008	-.137	-.053	-.151	.103	.100	-.065●	-.103●
Phonological awareness (ALEPE)	-.025	.339†	**-.355*●**	.241●	-.038●	.177	.163	.170
Reading index (3DM & Lobrot L3)	.178	.272	**-.402*●**	.127●	.280●	.043	-.338†●	-.178

Note. Significant results ($p < .05$, one-tailed) are in bold, marginal results are underlined.
● Significant association (at least, $|r| > .29$, $p < .05$) for the indexes computed on RTs.
†$p < .10$. *$p < .05$. **$p \leq .01$.

Figure captions

Figure 1. Experimental material. (A) Sequence of events in each experimental trial and illustration of the four trial types. The presentation of S1 and S2 was separated by a mask to ensure no involvement of iconic memory in performance. S2 was presented until response or for the maximum of 2.5 s if no response was given, after which another trial began. The two geometric shapes presented as S2 in the fully different and identical trials are the new figures used in this study (see text). (B) The two letter types (reversible and non-reversible) organized by the four trial types.

Figure 2. Mean performance – accuracy on the top, RTs on the bottom – of preschoolers (in blue) and first graders (in red) for geometric shapes. (A) Performance in the shape-based task. (B) Performance in the orientation-based task. Error bars represent the *SEM* in each condition.

Figure 3. Mean performance – accuracy on the top, RTs on the bottom – for reversible letters (in black) and non-reversible letters (in gray) by preschoolers and first graders in the experimental tasks. (A) Performance in the shape-based task. (B) Performance in the orientation-based task. Error bars represent the *SEM* in each condition.

Figure 1

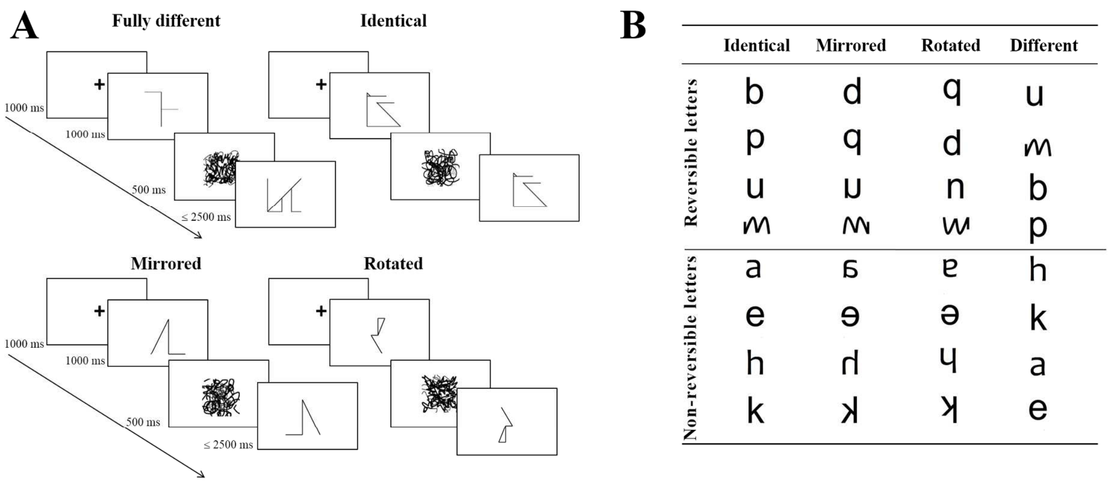

A
Fully different
Identical
1000 ms
1000 ms
500 ms
≤ 2500 ms
Mirrored
Rotated
B
Identical
Mirrored
Rotated
Different
Reversible letters
Non-reversible letters

Figure 2

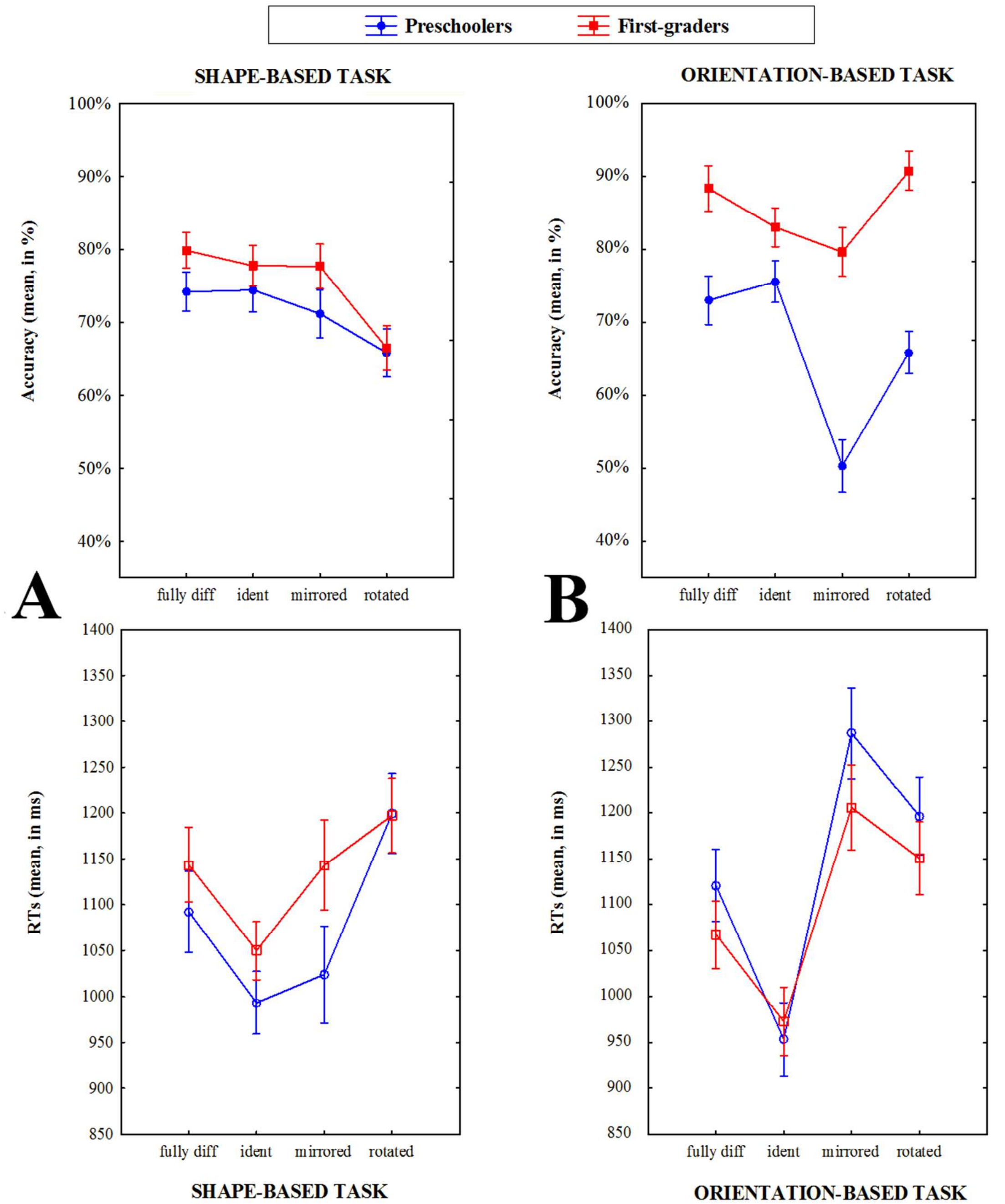
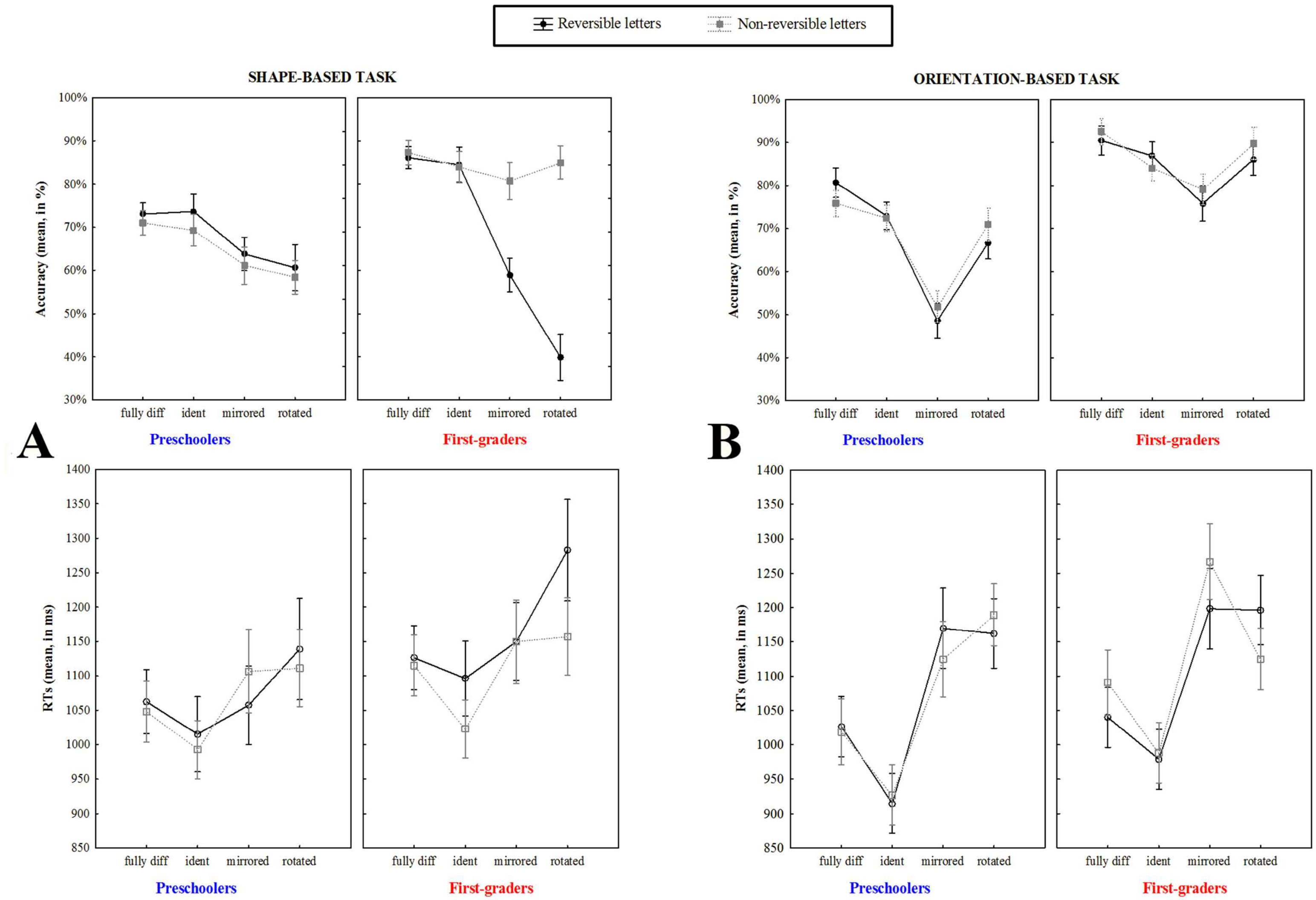

Preschoolers
First-graders
SHAPE-BASED TASK
ORIENTATION-BASED TASK
Accuracy (mean, in %)
100%
90%
80%
70%
60%
50%
40%
fully diff
ident
mirrored
rotated
A
B
RTs (mean, in ms)
1400
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
SHAPE-BASED TASK
ORIENTATION-BASED TASK

Figure 3



Reversible letters
Non-reversible letters
SHAPE-BASED TASK
ORIENTATION-BASED TASK
Accuracy (mean, in %)
100%
90%
80%
70%
60%
50%
40%
30%
fully diff
ident
mirrored
rotated
Preschoolers
First-graders
A
B
RTs (mean, in ms)
1400
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850