THE IMPACT OF LEARNING TO READ ON VISUAL PROCESSING

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THE IMPACT OF LEARNING TO READ ON VISUAL PROCESSING

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Reading is at the interface between the vision and spoken language domains. An emergent bulk of research indicates that learning to read strongly impacts on non-linguistic visual object processing, both at the behavioral level (e.g., on mirror image processing – enantiomorphy -) and at the brain level (e.g., inducing top-down effects as well as neural competition effects). Yet, many questions regarding the exact nature, locus, and consequences of these effects remain hitherto unanswered.

The current Special Topic aims at contributing to the understanding of how such a cultural activity as reading might modulate visual processing by providing a landmark forum in which researchers define the state of the art and future directions on this issue.

We thus welcome reviews of current work, original research, and opinion articles that focus on the impact of literacy on the cognitive and/or brain visual processes. In addition to studies directly focusing on this topic, we will consider as highly relevant evidence on reading and visual processes in typical and atypical development, including in adult people differing in schooling and literacy, as well as in neuropsychological cases (e.g., developmental dyslexia). We also encourage researchers on nonhuman primate visual processing to consider the potential contribution of their studies to this Special Topic.

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EDITORIAL
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Editorial: The impact of learning to read on visual processing

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In 1892, Déjerine published the first report of pure alexia (Déjerine, 1892). *Monsieur C.* became unable to read in the absence of any other cognitive disorder (even writing was preserved) after a lesion of the inferior occipitotemporal cortex, a neural region dedicated to visual recognition. Although reading is an intense visual ability, the relation between reading and visual processing has often been sell short. It was only ∼100 years after the report of Monsieur C. that part of this occipitotemporal region was coined *visual word-form area*, VWFA (Warrington and Shallice, 1980; see also Cohen et al., 2000; Polk and Farah, 2002). Since then an emergent bulk of research has demonstrated that learning to read, not only leads to the emergence of a specialized neurocognitive circuitry, but also impacts on the evolutionary older and pre-existing neurocognitive system of visual (non-linguistic) object recognition. Many questions regarding the exact nature, locus, and consequences of this impact are in debate or still unanswered. This Research Topic was aimed at setting a landmark forum on which researchers present and discuss recent work, their proposals, and open novel questions. We have compiled nine excellent articles on the relation between visual processing and literacy acquisition, reading development, and developmental dyslexia. This research topic is organized into three parts.

In the first part, opening this research topic, in an opinion article, Zhou et al. (2014) consider the relation between visual skills and learning to read, and the moderator role of the visual complexity of the written script in this equation (e.g., Chinese makes stronger demands of visual skills due to its complexity than alphabetic scripts). Qian and Bi (2014) argue that the visual complexity of the script modulates the expression of visual processing deficits (namely, in magnocellular processing) in developmental dyslexia. They examined the association between motion processing (in a coherent motion task, underpinned by V5/MT functioning) and reading (in a visual lexical decision task) in Chinese dyslexic children and chronological-age controls.

Second, regarding the emergence of a neurocognitive system specialized in letter processing, in a hypothesis and theory article, Lachmann and van Leeuwen (2014) propose the *functional coordination* approach. According to this hypothesis learning to read captures the analytic strategy of visual processing, which was already available before literacy took place, but then becomes the preference mode in letter processing. In their research article, Lachmann et al. (2014) used the Navon test to examine whether, when the hierarchical stimulus (a global figure composed of local figures) is presented at fixation with dimensions close to those in written text, letters compared to non-letters are processed using an analytic strategy instead of the usual holistic strategy adopted on hierarchical stimuli.

In the last part of this Research Topic, the impact of literacy on non-linguistic visual processing is considered. Indeed, according to the *neuronal recycling hypothesis* (Dehaene, 2009) the ventral occipitotemporal regions, originally devoted to object recognition, are partially recycled to accommodate literacy, with spillover effects on the former function. In a large-scale developmental study, Santi et al. (2015) show that the impact of learning to read on visual skills is not observed at a macro behavioral level assessed with general educational/neuropsychological tests. Note, however, that studies that reported an impact of literacy on general spatial skills have examined children learning to read scripts differing on visual complexity (e.g., Zhou et al., 2014, in this research topic), but this was not the case in Santi et al.: all children were learning the alphabetic English orthography. This might seem, however, inconsistent with the *neuronal recycling hypothesis* (Dehaene, 2009). Indeed, a key question, discussed in the last four articles of this collection, is to understand which aspects of visual processing are actually affected by literacy acquisition and why. Possibly only the visual properties that collide with learning to read are affected. This is the case of *mirror invariance*: lateral mirror images, such as d and b, are originally processed as equivalent percepts. Kolinsky and Fernandes (2014; following the prior work of Pegado et al., 2014) examined whether learning to read is able to modify the object recognition system as expressed by a loss of mirror invariance, by comparing the orientation cost for mirror images (e.g., ⌉-⌈) vs. plane-rotations (to which the visual system is originally sensitive to; e.g., ⌉-⌊), in identity-based same-different judgments of illiterate, late literate, and early literate adults. In the same vein, using transcranial magnetic stimulation (TMS) during identity-based same-different judgments, Nakamura et al. (2014) demonstrated the causal role of the left occipitotemporal cortex (comprising the VWFA) in mirror discrimination of visual words by literate Japanese adults. In their opinion article, Pegado et al. (2014) set a multisystem learning framework to answer how mirror discrimination is acquired during learning to read. They propose that a tight functional link between the visual and motor systems is crucial for this acquisition. Finally, given that literacy acquisition also impacts on face recognition due to competition for neural space (cf. Dehaene, 2009), in an opinion article, Ventura (2014) reviews these evidence, discusses the possible reasons for this competition, and proposes new directions considering literacy as a form of visual expertise.

Taken together, these articles represent an update overview and demonstrate the diversity of approaches in this research topic: miscellaneous scientific backgrounds (e.g., neuroscience, in Nakamura et al., 2014; neuropsychology, in Qian and Bi, 2014; developmental psychology, in Santi et al., 2015; experimental psychology; in Kolinsky and Fernandes, 2014), several techniques (e.g., TMS, Nakamura et al., 2014; behavioral tests, Lachmann et al., 2014; item response models, Santi et al., 2015), various written scripts considered (i.e., studies with alphabetic and non-alphabetic scripts; e.g., Lachmann et al., 2014; Nakamura et al., 2014, respectively), different populations examined (typical vs. dyslexic readers, in Qian and Bi, 2014; adults of varying schooling and literacy levels, in Kolinsky and Fernandes, 2014). These articles are Dejerine's legacy as pieces of the (still incomplete) puzzle on the impact of literacy on visual processing, which will hopefully contribute to understand the reasons behind this impact.

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OPINION ARTICLE
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What is the role of visual skills in learning to read?

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Although the issue of visual skills in relation to word reading has not been central to recent explorations of reading development, all visual word reading involves visual skill. Children constantly face tasks of differentiating visually similar letters or words. For example, distinguishing "b" from "d," "a" from "e," or "book" from "boot" all require visual differentiation. Children's orthographic knowledge and letter knowledge are causal factors in subsequent reading development in English (e.g., Badian, 1994; Lonigan et al., 2000). At a pure visual skill level, some researchers (e.g., Franceschini et al., 2012) suggest that core visual processing skills such as visual spatial attention in preschoolers could be a causal factor in subsequent reading acquisition. In addition, some alphabetic readers with dyslexia may have visual processing deficits (e.g., Valdois et al., 2004; Van der Leij et al., 2013). Following this hypothesis, Franceschini et al. (2013) showed that action video games that strengthened children's visual attention also improved their reading speed in Italian without sacrificing reading accuracy, similar to previous interventional research training facilitating visuospatial attention skills in Italian children with dyslexia (Facoetti et al., 2003). However, orthographic depth mediates the role of visual attention in reading (Bavelier et al., 2013; Richlan, 2014). English is a more opaque orthography than Italian, and Chinese is even more opaque than English.

Both eye movement and neuroimaging studies have demonstrated that reading Chinese affects visual processing differently than does reading alphabetic orthographies (e.g., Inhoff and Liu, 1998; Perfetti et al., 2010; Szwed et al., 2014). Inhoff and Liu (1998) found that Chinese readers used comparatively smaller visual perceptual spans than English readers. Szwed et al. (2014) found that readers of Chinese showed strong activations in intermediate visual areas of the occipital cortex; these were absent in French readers. Researchers have attributed these characteristics to perceptual learning resulting from learning to read Chinese characters (Rayner, 1998; Perfetti et al., 2010; Szwed et al., 2014).

Indeed, the role of visual skills for early reading development may be stronger for reading Chinese than reading English. Pure visual skills are sometimes relatively strong correlates of Chinese children's reading (e.g., Huang and Hanley, 1994, 1995; Ho and Bryant, 1997; Siok and Fletcher, 2001; Mcbride-Chang et al., 2005; Luo et al., 2013). Such visual tasks likely tap at least three visual skills that may be required for Chinese character reading. First, a focus on visual form constancy (e.g., is this square the same size as the one embedded in other designs on the previous page?) likely has some analogies with the fact that radicals within Chinese might appear as larger or smaller or even reversed in appearance across characters. Second, a focus on visual spatial skills, i.e., identifying the same form when it is in a different direction or placed differently, might be useful when Chinese character identification requires children to reduce a compact character into component radicals. Third, visual memory may be useful in learning to read Chinese in at least two ways, namely, making associations between characters and sounds, many of which are arbitrary, sometimes referred to as visual verbal paired associate learning, and helping children to build a mental memory of how different radical parts are located within a character.

What is the evidence that learning to read Chinese trains one's visual skills? A cross-cultural study (McBride-Chang et al., 2011b) found that Chinese and Korean kindergartners performed significantly better than Israeli and Spanish children on a task of visual spatial relationships, the only visual task tested across all four cultures. Korean kindergartners tend to learn to read Korean syllables holistically initially, similar to how Chinese characters are taught. A superior performance on visual skills was also found by Demetriou et al. (2005) for older Chinese as compared to Greek children. In addition, Huang and Hanley (1994) found that both Taiwanese and Hong Kong children showed a clear advantage on the visual form discrimination task as compared to their British peers.

Interestingly, the Chinese written system has two versions, the simplified and the traditional. The simplified script, which has fewer visual features to distinguish one character from another, may make more visual demands than does the traditional version. In one study of those learning to read traditional (in Hong Kong) as compared to simplified (in Mainland China) script, those learning the simplified script outperformed those learning the traditional one on three visual tasks, namely visual discrimination, visual spatial relationships and visual closure tasks (Mcbride-Chang et al., 2005), even across time. Peng et al. (2010) found that electrophysiological response potentials (ERPs) in the brains of those expert readers who saw characters with one stroke either added or subtracted in a few milliseconds showed the same basic pattern:

The brains of simplified script readers appeared to register the alterations early in processing; those of traditional script readers did not.

Importantly, most studies on the topic of visual skills and word reading were carried out at a single point in time, rather than in a longitudinal study, and there are few experimental studies on this topic. Thus, the issue of causality is not clear (e.g., McBride-Chang et al., 2011b; Yang et al., 2013). However, there is probably a bidirectional association between pure visual skills and learning to read in the early years (e.g., McBride-Chang et al., 2011b). Future directions in this area should focus on at least three aspects of research in order to gain a better understanding of the causal associations between literacy and visual skills. First, more research should explore how and which visual skills may promote word reading in the early grades. Second, researchers can consider more broadly how learning to read particular orthographies might facilitate given visual skills. Third, an exploration of pure visual skills and word reading could be expanded further to visual-motor skills and writing.

The issue of how visual skills facilitate word reading is important to explore in a variety of orthographies. For example, Nag (2007, 2011) has presented a model of orthographically contained vs. extensive orthographies. At the most extensive level is Chinese, with thousands of possible characters. At the most contained level are alphabetic orthographies with sets of around 24 to 30 letters each. In the middle, she placed Bengali, Hindi, and Kannada, each with 400+ possible symbols. Collectively, these are referred to as the ashkara languages. As with Chinese, small changes in visual symbols in ashkara scripts signal potentially large changes in phonological or meaning representations. For example, native readers of Arabic are slower to process it than a second language of Hebrew because of differences in visual complexity (Ibrahim et al., 2002; Abdelhadi et al., 2011). Even in simple alphabetic orthographies, young children might memorize words based on particular visual features (e.g., M has two humps; the word "bed" in English actually looks like a bed). Therefore, it is important for researchers to continue to explore whether and which visual analysis skills might explain early literacy in diverse orthographies. Perhaps more varied visual skills would best explain performances in ashkara languages and Chinese given their visual complexities. For this research question, the focus is on individual differences within a group learning to read in a single orthography.

The second question focuses more on group differences across orthographies: Do orthographies facilitate visual flexibility and analysis in different ways? Perhaps not only are the visual characteristics of the orthography important, but the style of teaching and learning the orthography is additionally important for facilitating visual skills. For example, although Korean Hangul is ultimately a relatively simple alphasyllabary, it is taught initially to children more in the form of syllables with different components, such that children have many different configurations to learn. Perhaps children's visual memorization loads would be reduced if they were taught the basic phonological rules of Korean first, but this is not the way in which they are instructed. Future research should consider both the dimensions of visual demands of the orthography and also teaching approaches. For example, young children are often taught to read Thai with spaces in between words indicated before they are gradually coaxed to read Thai as it is written for adults—without spaces between words. Conceivably, those learning to read Thai with and without spaces might show different visual patterns of discrimination early on. Another area for research on this topic would be to compare children learning to read orthographies that differ on the dimension of contained vs. expansive as defined by Nag, at least in three aspects, i.e., alphabetic, ashkara, and Chinese, across the early years of literacy development (perhaps ages 4–7 years) to determine whether those learning an alphabet are least sophisticated in visual skill, those learning an ashkara in the middle, and Chinese learners the best. Although McBride-Chang et al. (2011b) compared 5-year-olds learning Chinese, Korean, and alphabets, this study could be expanded to include ashkara learners and to examine the developmental trend with age across several dimensions of basic visual skill.

A third issue to consider makes an analogy from word reading and visual recognition, considered above, to word writing and visual copying. We have recently established that children who tend to write Chinese characters better tend also to show better abilities to copy 2-dimensional unfamiliar forms (e.g., Wang et al., 2013). These forms were foreign scripts that were coded by those unfamiliar with each (e.g., a Chinese research assistant evaluated children's writing of Hebrew based purely on the visual representation of the writing perceived). Unfamiliar scripts were selected to ensure that the 2-dimensional writing was equally unfamiliar to all children. (In contrast, copying of geometric shapes or one's own script would be potentially problematic because those who are academically more skilled often tend to write all familiar stimuli better than those who are less so). Tan et al. (2005) have suggested that copying skills are important for learning to write/spell Chinese. However, there is very little research that has examined this question for orthographies other than Chinese. Vellutino et al. (1975) found that the copying of Hebrew did not distinguish dyslexic from non-dyslexic children who were native English speakers unfamiliar with Hebrew. In contrast, such copying skills did distinguish those with and without dyslexia in Chinese (McBride-Chang et al., 2011a). However, few, if any researchers, have gone further with this research, examining to what extent the ability to copy unfamiliar materials is associated with the ability to write words in a native orthography. Given a proposed first stage of word reading as primarily visual (Ehri, 2013), a first stage of word writing might be, correspondingly, associated with visual-motor skills that can be measured using pure two-dimensional patterns. Perhaps such copying abilities are particularly linked to learning to write in Chinese or in ashkara. However, it is important to examine these abilities independently within, as well as across, orthographies. While it may be the case that copying of unfamiliar stimuli explains subsequent spelling skills for Hindi, Chinese, Korean, or even Dutch children within a group, for example, it is also interesting to consider whether learning to read the most expansive orthography of Chinese facilitates superior visuo-motor skills more generally (as compared to those learning to read and write Dutch, for example). More research on the interface between literacy skills within and across orthographies and visual and visuo-motor skills, can potentially yield new directions that are theoretically interesting and possibly practically important.

To conclude, the role of visual skills in learning to read is apparently complex, and our understanding of this role depends upon the extent to which we look within as compared to between orthographies. The types of visual skills, the types of orthographies, and the teaching methods for literacy instruction all influence this association. Moreover, the association between visual skills and literacy development is likely bidirectional. This association can be expanded to focus on visuo-motor skills and writing. These issues cross-culturally represent some new avenues for future research.

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The visual magnocellular deficit in Chinese-speaking children with developmental dyslexia

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Many alphabetic studies have evidenced that individuals with developmental dyslexia (DD) have deficits in visual magnocellular (M) pathway. However, there are few studies to investigate the M function of Chinese DD. Chinese is a logographic language, and Chinese characters are complicated in structure. Visual skills and orthographic processing abilities are particularly important for efficient reading in Chinese as compared to alphabetic languages. Therefore, it is necessary to investigate the visual M function of Chinese DD and whether the M function was associated with orthographic skills. In the present study, 26 dyslexic children (mean age: 10.03 years) and 27 age-matched normal children (mean age: 10.37 years) took part in a coherent motion (CM) detection task and an orthographic awareness test. The results showed that dyslexic children had a significantly higher threshold than age-matched children in CM detection task. Meanwhile, children with DD responded more slowly in orthographic awareness test, although the group difference was marginally significant. The results suggested that Chinese dyslexics had deficits both in visual M pathway processing and orthographic processing. In order to investigate the relationship between M function and orthographic skills, we made a correlation analysis between CM threshold and orthographic awareness by merging performance of dyslexic children and age-matched children. The results revealed that CM thresholds were positively correlated with reaction times in orthographic awareness test, suggesting that better M function was related to better orthographic processing skills.

Keywords: developmental dyslexia, magnocellular pathway, coherent motion detection, orthographic processing skills, Chinese reading

INTRODUCTION

Developmental dyslexia (DD) is a neurobiological reading disorder. Individuals with DD have difficulties in accurate or fluent word recognition, spelling, and word decoding despite adequate instruction and intelligence (Lyon et al., 2003). Although it is widely accepted that there are phonological deficits in DD, some researchers indicate that dyslexia can be traced back to a more general perceptual dysfunction. Magnocellular (M) deficit theory postulates that the core deficit of DD is the impairment in M pathway, which is specialized for temporal processing (Stein and Walsh, 1997; Stein, 2001).

In alphabetic languages, phonological information of words can be activated according to grapheme–phoneme correspondence (GPC) rules. Efficient auditory function is essential for phonological processing (Boets et al., 2006). Tallal and Piercy (1973) and Tallal (1980) first found individuals with dyslexia performed worse than typical readers in discriminating rapid speech and non-speech stimuli. Later, many studies consistently found that dyslexics showed poor performance on a number of auditory tasks, including frequency discrimination (McAnally and Stein, 1996; Ahissar et al., 2000) and temporal order judgment (Nagarajan et al., 1999; Schulte-Körne et al., 1999). Longer intersound intervals were needed for dyslexics to perceive an illusory auditory saltation or follow each successive sound in a continuous fashion, suggesting a prolonged "cognitive integration window" (Hari and Kiesila, 1996; Helenius et al., 1999). The deficits in temporal auditory processing were also confirmed in event-related potential (ERP) and functional magnetic resonance imaging (fMRI) studies (e.g., McAnally and Stein, 1997; Kujala et al., 2000, 2003; Temple et al., 2000; Paul et al., 2006; Stoodley et al., 2006; Gaab et al., 2007; Khan et al., 2011). These results consistently revealed that dyslexics have deficits in temporal auditory processing in alphabetic languages.

With respect to visual processing skills, dyslexics also exhibit deficits in visual M pathway. Vidyasagar and Pammer (2010) indicated that reading can be affected by a deficit at any step along the visual M pathway, which stretches from the retina to the posterior parietal cortex, including middle temporal area (MT/V5; Boden and Giaschi, 2007). Many studies found that dyslexics were less sensitive to coherent motion (CM) than age-matched controls (Cornelissen et al., 1995; Talcott et al., 1998, 2003; Witton et al., 1998; Hansen et al., 2001; Conlon et al., 2004; Pellicano and Gibson, 2008), reflecting the deficient M processing of DD. Pre-reading children at familial risk for DD exhibited the disability in detecting CM, suggesting deficits in M pathway occur before reading commencement (Kevan and Pammer, 2008). The deficient CM detection was persistent and not affected by stimulus duration, dot density or practice (Talcott et al., 2000a;

Conlon et al., 2009; Wright and Conlon, 2009). Slaghuis and Ryan (2006) found CM sensitivity in mixed subgroup of dyslexics was significantly lower than that in normal group, but CM sensitivity in surface and phonological DDs was not different from that in normal readers. In a meta-analysis study, larger effect sizes were obtained for adult subjects compared with children, suggesting CM deficit was more reliable in dyslexic adults (Benassi et al., 2010). However, some studies didn't support M theory of dyslexia. Ramus et al. (2003) found that only 2 of 16 dyslexic adults had visual M deficit. The low incidence, together with that the two visually impaired dyslexics also had auditory and phonological problems, might not confirm that visual M deficit was an independent core deficit of DD. Sperling et al. (2005) pointed out that deficits in noise exclusion, not M processing, contributed to the etiology of dyslexia. In the high-noise conditions, dyslexic children's contrast thresholds were significantly higher than non-dyslexic children's in both M and parvocellular (P) pathways. But in the no-noise conditions, contrast thresholds of dyslexic and non-dyslexic children did not significantly differ in either M or P pathway. The results suggested that dyslexics had deficits in noise exclusion rather than M processing. However, Conlon et al. (2012) discussed that DD's difficulty in noise exclusion was the consequence of a sensory processing deficit in the M or dorsal stream. One explanation of noise exclusion was greater internal noise in the visual system, which was evidenced by the small number and disorganized manner of neurons in the M and dorsal stream. In addition, dyslexics had normal coherent form thresholds (Conlon et al., 2009), which could not be interpreted by noise exclusion theory. Skottun (2011) indicated that area MT receives inputs from M pathway as well as P and koniocellular pathways. CM sensitivity could not be only attributed to M pathway. As a result, he claimed CM detection might not be a reliable test of M processing. Nevertheless, he also underlined that the results should not be taken to mean that M deficiencies have no effect on motion perception or M deficits do not have the potential to create deficient motion perception. In fact, CM sensitivity was still a widely accepted test to measure M processing, although there were a lot of questions to be answered. Apart from the above problems, there was another question: was CM deficit general for different languages? A study found that poor readers in Thai were less sensitive to detect CM, while poor readers in Korean were not. It might result from the fact that Korean script was more complex than Thai. The authors thought the visual complexity of a script might modulate the expression of M pathway deficits in DDs (Kim et al., 2004).

Chinese is a logographic language without GPC rules. Chinese character is visually compact (Ho et al., 2004) and looks like a two-dimension picture (Zhang et al., 2006). Visual skills are particularly important for Chinese reading (Chung et al., 2008; Li et al., 2012; Yang et al., 2013). Additionally, Chinese dyslexic children have deficits in multiple cognitive skills, including phonological awareness, morphological awareness, rapid naming and orthographic awareness (Huang and Hanley, 1995; Ho and Lai, 1999; Ho et al., 2002, 2004; Shu et al., 2006). Thereinto, orthographic processing deficit is one of the most dominant defects in Chinese DD (Ho et al., 2004). As known, orthographic processing needs efforts in visual analysis. Then, are orthographic processing skills associated with M function? Previous alphabetic studies revealed CM sensitivity was related to orthographic processing skills (Talcott et al., 2000b). Skilled readers who excelled at motion detection performed better in a lexical decision task than those who are poor at detecting CM (Levy et al., 2010). In Chinese character reading, visual analysis and orthographic processing were specifically required. A prior study found Chinese children with dyslexia showed reduced amplitude of visual mismatch negativities (vMMNs) than both age-matched and reading level matched children in the visual M condition, whereas there was no difference in auditory mismatch negativities (aMMNs) of auditory modality between dyslexic children and the two control groups. This result suggested Chinese dyslexic children only had deficits in visual M pathway, while the auditory temporal processing skills were intact (Wang et al., 2010). Meng et al. (2011) found Chinese dyslexics had significantly higher CM threshold than age-matched children, which also confirmed the visual M pathway impairment in Chinese DD. Additionally, Meng et al. (2011) revealed the CM threshold made a significant contribution to the speed of orthographic similarity judgment in a random sample. However, orthographic similarity judgment might be not a proper task to measure orthographic awareness, because the stimuli were all real characters. There were no non-characters violating orthographic rules. Processing in this task only involved simple form comparison. It was unnecessary for children to judge whether a character conformed to orthographic rules or not, which reflected orthographic processing. In the present study, we adopted a lexical decision task, in which children were required to judge whether the target character was a real character. There were three kinds of characters: real character, pseudo-character (orthographic-legal) and non-character (orthographic-illegal). By comparing the group difference in rejecting pseudo-characters and non-characters, we investigate orthographic awareness deficits in Chinese dyslexic children.

Therefore, there are two aims in the current study. The first aim is to investigate the deficits of Chinese dyslexics in visual M pathway and orthographic awareness. The second aim is to explore the relationship between visual M function and orthographic processing ability.

MATERIALS AND METHODS

PARTICIPANTS

Twenty-six dyslexic children [6 females and 20 males, mean age: 10.03 years (range: 9–11 years)] and twenty-seven age-matched controls [CA, 9 females and 18 males, mean age: 10.37 years (range; 9–11 years)] took part in the study. The children were recruited from ordinary primary schools in Beijing. The study was conducted under the informed consent of parents, and was approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences. All of the participants were right-handed, and had normal hearing and normal or corrected-to-normal vision without ophthalmological or neurological abnormalities. The inclusionary criteria for dyslexics were that the IQ was above 85 as measured by Raven's Standard Progressive Matrices (Raven et al., 1996), while the written vocabulary test score was at least one and a half standard deviations below corresponding age norm in the Standard Character Recognition Test (Wang and Tao, 1996). This was a widely used test for screening Mandarin-speaking Chinese dyslexia children in Mainland China (e.g., Shu et al., 2006; Li et al., 2009; Wang et al., 2010; Meng et al., 2011). In this test, children were asked to write down a compound word based on a character (constituent morpheme) provided on the sheet. The characters were selected based on the grades. The performance was measured by adding the total number of correct characters the participants could make use of in word-composition and the constant which was the number of characters almost all children in this grade could recognize. Additionally, rapid naming speed was tested. Digits (2, 4, 6, 7, and 9) were repeatedly presented visually in random order on a six row × five column grid. Children were asked to name each digit in sequence as quickly as possible. The total time (s) was collected. Characteristics of participants were shown in **Table 1**.

ORTHOGRAPHIC AWARENESS TEST

This task was consisted of 40 real characters, 20 pseudo-characters, and 20 non-characters. Pseudo-characters (*e.g.*,𢑉) were made up of two position-legal radicals. The radicals of non-characters (*e.g.*,䚬) were in illegal positions. Pseudo-characters conformed to orthographic rules, while non-characters did not. A lexical decision task was adopted, participants were asked to judge whether a presented item was a real character. So, the correct response to a real character was "yes," but to a pseudo-character or a non-character was "no." The task was presented in a computer, which after a 500-ms fixation, each character was presented in isolation in the center of the computer screen until participants responded (the longest duration was 3000 ms). Although pseudo-characters and non-characters are not real characters, pseudo-characters conformed to orthographic rules while non-characters didn't. So, the different performance between pseudo-character and non-character judgment reflected the orthographic skills. Therefore, only reaction time (RT) and accuracy in pseudo-character and non-character responding were recorded. The reliability (Cronbach's Alpha) was 0.804.

COHERENT MOTION DETECTION

The CM task was similar to that in the study of Solan et al. (2004). Two patches of 300 randomly moving white dots with a speed of 7°/s and a lifetime of 225 ms were presented on the left and right sides of screen with dark background. The luminance of dots was 125 cd/m^2, and the luminance of background was 0.39 cd/m^2, Michelson contrast was 99.4%. The patches were 10° wide and 14° high, separated by 5°, and were presented for 2300 ms in each trial. In one patch, all dots moved randomly, while the other patch had a certain percentage of dots moving coherently leftward and rightward. Participants had to judge which patch had such coherently moving dots after patches disappeared. CM threshold was varied according to a 1-up-1-down staircase procedure. Incorrect responses led to an increase in the number of coherent moving dots by 1%, while correct responses led to a decrease by 1%. After 10 reversals, a session was terminated. Threshold was defined by the mean of the number of coherent moving dots of the last six reversals. The experiment included three sessions, and the thresholds were averaged as the final CM threshold presented here.

RESULTS

The performance in orthographic awareness test and CM detection task of DD group and age-matched control (CA) group was shown in **Table 2** and **Figure 1**. t-test revealed that the CM threshold of DDs was significantly higher than that of CA [$t(51) = 2.76$, $p < 0.01$, $d = 0.77$]. With respect to orthographic awareness, the difference in average accuracy of pseudo-characters and non-characters was not significant between the two groups. The difference in average RTs of pseudo-characters and non-characters was marginally significant [$t(51) = 1.78$, $p = 0.08$, $d = 0.50$], dyslexics responded more slowly than controls. In order to explore the relationship between orthographic processing skills and the performance in CM detection, we made a correlation analysis between average RTs to pseudo-characters and non-characters and CM threshold by merging the data of two groups. As shown in **Figure 2**, the RTs of pseudo-characters and non-characters were significantly correlated with CM threshold ($r = 0.28$, $p = 0.046$). In order to explore whether orthographic awareness influenced the difference in CM thresholds of the two groups, RT in orthographic awareness test was put in a general linear model as a covariate. The results showed that the interaction between RT and group was not significant [$F(1,49) = 0.18$, $p = 0.68$, $\eta^2 < 0.01$]. As shown in **Figure 3**, a deviance analysis was applied to explore the distribution of CM thresholds in DD and CA. There were eight dyslexic children had CM thresholds significantly higher than 1.65 SD above the mean of CA group.

DISCUSSION

The present results showed that Chinese dyslexics had deficits in CM detection and orthographic awareness. Compared with typical children, dyslexic children had higher CM detection thresholds and slower response to pseudo-characters and non-characters.

Table 1 | Characteristic of dyslexics and age-matched controls.

	DD ($n = 26$)	CA ($n = 27$)	p
Age (years)	10.03 (0.46)	10.37 (0.90)	>0.05
IQ	110.27 (12.99)	114.22 (9.92)	>0.05
Vocabulary	1113.16 (327.81)	1864.61 (324.87)	<0.001
Time of rapid naming (s)	13.31 (2.76)	10.82 (2.29)	=0.001

Table 2 | Performance in CM detection task and orthographic awareness test of dyslexics and age-matched controls.

		DD ($n = 26$)	CA ($n = 27$)	p value
CM threshold		72.59 (31.66)	52.07 (21.73)	<0.01
Orthographic awareness	Accuracy	0.78 (0.14)	0.82 (0.12)	0.23
	Reaction time (ms)	1010.48	911.20	0.08

ACC, accuracy; RT, reaction time.

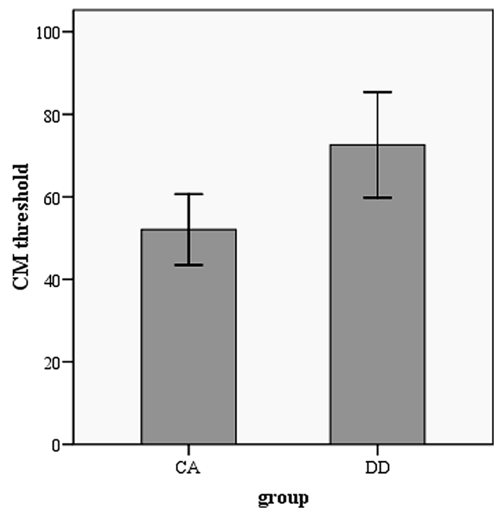

FIGURE 1 | CM threshold in dyslexia group and age-matched control group.

Moreover, the CM thresholds were correlated with average RTs to pseudo-characters and non-characters, suggesting visual M pathway function was closely associated with orthographic processing skills in Chinese-speaking children.

DEFICITS IN VISUAL M PATHWAY AND ORTHOGRAPHIC PROCESSING

As shown in **Table 2**, dyslexics had significantly higher CM thresholds than age-matched controls. The result was consistent with the findings both in alphabetic languages and Chinese (e.g., Hansen et al., 2001; Conlon et al., 2004; Pellicano and Gibson, 2008; Meng et al., 2011). On account of the insignificant interaction between group and orthographic awareness (as a covariate), the deficits in CM perception of DD were not influenced by the deficient orthographic processing. The deviance analysis revealed that 8 of 26 dyslexic children had thresholds higher than 1.65 SD of control means, suggesting that the percentage of M deficit was relatively small in DD. However, the percentage (about 52%) of CM deficits in Chinese children found by Meng et al. (2011) was higher. The difference of incidence might be related to sampling. The sample size in both studies was too small to investigate the incidence effectively. In the future, larger sample size and more visual M tasks should be adopted to explore the prevalence of M deficits.

Meanwhile, Chinese dyslexics performed more slowly in orthographic awareness test than typical children. In line with the findings of Ho et al. (2004), the results suggested that orthographic processing skills were impaired for Chinese dyslexic children. However, in the present study, the group difference was merely marginally significant in RTs, and not significant in accuracy. One possible reason is that the task (lexical decision task) is easy for children, as their accuracy was about 80%. In addition, a prior study found that orthographic awareness (measured by accuracy) made a unique and significant contribution to Chinese reading for younger children, while the contribution became insignificant after second grade (Wei et al., 2014). Orthographic processing skills might reach a mature level at an early age, which might lead to the less significant differences between dyslexic and typical children at 10 years of age.

THE RELATIONSHIP BETWEEN M PATHWAY DYSFUNCTION AND DEFICIENT ORTHOGRAPHIC PROCESSING SKILLS

As shown in **Figure 1**, a significant correlation between CM thresholds and RTs in orthographic awareness test was observed in the present study. This finding suggested M pathway function was associated with orthographic processing skills. However, it was just a correlation relationship, and could not reveal causality between M pathway function and orthographic processing skills. As indicated by M deficit theory, it is probable that M deficit causes sluggish orthographic processing. M deficit theory treats M dysfunction as the core cause of dyslexia, which affects a variety of reading skills, including orthographic processing skills (Stein, 2001). M pathway is involved in normal eye movement control, visuospatial attention, visual search, letter position encoding and peripheral vision, which are obviously involved in the development of orthographic skills (Stein, 2001). A longitudinal study, using causal path analysis, found CM detection ability in preschool was related to reading ability in first grade, and the relationship was mediated by orthographic skills (Boets et al., 2008).

There is another possibility that cognitive deficits caused M pathway dysfunction, which was supported by a recent fMRI study. They found the V5/MT activity for dyslexic children was lower than that for age-matched controls, but no different from reading level matched controls. In addition, V5/MT activity for dyslexics increased after phonological-based intervention along with reading gains. The results suggested phonological deficits, by restricting the amount and quality of reading in dyslexics, limited the opportunity for reading to induce changes in the visual M system (although by mechanisms that remained to be determined; Olulade et al., 2013). However, the conclusion was constrained by some confounding factors, such as the small sample size and the visually presented intervention program. Nevertheless, the study of Olulade et al. (2013) provided a possible perspective to explore the causal relationship between cognitive deficits and M pathway dysfunction. In Chinese, will orthographic processing deficits cause the impairment in M pathway? This problem can be investigated in the future by adopting a reading-level matched group and an intervention study.

Butterworth and Kovas (2013) indicated that the same genes might affect multiple traits implicated in diverse cognitive processes. It was possible that the deficits in M pathway and orthographic processing were affected by the same genes. KIAA0319 is a susceptibility gene for dyslexia (Cope et al., 2005; Harold et al., 2006). KIAA0319 is situated within the major histocompatibility complex (MHC) immune control gene complex, which seems to play a particularly important role in the development of M pathway (Stein, 2012). Additionally, FMR1 is also one of dyslexia candidate genes (Poelmans et al., 2011). A study on patients with fragile X syndrome found that the deficient FMR1 gene led to the degeneration of M cells in the lateral geniculate nucleus (LGN; Kogan et al., 2004). Thus, it is reasonable to speculate that deficits

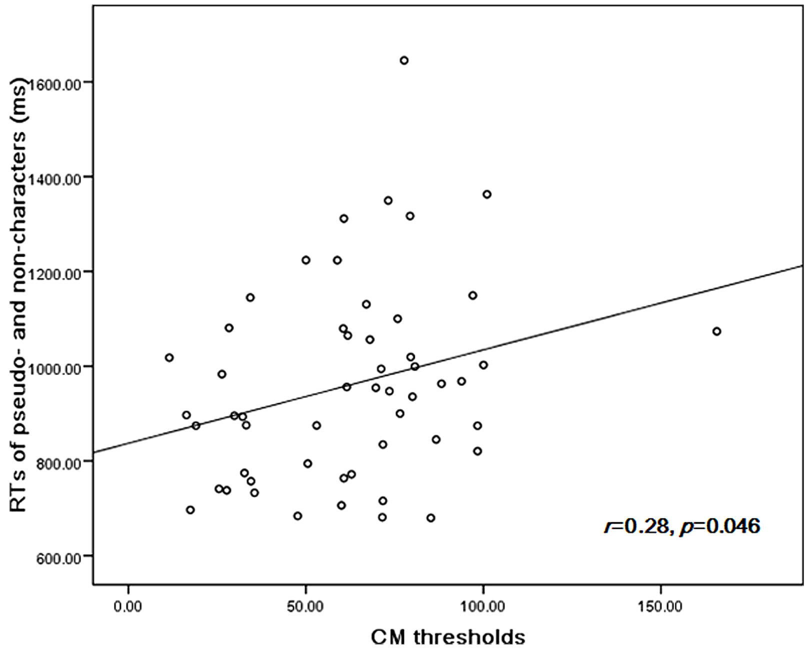

FIGURE 2 | The correlation between CM thresholds and average RTs of pseudo-characters and non-characters.

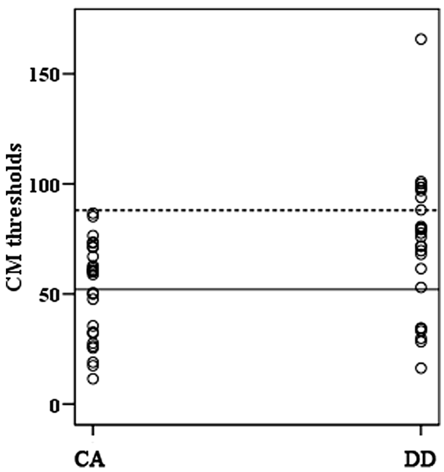

FIGURE 3 | Individual CM threshold in DD and CA groups. The solid line indicated the mean of CA group and the dashed line the chosen deviance threshold (1.65 SD above the mean of CA group).

of KIAA0319 and FMR1 might give rise to dysfunction in M pathway for children with dyslexia. However, there are no studies to investigate the association between these genes and orthographic awareness. So, it is still unclear whether there is a specific gene to affect both M pathway function and orthographic processing skills. More genetic researches were needed to verify the relationship.

In summary, the current study found Chinese children with DD exhibited deficits both in CM perception and orthographic processing. Moreover, CM thresholds were significantly correlated with RTs of pseudo-characters, suggesting the dysfunction in M pathway was highly associated with impairment in orthographic processing skills.

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Reading as functional coordination: not recycling but a novel synthesis

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The Functional Coordination approach describes the processes involved in learning to read as a form of procedural learning in which pre-existing skills, mainly from the visual, and auditory domain, are (1) recruited, (2) modified, and (3) coordinated to create the procedures for reading text, which form the basis of subsequent (4) automatization. In this context, we discuss evidence relating to the emerging prevalence of analytic processing in letter perception. We argue that the process of learning to read does not have to lead to a loss of perceptual skill as consequence of a "cultural recycling"; learning to read just leads to a novel synthesis of functions, which are coordinated for reading and then automatized as a package over several years. Developmental dyslexia is explained within this framework as a Functional Coordination Deficit (Lachmann, 2002), since the coordination level is assumed to be most liable to manifest deficiencies. This is because, at this level, the greatest degree of fine tuning of complex functions is required. Thus, developmental dyslexia is not seen as a consequence of a deficient automatization per se, but of automatization of abnormally developed functional coordination.

Keywords: reading acquisition, visual processing, analytic vs. holistic processing, literacy, developmental dyslexia, congruence effect, child development

ARE LETTERS SPECIAL?

Reading is so much part of everyday life that normally we do not realize how complex this skill is, and how arduous it was to acquire. Reading is a secondary process: beginning readers draw on established cognitive and sensory abilities that are recruited, modified, and coordinated in novel ways to establish the specific strategies of information processing that are optimized for text. According to the *neuronal recycling hypothesis* (Dehaene and Cohen, 2007; Dehaene et al., 2010), these processes may even have the consequence that some of original information processing skills are reduced, as original resources are being redeployed for achieving the newly required functionality. Here we will consider to what extent this may apply to one basic component processing skill: that of analytic visual processing.

Letters, which form the smallest meaningful units of a written text, are not any different in their physical characteristics from meaningless small scribbles, signs of a writing system we don't understand, or simple geometric shapes. That is, prior to learning to read, letters, and non-letters will not be processed in any systematically different ways. However, even prior to learning to read, such simple items are not natural objects. The latter are most likely 3-dimensional, can be seen in different orientations, can move in space over time, and can occur in cluttered environments, in which they often are partially occluded. All these characteristics necessitate that for natural objects, we make the best out of what is visually available. When an object is partially occluded, we may use global object characteristics such as symmetry to complete them perceptually. We make the most out of an object, if we concentrate on its invariant properties, for instance properties that remain unchanged under positional transformations and different orientations, and we are poised to take clues from the context as to what the nature of the object may be.

Even though those small scribbles and simple geometric drawings are not natural objects, it is plausible to assume that they still trigger these processes. For instance, effects of mental rotation were found to be similar for both 2- and 3-dimensial objects (Shepard and Metzler, 1971; Cooper and Shepard, 1973) and visual completion is based on criteria of mergability of 3-dimensional volumes, both in actual 3-dimensional occluded objects, and in 2-dimensional drawings of them (Tse, 1999). In other words, we may observe that there is, even though with individual differences depending on age (Dror et al., 2005) gender (Alexander and Evardone, 2008; Jansen and Kaltner, 2013) and stimulus material (Geiser et al., 2006) a robust over-all tendency to perceive natural objects *holistically*, and that these preferences extend to 2-dimensional drawings.

Yet, also prior to learning to read, natural 3-dimesional objects, and 2-dimensional drawings alike, can already be perceived in another mode as well, i.e., *analytically*. The analytic-holistic distinction is a broad one known under a variety of, often conflicting terminology laden with theoretical baggage. Here we simple mean to address a collection of empirical distinctions, depending on the extent to which a perceptual configuration is perceived as independent of its context, the extent to which the percept emphasizes properties of the parts over the whole, the extent to which it is tolerant with respect to the constraints non-local properties impose on component organization[1], and the extent to which it is oblivious to transformational invariants and/or symmetries. We speak of analytic, when some or all of this applies, and of holistic if otherwise.

Whereas perception is naturally holistic to various degrees, it is sometimes efficient to use an analytic strategy. Consider that while holistic perception would not allow us to see the tiger hiding in the bushes, analytic perception may be able to beat the camouflage. When finding an object, or a path, is difficult, we shift from holistic to analytical strategies and scan parts of the scene or display serially, one by one, in small fragments. As soon as we start doing so, we automatically become oblivious to global symmetries of objects that normally play an implicit role in their identification (Hogeboom and van Leeuwen, 1997; Roelfsema and Houtkamp, 2011; Korjoukov et al., 2012).

LEARNING TO READ

Learning to read involves both holistic and analytic perception, and both are playing different roles during the development of several reading and writing-related sub-skills. According to Frith (1985; see also Chall, 1983; Ehri, 1995), at the beginning of the process of learning to read, *logographic skills* prevail (logographic phase); in this phase, letter configurations will be perceived, just like non-letter ones, in an orientation-unspecific way (see **Figure 1**). The order of letters in a word and other phonological factors are more or less ignored. Unfamiliar words and non-words cannot be read. In fact, instead of "read" we should better use the term "recognized," because in this stage, the child recognizes a word as a whole and reproduces ("writes") it as such, mainly based on salient graphic features, just as in object recognition.

Strictly speaking, the logographic sub-skills do not qualify as "reading" or "writing." This requires the knowledge and use of individual graphemes and phonemes and their correspondences. If this knowledge is available for use, the *alphabetic sub-skill* is developed (alphabetic phase, Frith, 1985, 1986). This sub-skill involves analytic processing; the letters of a word, i.e., the graphemes, are decoded into the corresponding sound one by one, and the sounds are merged together into syllables and words. Fine details of each individual grapheme, its orientation and the order of the graphemes in the configuration are crucial in this stage. Known words, unknown words, as well as non-words can be pronounced, quite likely correctly, i.e., if the correspondence between grapheme and phoneme for the word is according to the learned rule (as for regular words and most words of transparent orthographies, e.g., Italian). In this phase of learning to read, analytic processing is essential. First of all, this is because initially, identifying letters in the context of written text is difficult, and in this case an analytic strategy may be useful. Second, orientation-invariance is not helpful to identify letters; clearly, a "b" is not a "d" nor a "p" nor a "q" either, but also more generally the identity of letters depends on their orientation (van Leeuwen and Lachmann, 2004). Third, and most importantly: the analytic strategies helps establishing a connection with phonology. In skilled readers letters are represented for cross-modal usage (Froyen et al., 2008; Blau et al., 2010; Blomert, 2011), not as a purely visual item, but as connected with auditory information.

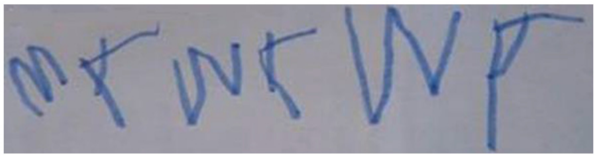

FIGURE 1 | Children in a very early stage of learning to read do not care about letter orientation, letter order or the fact that single letters represent certain phonemes. Instead, reading and writing is based on graphic features. Word: "MAMA, Artist: Anton Lachmann (4; 6).

More important to reading than auditory categorization are the phonological categories ("a listener will identify as a /*b*/ quite a large number of acoustically different sounds," Liberman et al., 1957, p. 358, e.g., when spoken by a man or by a woman) developed in this phase of reading acquisition. But just like letters are not natural objects of visual perception, phonemes are not natural objects of auditory perception. The system of phonemic representation gains prominence in the process of learning to read, evolving along with the graphemic representation (Serniclaes et al., 2005; Port, 2007). In transparent languages, such as Italian, the grapheme-phoneme mapping is almost 1:1, but even in the most intransparent cases, morphological units below the word level can be informative with respect to the phonetic expression. This means that in a representational system optimized for efficiency of reading and writing, the building blocks of linguistic codes will emerge that take the form of cross-modal, visual-acoustic (grapheme-phoneme) units (Froyen et al., 2008; Blomert, 2011).

As a consequence of reading expertise in the orthographic phase (Frith, 1985, 1986) of reading acquisition, a sub-skill is developed which enables the instant analysis of larger grapheme units into orthographic units which ideally coincide with morphemes. As a consequence, words can be read as a whole, i.e., without a one-by-one grapheme-phoneme conversion. In this level of processing, the holistic mode again dominates (Wong et al., 2011). Note, however, that this observation is perfectly compatible with the cross-modal character of the representation.

Even though the holistic orthographic sub-skill is relatively effortlessly applied in reading, even in expert readers the analytic alphabetic sub-skill may still be running in parallel (Van Orden et al., 1990) or, at least, remain available for unfamiliar or foreign words (Morton, 1969; Coltheart, 1978, 2007; Davelaar et al., 1978) for both transparent and non-transparent orthographies (Lachmann et al., 2010). Thus, the analytic processing skill remains important even after learning to read has fully been established.

[1]Note that, theoretically speaking, the dimensions analytic-holistic and whole-part, local-global etc. do not necessarily all refer to the same construct (Wagemans et al., 2012). Here, however, we consider these different aspects simply together as an encompassing visual strategy predominant in object recognition.

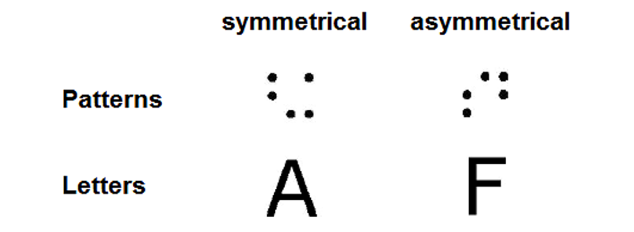

FIGURE 2 | Examples of symmetrical and asymmetrical dot-pattern (first used by Garner and Clement, 1963) and letter stimuli used in Lachmann and van Leeuwen (2007).

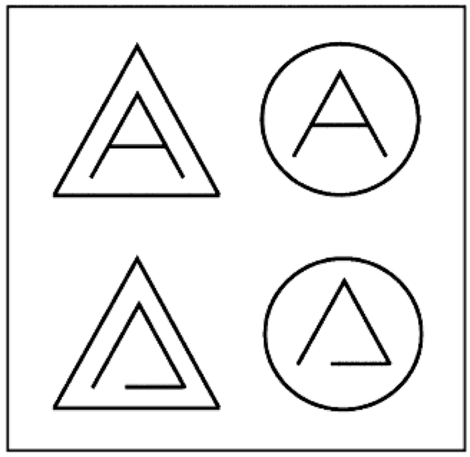

FIGURE 3 | Letters (top) and pseudo-letters (bottom) in congruent (left) and incongruent (right) surroundings, as used in our flanker studies. See also Fernandes et al. (2014) for similar stimuli.

ANALYTIC PROCESSING OF LETTERS IN EXPERIMENTAL STUDIES

We may conclude that analytic processing is likely to be more specifically associated with reading letters as compared with processing similar non-letter objects. We tested this prediction in a variety of experimental tasks involving different aspects of analytic processing, three of which we will describe in some more detail in the following sections.

One set of experiments deals with the perception of symmetry (Lachmann and van Leeuwen, 2007). Letters and dot patterns (five-dot patterns as first used by Garner and Clement, 1963), with different degrees of symmetry, were presented in a *same–different* task (see **Figure 2**). It had previously been established that the symmetry of the dot patterns is decisive for the speed and accuracy of their comparison (Lachmann and Geissler, 2002; Hermens et al., 2013; Takahashi et al., 2013): symmetrical dot patterns are processed faster (depending in an almost perfectly predictable way on the number of symmetries or, according to Garner and Clement, 1963, the pattern *Goodness*). It is safely to assume, therefore, that these patterns are processed holistically. If letters are processed in a similar way, we should observe symmetry advantages for letters as well. However, in normal reading school-children of the study by Lachmann and van Leeuwen (2007), symmetry effects were observed for dot patterns but not for letters. Interestingly, in this study, age-matched children diagnosed with developmental dyslexia showed the symmetry advantage for both patterns and letters. In addition, this group of children showed transfer between letter and non-letter stimulus blocks, whereas normal reading children did not. The remarkable consequence is that dyslexics are *faster* on this task, in particular also with letters, than normal readers. We interpret this seemingly paradox result (i.e., that developmental dyslexics performed better then controls in a letter task) as indicating that normal readers differentiate in their perceptual strategy between letters and non-letter shapes, whereas dyslexics do not. For the particular task in described study (letters of different orientation have to be rated as "same"), this led to a processing advantage for the latter group. Since analytic and holistic strategies both are available to the normal readers, why then is it the case that for this task the normally reading control children did not apply the holistic strategy to letters too, since this seems to work best for the given task? One possibility is because these readers have automatized the analytic strategy for letters.

Does our result mean that, as recent adoptions of the cerebellar theory (Fawcett, 2002) suggests, developmental dyslexics have a deficit in automatization (Nicolson and Fawcett, 2011)? A deficit in automatization may indeed result in dyslexics failing to automatically apply analytic processing to letters, which happens to be of advantage for the particular version of the *same–different* task used in Lachmann and van Leeuwen (2007), which involved responding to rotated/mirror-imaged versions of two items as "same."

But the automatization deficit approach cannot explain a number of effects (Rusiak et al., 2007), as for instance the ones observed in another set of experiments using stimuli such as those displayed in **Figure 3** (Lachmann and van Leeuwen, 2004, 2008b; van Leeuwen and Lachmann, 2004; see also Fernandes et al., 2014). Similarly to Eriksson's classical Flanker study (Eriksen and Eriksen, 1974), we investigated effects of congruence of the surrounding context on the processing of the central target. Non-pseudo- and rotated letter targets all show positive effects of flanker congruence, i.e., processing is facilitated if the surroundings are similar in shape to the central target. According to our terminology, this implies that these items are processed holistically. Interestingly, for letters the surrounding shape congruency is irrelevant[2], which is reflected in absence of congruence effects, or even interferes with processing, leading to a *negative* congruence effect (Bavelier et al., 2000; Briand, 1994; van Leeuwen and Bakker, 1995). These effects can be explained by assuming that letters are processed analytically; in cases where the surrounding context makes analytic processing difficult the surrounding context is actively suppressed, resulting

[2]Recent research (Buetti et al., 2014) suggests that the term "irrelevant" within the context of stimulus-response compatibility effects may be misleading, since, e.g., in flanker tasks, the term "task irrelevant flankers" implies the assumption that distracters are not at all related to the task. This is usually not the case, because they are "attentionally relevant" (Buetti et al., 2014). In the context of our approach, however, in which congruence effects are used to estimate whether the processing strategy is analytic versus holistic, this terminology discussion may be considered *irrelevant*.

in negative congruence effects: more effort is needed to suppress a congruent than an incongruent context.

Variations of this paradigm have been informative about the strategic character of the processing dissociation between letters and non-letter shapes. First, the dissociation is task-dependent. *Positive* congruence effects in letters appear in conditions where the task can be performed by identifying the global shape of the items (Lachmann and van Leeuwen, 2004; van Leeuwen and Lachmann, 2004). This means that the holistic processing strategy for letters is still available and is likely to be recruited if it is recognized to be beneficial to the task. Second, the process dissociation between letters and non-letter shapes has been studied in developmental dyslexics and was compared to that of normally reading controls (Lachmann and van Leeuwen, 2008a; Fernandes et al., 2014). Fernandes et al. (2014) replicated the aforementioned dissociation between letters and non-letters in normal readers, but found that it is absent in developmental dyslexics (depending on their phonological recoding skills). In other words, dyslexics in this study failed to apply the analytic strategy – in line with our results from the symmetry paradigm. Interestingly, a seemingly contrasting result for dyslexics was obtained in Lachmann and van Leeuwen (2008a); here, the largest subgroup of developmental dyslexics showed a *negative* congruence effect, much more strongly than the normal readers. Besides methodological differences (e.g., shorter presentation rate, different stimuli, and different diagnostic criteria), between the two studies, this discrepancy can also be explained on the basis of the specific context from which the dyslexics in the latter study were recruited: in our study they were pupils of a special concentration school, which provided intensive training to its dyslexic pupils. The training strongly emphasizes the grapheme-phoneme correspondence. In other words, for these dyslexics, unlike those in the Fernandes et al. (2014) study, who did not receive this intensive and specific kind of training, their background strongly encouraged them to use an analytic strategy (as in the alphabetic phase at the beginning of the process of learning to read), even though they must have found this hard. Given that doing so is difficult for them, this can explain that they showed a negative congruence effect. Thus, overall, the results of both dyslexia studies are in good mutual agreement.

A third experimental method which we used in order to study analytic processing in letters is found in Lachmann et al. (2014, current research topic). This study used the well-known Navon paradigm (Kinchla, 1974; Navon, 1977; see Kimchi, 2014, for a review). The Navon paradigm typically uses compound letters, e.g., a large F composed of a number of identical small Fs or a large H composed of small Hs (congruent), or a large F composed of small Hs or a large H composed of small Fs (incongruent; see **Figure 4**). The large letters are called "global" items, the small ones "local" items. The instruction is varied in a way that a response has to be given either to the local or to the global level, while ignoring information provided in the other level, respectively. With this type of stimuli, global precedence has been established, i.e., faster processing of the global level than the local level (global advantage effect), and an asymmetric congruence effect: incongruency interferes with the local-level target responses but not with global level ones. We may consider both

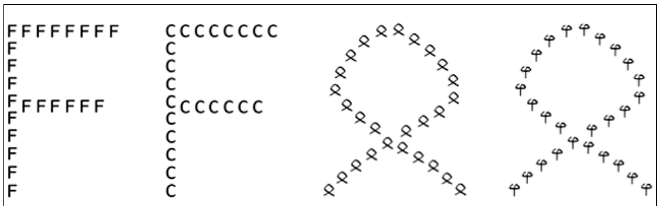

FIGURE 4 | Illustration of the hierarchical stimuli presented in a study by Lachmann et al. (2014) using the Navon paradigm (Kinchla, 1974; Navon, 1977). Left side: examples for letters, right side: examples for non-letters. First stimulus example: the local and the global level consists of the same letter F (congruent letter stimulus). Second stimulus example: the global-level letter (F) differs from the local level one (C). Third stimulus example: congruent non-letter stimulus; fourth stimulus example: incongruent non-letter stimulus.

these effects combined as reflecting holistic processing. Thus, the global precedence effect might seem to be in contrast to what one would expect, intuitively, if letters are preferably processed analytically. Note, however, that the global precedence effect strongly depends on the presentation mode (see Kimchi, 2014 for a review) and that the viewing conditions in which the effect is typically found do not resemble those of our flanker/symmetry studies. In Lachmann et al. (2014) we therefore used conditions for which analytic letter processing is expected, because the size and foveal presentation more closely resemble conditions of fluent reading, so the automatized reading specific visual processing strategy was more likely to kick in. With the global stimulus size close to the functional visual field in word reading and local stimuli close to the critical size for fluent reading of individual letters, we compared the global precedence effect for letters and non-letters in central viewing. With these conditions we found the global precedence effect to remain robust for non-letters. For letters, in contrast, the effect disappeared. We interpret these results as according to the view that reading is based on analytic visual processing strategies for letters. In other words, the dissociation in analytic and holistic processing between letters and non-letter shapes is manifest also in the Navon-paradigm, but is limited to viewing conditions that are akin to reading. The automatization of analytic processing for letters, therefore, is highly context-specific.

READING AS PROCEDURAL LEARNING: AUTOMATIZATION OF FUNCTIONAL COORDINATION

The context-specific process dissociation observed for letters versus non-letters fit a modeling framework (Lachmann, 2002, 2008), schematized in **Figure 5**. The model describes the process of learning to read as a form of procedural learning (Nicolson et al., 2010; Nicolson and Fawcett, 2011) in terms of four stages. We propose that in this process, first, pre-existing skills, principally from the visual and auditory domain, are recruited as a consequence of instruction; for instance, in the perception of script the ability to distinguish small two-dimensional line drawings helps establish letters as the recurring elements of words and sentences. In our interactions with children we scaffold this process by pointing out the distinctive aspects of letters by instantiation, simply like "Look, this is an A," and by encouraging children to "draw" (rather than

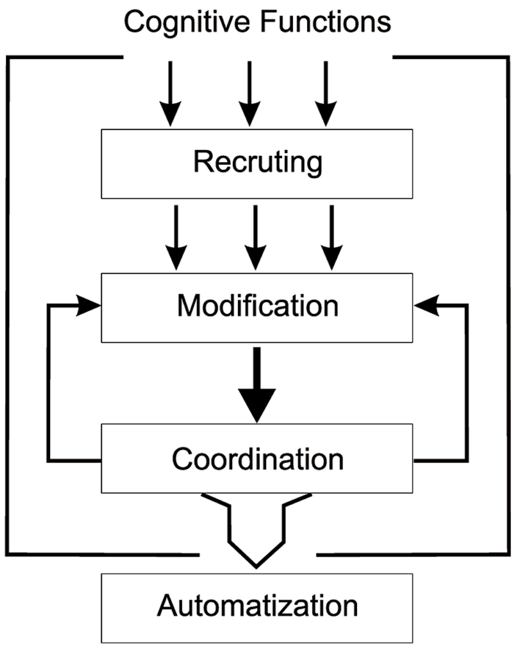

FIGURE 5 | Functional Coordination Framework for describing the processes involved in learning to read. Learning to read is described as a form of procedural learning in which, as a consequence of instruction, pre-existing functions and skills, principally from the visual and auditory domain, are recruited, modified and coordinated, leading to cross-modal codes of letters and procedures. After training these get automatized, after which experienced readers are biased against processing strategies for letter perception that do not form part of the procedure. The coordination stage is the most critical one, it stabilizes the modifications. A failure of coordination will result in automatization of an abnormal procedure, leading to reading and writing problems (Lachmann, 2002, 2008). The whole process, including the structural and functional changes related to it, takes several years (Lachmann and van Leeuwen, 2008b; Froyen et al., 2009).

write) them. Such abilities are then, in the second stage, modified in a way to optimize their usage in the context of reading and writing, for instance the suppression of orientation invariance and symmetries ("this is not correct, it is upside down"). In other words, this stage involves the emergence of the analytic preference for letters.

Such modifications do not occur in isolation, but co-emerge with the fine-tuning of the phonological system (McBride-Chang, 1999; Lachmann, 2002; Blomert, 2011; Fernandes et al., 2014). These developments take place in a learning context, where both reading and writing are extensively practiced (in fact every day for hours and over years). In this context, considered as third stage in the model, the specific analytic visual abilities and the phonological processing skills become functionally coordinated, giving rise to grapheme-phoneme (reading) and phoneme-grapheme correspondences (writing), leading to cross-modal codes of letters, which form the basis of subsequent automatization processes, the final stage in the model. Given the complexity of these processes, automatization is spread over a period of several years (Lachmann and van Leeuwen, 2008b). Note, that even though children may be able to read and to name letters relatively fast and correctly, i.e., even if they have an established representation of the grapheme-phoneme and the phoneme-grapheme correspondences, the underlying structural und functional basis for its automatization process in the neural system may take 3–4 years (Froyen et al., 2009).

In this framework, developmental dyslexia is not a matter of a deficient automatization per se, but of an automatization of abnormally developed functional coordination (Lachmann, 2002, 2008). Abnormal coordination can be a product of early-stage deficiencies of various kinds: lacking auditory abilities (Ahissar et al., 2000; Talcott and Witton, 2002; Richardson et al., 2004; Goswami, 2011; Groth et al., 2011; Hamalainen et al., 2013), visual instabilities (Slaghuis and Ryan, 1999; Stein and Talcott, 1999; Stein, 2002; Becker et al., 2005) or a combination thereof (Au and Lovegrove, 2007; see Farmer and Klein, 1995, for a review). In these cases, problems may arise already in the recruitment stage; yet they are manifested only in the coordination. This is the case, because the anomalities (e.g., in contrast sensitivity, Slaghuis and Ryan, 1999; or in temporal processing, Steinbrink et al., 2012) at the early levels are not severe enough as to lead to modality-specific deficiencies by themselves. However, such early-stage deficiencies do not *necessarily* lead to problems in coordination, they may be compensated, e.g., by coping strategies or brain plasticity (Frith, 1986).

Alternatively, the anomalies may arise in the "modification" stage, for instance failure to suppress symmetry or other holistic strategies (e.g., von Károlyia et al., 2003; Pegado et al., 2011; Perea et al., 2011) or problems in developing phonological (e.g., Snowling, 2001; Fawcett, 2002) or orthographic skills (Seymour and Evans, 1993). Yet again, even though these problems may arise at this stage, they will be manifested at the coordination level. Failed coordination may lead to compensation strategies resulting in further modifications, just as normal coordination does (see **Figure 5**). For instance, failure to automatically suppress symmetry may lead to active symmetry suppression, which then becomes an engrained strategy. Or, alternatively, it may lead to a strategy of perceiving letters as images just like non-letters (Lachmann and van Leeuwen, 2007).

Functional coordination deficits may arise, however, even without any deficiencies in the recruiting and the modification stage, originating from within the coordination process (Froyen et al., 2011) or resulting from deficiencies in automatization (Nicolson and Fawcett, 2011). Rather than automatization, the coordination level may be most liable to manifest the deficiencies, however, because this is the level where the greatest degree of fine tuning of complex functions is required. Note, that this idea is not inconsistent with the cerebellar approach of Nicolson and Fawcett (2011; Fawcett, 2002) since the cerebellum seems to be essentially involved in such fine tuning and coordination processes (Stoodley and Stein, 2011), including language processing (Ackermann and Hertrich, 2000).

SUMMERY AND CONCLUSIONS

We discussed evidence relating to the emerging prevalence of analytic processing in the perception of letters, and described its relevance to reading, in the context of a modeling framework for learning to read, the Functional Coordination Model. According to this framework, existing skills are recruited, modified, and coordinated in the process of learning to read. It is not the case, therefore, that new basic skills emerge as a consequence of learning to read; for instance, analytic processing is a resident skill also present in children or non-reading adults (Lachmann et al., 2012). Neither is it the case that reading implies loss of perceptual skills; for instance we are still able to perceive non-letter items analytically or, for that matter, letters holistically, if this is recognized as beneficial to the task (Lachmann and van Leeuwen, 2004; van Leeuwen and Lachmann, 2004). Thus, what has been called "recycling" (Dehaene and Cohen, 2007) of basic perceptual or cognitive abilities does not lead, at least in case of our ability to process visual objects, to any loss of this ability. Rather, what we are looking at is the outcome of procedural learning that has resulted in habits that form the building blocks of complex cognitive skills such as reading.

The question if letters are special, that is, whether they are processed differently as compared to non-letters, may thus be answered affirmatively, but only as long as these are taken as part of a reading process. The habitual tendency to do so is strong enough to be manifest in our experiments, even though these used letters outside of a reading context, as long as the task and presentation conditions are sufficiently similar to those of reading. It is the reading skill as such which is special, not the letter configurations. If we exchange all "a"s in a text by a novel visual symbol and ask our participants to read the text, the novel symbol will be incorporated in the automatized skill rather fast and consequently will be treated as letter. Reading is not a matter of certain letters and sounds, these are only concretizations within a complex, higher-order procedural learning process which takes years to get automatized. Afterward, when perceiving letter stimuli, experienced readers may sometimes experience difficulty in suppressing their modified visual and auditory functions which are part of the automatized coordination. These are then habitually processed as letters, and as a result are special to an experienced reader.

From the point of view that failure in learning to read is the consequence of abnormal coordination followed by the process of automatization, it makes no sense to search for a single cause of reading problems. There might be many possible reasons for failure to become a fluent reader, like those described in different theories of developmental dyslexia (e.g., Farmer and Klein, 1995; Bishop et al., 1999; Snowling, 2001; Fawcett, 2002; Stein, 2002; Ramus et al., 2003; Goswami, 2011). All of these may lead to failures in functional coordination. A consequence of this view is, that isolated training of basic functions, such as visual-auditory integration or temporal processing, may have only limited effects, once automatization is already advanced. In that case the skills must be reorganized and then reautomatized (Klatte et al., 2014).

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Letters in the forest: global precedence effect disappears for letters but not for non-letters under reading-like conditions

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Normally skilled reading involves special processing strategies for letters, which are habitually funneled into an abstract letter code. On the basis of previous studies we argue that this habit leads to the preferred usage of an analytic strategy for the processing of letters, while non-letters are preferably processed via a holistic strategy. The well-known global precedence effect (GPE) seems to contradict to this assumption, since, with compound, hierarchical figures, including letter items, faster responses are observed to the global than to the local level of the figure, as well as an asymmetric interference effect from global to local level. We argue that with letters these effects depend on presentation conditions; only when they elicit the processing strategies automatized for reading, an analytic strategy for letters in contrast to non-letters is to be expected. We compared the GPE for letters and non-letters in central viewing, with the global stimulus size close to the functional visual field in whole word reading (6.5° of visual angle) and local stimuli close to the critical size for fluent reading of individual letters (0.5° of visual angle). Under these conditions, the GPE remained robust for non-letters. For letters, however, it disappeared: letters showed *no* overall response time advantage for the global level and symmetric congruence effects (local-to-global as well as global-to-local interference). We interpret these results as according to the view that reading is based on resident analytic visual processing strategies for letters.

Keywords: reading acquisition, global advantage effect, analytic processing, holistic processing, literacy, developmental dyslexia, congruence effect

INTRODUCTION

The ability to read is built on established visual and auditory skills: in the auditory domain, these skills involve the use of spoken language (Friederici and Lachmann, 2002); in the visual domain, they include the capacity to detect and encode small components and to process them in parallel at the level of objects of a certain complexity. These skills are recruited for, respectively, the processing of letters and words. In being recruited, original skills may become modified (Lachmann, 2002; Dehaene and Cohen, 2007; Dehaene et al., 2010b; Lachmann and van Leeuwen, this issue). For instance, in the auditory domain, the phonological structure of language will gain prominence in the process of learning to read (Serniclaes et al., 2005; Port, 2007; Ventura et al., 2008a; Kolinsky et al., 2012). The question is, whether we can likewise observe modifications of the visual domain that emerge in the process of learning to read.

Normally skilled reading involves special processing strategies for letters; these are habitually funneled into an abstract letter code, i.e., a representation for cross-modal usage, derived from both visual and auditory characteristics (Blomert, 2011; Mittag et al., 2013). Several authors have proposed that in acquiring a normal-level of reading ability, visual processing of letters (more precisely graphemes), is singled out from that of similar non-letter shapes (Lachmann and van Leeuwen, 2004, 2008a, this issue; van Leeuwen and Lachmann, 2004; James et al., 2005; Burgund et al., 2006; Pegado et al., 2011; Duñabeitia et al., 2013; Fernandes et al., 2014). According to our views (Lachmann and van Leeuwen, 2008a, this issue), the special strategy for reading letters involves a preferential association of letters with analytic processing, whereas holistic processing is preferred for non-letter visual shapes.

The latter include pseudo-letters, but also whole written words. In non-lexical serial pattern learning, holistic preference develops as a function of practice (van Leeuwen et al., 1988). For words, this may be the product of reading expertise (Frith, 1985; Ehri, 1998; Wong et al., 2011). As a result, words can be processed via a direct lexical route without grapheme–phoneme conversion (Davelaar et al., 1978; Coltheart, 2007). Because of this we may observe in skilled readers the effects of analytic letter processing mainly in case of letters out of word context or in pseudo- or unfamiliar words, i.e., whenever processes of the single-letter level predominate. Still, this condition constitutes a fundamental phase in the development of skilled reading (Frith, 1985; Ehri, 1998). In expert readers it survives as a fall-back strategy to direct word processing (Coltheart, 2007).

To illustrate the differentiation in letter and non-letter processing: in a *same-different* task, in normally reading children, global symmetry led to faster responses in non-letter dot patterns, whereas symmetry did not affect response speed in letters (Lachmann and van Leeuwen, 2007). Clearly, in skilled reading the holistic property of symmetry has become irrelevant for letters and must be suppressed (e.g., Lachmann, 2002; Dehaene et al., 2010a; Pegado et al., 2011, 2014; Fernandes and Kolinsky, 2013;

Borst et al., 2014). Another example is that in flanker studies, congruent flankers facilitate responses to non-letters, whereas they do not in case of letters (Lachmann and van Leeuwen, 2004, 2008a; van Leeuwen and Lachmann, 2004). Holistic processing of non-letters leads to binding of the flankers, whereas such effects are absent due to analytic processing in letters. If such differentiations are a consequence of reading experience, they should be absent in adults who never learned to read (Kolinsky et al., 2011; Lachmann et al., 2012; Fernandes et al., 2014) and moreover, are likely to have developed anomalously in dyslexic children and adults (Lachmann and van Leeuwen, 2007, 2008b; Lachmann et al., 2010; Fernandes et al., 2014; Perea and Panadero, 2014).

READING AND GLOBAL PRECEDENCE

The preference for analytic letter processing in normal readers is apparently in conflict with some well-known observations in a classical paradigm. This paradigm uses compound, hierarchical figures with both a local and a global structure (Kinchla, 1974; Navon, 1977; see Kimchi, 1992 for a review) that give rise to the well-known global precedence effect (GPE): "*forest before trees,*" to use a common metaphor (Navon, 1977). The global structure in these patterns is a configuration, defined by the spatial relationship between its elements, which all have identical local shapes. The task can involve identification, classification, or discrimination of a target either at the global or local level. Consider, for example, a stimulus described by four triangles arranged in a square pattern. The square pattern consists of the global level ("forest"); the triangles are the local level ("trees"). These compound figures have the advantage that the global and local level can be independently varied: besides a square of triangles, we can have a triangle of squares, a square of squares, and a triangle of triangles (see Navon, 1981a, 2003).

The GPE implies, firstly, that for the global-level targets responses are faster than for the local-level ones (*global advantage* or *global superiority effect*). The second observation pertaining to the GPE is called *asymmetric congruence,* which should be understood as follows: Of the above-mentioned four patterns, the square of squares and the triangle of triangles qualify as congruent and the other two as incongruent. Typically for such patterns, incongruency interferes with the local-level target responses but not with global level ones. This and the global advantage effect together constitute the GPE.

The presence of a GPE leads to the conclusion that the global-level properties are given priority in processing, compared to the local ones (we first see the forest, then the trees). We might want to call this type of processing holistic. Note, however, that the dimensions local–global and analytic-holistic do not necessarily refer to the same construct (Wagemans et al., 2012).

The GPE is mostly observed with compound figures in which the local and global levels both consist of letters (Navon, 1977; Lux et al., 2004; Dulaney and Marks, 2007; see Kimchi, 1992, for an overview). This observation might well be considered in contradiction to our claim that while non-letter shapes are typically processed holistically, letters are processed analytically. We would at least prima facie expect an observer in analytic mode not to give priority in processing to the properties of the global shape – this, even though the present task is not quite the same as reading.

We note, however, that there are reasons to expect analytic processing leading to the disappearance of the GPE under particular circumstances. In spite of its abiding character in the literature, the GPE is modulated by a variety of factors, including (1) *stimulus* factors, such as its absolute and relative size (Kinchla and Wolfe, 1979; Martin, 1979; Lamb and Robertson, 1990; Luna et al., 1995; Amirkhiabani, 1998), number of components (Kimchi and Palmer, 1982; Navon, 1983), and spatial frequency characteristics (LaGasse, 1993; Hübner, 1997); (2) factors involving the *mode of presentation*, such as detectability of the local and global features (Kimchi, 1992), visual hemifield (Amirkhiabani, 1998), eccentricity from the focal point of view (Navon and Norman, 1983; Pomerantz, 1983; Amirkhiabani and Lovegrove, 1996) and positional uncertainty (Lamb and Robertson, 1988); and (3) *individual* factors such as prior set (Kimchi, 1992), order of instruction (Foerster and Tory Higgins, 2005), meaningfulness (Poirel et al., 2006) field-dependence-independence (Poirel et al., 2008a) and the stage of brain-development (Poirel et al., 2011).

With few exceptions (e.g., Poirel et al., 2008b), researchers used either letters or non-letters when testing the effect of various factors on the GPE, rather than systematically comparing letters and non-letters. However, across these studies GP effects appear to differ between letters and non-letters. Whereas the GPE, in particular the global advantage, reliably appears with non-letters (Hughes et al., 1984; Luna et al., 1990; Harrison and Stiles, 2009; Kimchi et al., 2009; Bouvet et al., 2011), with letters it depends on a number of factors. One of these is target placement. The original study by Navon (1977) as well as a number of later studies (e.g., Lux et al., 2004; Volberg and Hübner, 2004; Dulaney and Marks, 2007) involved presentation of the local and global letters away from fixation, in combination with positional uncertainty.

For letter-specific analytic processing, it appears crucial that the targets are presented in central view, without positional uncertainty (Plomp et al., 2010). The reason may be that reading typically occurs in a piecemeal fashion, while the sensory information is close to the locus of fixation (Rayner et al., 1986); parafoveal vision in order to control saccades may be important for reading, but uptake of orthographic information takes place only within central vision (Rayner et al., 1986; Jordan and Martin, 1987; Pollatsek, 1993; Stein et al., 2001; Stein, 2002). If analytic processing of letters is due to reading expertise, we are more likely to find it in conditions where the target is placed centrally in visual field.

Since Navon's seminal work, several studies have presented compound stimuli in the center of the screen without uncertainty and still obtained a GPE (e.g., Kinchla and Wolfe, 1979; Grice et al., 1983; Poirel et al., 2008b). For letters in these conditions, however, the effects were often found to be unstable, reduced, absent or sometimes even reversed (Kinchla and Wolfe, 1979; Pomerantz, 1983; Lamb and Robertson, 1988, 1990; Amirkhiabani and Lovegrove, 1996; Ahmed and Fockert, 2012; see Kimchi, 1992, 2014, for a review).

Whereas for non-letters effects appear relatively invariant, for letters they crucially depend on the visual angle of the global target. The dependency was consistently observed across a number of studies (Kinchla and Wolfe, 1979; Lamb and Robertson, 1990; Luna et al., 1995; Amirkhiabani and Lovegrove, 1996; see Kimchi, 1992 for a review). Amirkhiabani and Lovegrove (1996) found the GPE to disappear with a visual angle extending a size of between 2.5 and 4.6°. Lamb and Robertson (1990) varied the visual angles of global letters from 1.5 to 12° and found that the global advantage effect with letters is restricted to visual angles smaller than 4.5°. Luna et al. (1995) presented the global letter targets with visual angles of 3, 6, and 12° and found, in agreement with the previous studies, the GPE with letters to be restricted to the small visual angle condition of 3°. With 6° the GPE disappeared and in the 12° condition it reversed. All these results are, by and large, in accordance with the earlier finding by Kinchla and Wolfe (1979) that the GPE with letters reverses from a visual angle of about 6–9° upward. These results make it likely that central presentation of global stimuli between 5 and 6° approximately in size leads to a differentiation between letters and non-letters in their GPE effect. However, since for this type of conditions, no comparison between letters and non-letters has so far been made, this conclusion would be based on indirect evidence.

The few studies that did compare letters and non-letters used either peripheral presentation (Dulaney and Marks, 2007) or, if they used central presentation, did not vary the material systematically (Peresotti et al., 1991 only varied material at the global level) and if they did, they used rather large visual angles for the global level (Poirel et al., 2008b; Beaucousin et al., 2011). In the present study we compared in one experiment letters and non-letters, using central placement and a scale of around 5–6° of visual angle for which we may expect the GPE to disappear for letters but to remain for non-letters.

We predict this discrepancy based on the assumption that analytic processing of letters is associated with reading and thus analytic processing most likely will occur with stimulus dimensions, appropriate for fluent reading. This is because for these conditions the reading specific visual processing strategy is automatized (Lachmann and van Leeuwen, this issue). The crucial 5–6° of visual angle may be related to the fact that the word-level information needs to be captured within the *functional visual field*. This is a restricted area of approximately 5–10° of visual angle around the fixation point. Within this field we can perceive an object and its component parts (Sanders, 1970). This means that the local (letter) and global level can be processed in parallel. The size of the functional visual field depends dynamically on the context and varies with factors such as stimulus complexity, crowding, contrast, and attentional demands (Motter and Simioni, 2008). Under conditions typical of reading, with relatively uniform and densely crowded stimuli, the field is relatively small (Legge et al., 2007). On the other hand, the global level stimulus is not surrounded by any flankers. On balance, this means that the size of a global level of 6–7° of visual angle approximately matches the functional visual field. Therefore, we used this size of the visual angle for the global stimulus in the present study.

As for the size of the local level, there is a *critical threshold* for fluent reading in central vision, which is approximately 0.2/0.3° of visual angle (Legge et al., 1985; Jordan and Martin, 1987). We chose local stimuli in the present study to be of the size of 0.5°. Whereas reading becomes less fluent with still larger stimuli, the chosen size of the local stimuli is still quite appropriate with reading. We propose that under the joint constraints of the *critical threshold* and the *functional visual field*, effects of analytic processing in letters are most likely to be found in centrally placed compound letters, and thus contrast with a GPE for non-letters.

EXPERIMENT

PARTICIPANTS

Thirty-seven participants (16 female), all students from the University of Kaiserslautern, Germany (mean age: 26 years; SD: 3), took part in this study. All participants were native speakers of German, had normal hearing and normal or corrected-to-normal vision, and were not diagnosed as having any reading disorder. The study was approved by the ethical committee of the Faculty of Social Sciences of the University of Kaiserslautern. Participants gave written informed consent prior to performing the task, and were paid for their participation.

MATERIAL

Compound, hierarchical (Navon, 1977) letter and non-letter stimuli were used, as illustrated in **Figure 1**. Mixed stimuli (e.g., local letters with global non-letters or vice versa) were not used; the stimuli were either entirely composed of letters (C or F) or of non-letter shapes (the two in **Figure 1**), in all possible hierarchical combinations, which accordingly could be congruent (as far as letters are concerned: a C of Cs or an F of Fs) or incongruent (a C of Fs or an F of Cs, and analogously for non-letters). Stimuli were presented using E-prime 2.0 (Psychology Software Tools, Pittsburg, USA), controlled by a laptop computer running Microsoft Windows XP in a test cubicle with sound attenuation and controlled lighting. The stimuli were presented in black (0.4 cd/m^2) against a white background (28.9 cd/m^2), the global stimulus with a visual angle of approximately 6.5° in height and 5.5° in width, the local stimuli with a visual angle of approximately 0.5°.

DESIGN AND PROCEDURE

Participants performed a two-alternative-forced-choice identification task on the compound, hierarchical letter or non-letter characters. The experimental session consisted of four blocks of 100 trials each. In two blocks, one with letters, and one with non-letters, participants were asked to respond to the identity of the local elements and to ignore the global shape, while in the remaining two blocks, again, one with letters, and one with non-letters, they were instructed to identify the global stimulus while ignoring the local elements. Participants responded by pressing the left key of the embedded laptop mouse with the left index finger or with the right key using their right index finger to the response alternatives, which depended on the specific instructions for a block (e.g., level = global: "F" = left key, "C" = right key). Each block contained 50 congruent trials, i.e., when the identity of the local and the global elements were matched (e.g., global "F" target consisted of local "F" elements) and 50 incongruent trials, i.e., when the identity of the local and global elements were not matched (e.g., local "F" targets formed a global "C" letter shape; see **Figure 1**). Each block started with an instruction screen on which all four possible target figures and the correct responses were shown, respectively.

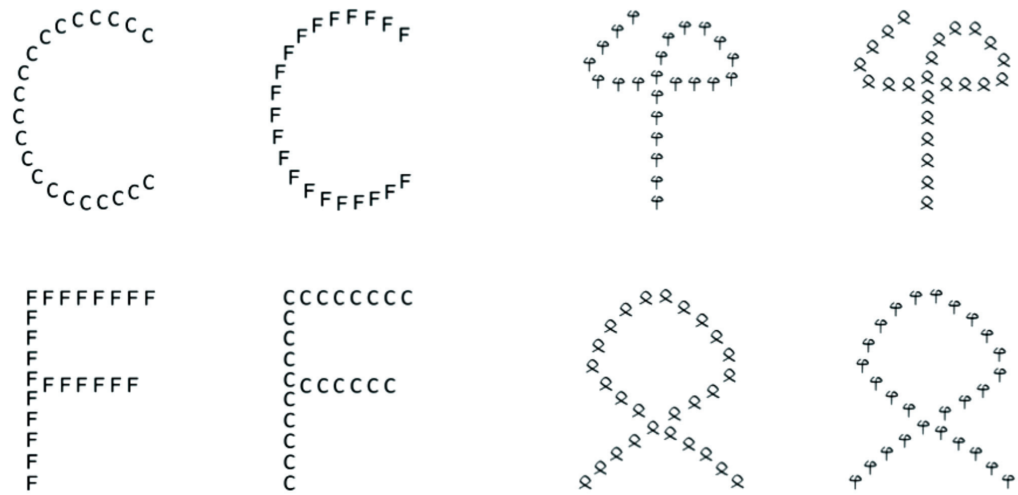

FIGURE 1 | Illustration of the hierarchical stimuli used in the experiment, left side: letters, right side non-letters. Leftmost column: congruent letter stimuli, of which the local and the global level consists of the same letters, C or F, respectively. Second column: incongruent letter stimuli, i.e., the global-level letters differ from the local level ones. Third column: congruent non-letter stimuli; right most column: incongruent non-letter stimuli.

Each trial started with a fixation cross displayed for 250 ms, followed by a blank screen (250 ms), after which, at the location were the fixation cross had been presented, the compound, hierarchical figure was displayed centrally and without positional uncertainty, until the participant responded (or for 2000 s in case no response was given), followed by another blank screen for 250 ms. Eight practice trials were performed prior each block for which a visual feedback for correct and incorrect responses was given, displayed for 500 ms. All conditions were randomized for each participant or counterbalanced between participants.

RESULTS

Reaction times (RT) of correct responses within a range of 200-2000 ms and Error Rates were analyzed. No outliers needed to be excluded. There was no evidence for a speed-accuracy trade off, $r(35) = 0.3$ ns. Therefore, in the following sections we will report RT analyses only. The RT data were analyzed by means of repeated-measures Analysis of Variance (ANOVA) with the following factors: Material (letters or non-letter shapes), Level (global or local target), and Congruency (congruent or incongruent); preliminary analyses showed no differences between individual letters or shapes within the letter or non-letter condition, respectively, so this factor was pooled. Mean RTs for the conditions are displayed in **Figure 2**.

Main effects were observed for all factors: for Material $F(1,36) = 9.8$, $p < 0.001$, with faster reactions for letters than for non-letter shapes; for Level $F(1,36) = 58$, $p < 0.001$, with faster responses for global than for local level targets and for Congruency $F(1,36) = 38.1$, $p < 0.001$, with faster responses for congruent stimuli than for incongruent stimuli.

There were two-way interactions between Material and Level, $F(1,36) = 18.2$, $p < 0.001$, showing that the difference in response times between global and local targets was larger for non-letter shapes than for letters, as well as between Material and Congruency, $F(1,36) = 7$, $p = 0.012$, showing that the Congruency effect was larger for letters than for non-letter shapes. In addition to this, we observed a three-way interaction between Material, Level and Congruency, $F(1,36) = 6.7$, $p = 0.014$, showing that the Congruency effect differed between letters and non-letter shapes, depending on whether participants were asked to respond to the global or the local level. Due to the three-way interaction, we then analyzed the data separately for letters and for non-letters.

For non-letters, participants responded faster to congruent compared to incongruent targets, $F(1,36) = 7.4$, $p = 0.01$ (congruence effect), and to global compared to local targets, $F(1,36) = 54.4$, $p < 0.001$ (global advantage effect). We obtained an interaction between target level and congruency, $F(1,36) = 5.5$, $p = 0.025$, with greater interference from the global level when participants attended to the local level, $t(36) = 3$, $p = 0.005$, but no interference from the local level to the global, $t < 1$, $p = 0.9$ (asymmetric congruence effect).

For letters, there was a main effect of Congruency, $F(1,36) = 26.5$, $p < 0.001$, with slower responses to incongruent compared to congruent targets (congruence effect). This effect did not differ depending on the level of the target, $F(1,36) = 2.6$, $p = 0.118$, and there was interference both from the local level when attending to the global targets, $t(36) = 5.1$, $p < 0.001$, as from the global level when attending to the local targets, $t(36) = 2.9$, $p = 0.006$.

DISCUSSION

We investigated the GPE for Navon's (1977) compound figures, i.e., *global advantage* in combination with an *asymmetric congruence* effect, comparing letters and non-letter shapes, which were expected to differentiate in their GPE. We used a variant of the classical Navon-paradigm, with central presentation and without positional uncertainty, and a specific combination of visual angles for the local and global level of the stimuli.

Central presentation was used, because we were interested in emulating the conditions of reading on the global–local task.

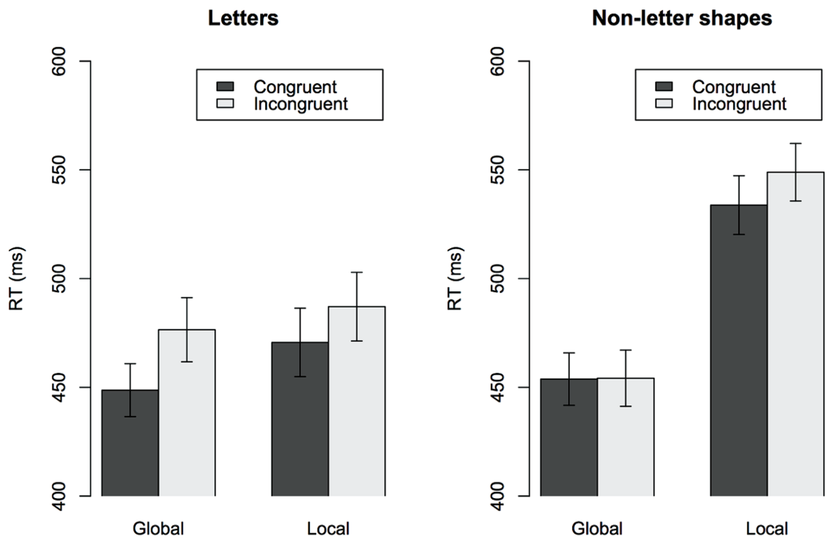

FIGURE 2 | Mean RT in ms for letter stimuli (left side) and non-letter stimuli (right side) for congruent and incongruent trials in the local and global trial blocks.

In reading, graphemic (phonological), morphological or lexical decoding and identification is limited to what is centrally present during a fixation, typically a word (see Pollatsek, 1993, for an overview), as can be demonstrated in eye-movement studies using gaze- contingent display change techniques (Rayner et al., 1986). Thus, central presentation is a necessary condition for the expected differentiation between letters and non-letters to occur (Plomp et al., 2010). This is consistent with the fact that for peripheral presentation the GPE is robust for non-letters and for letters alike.

For compound figures presented centrally a survey of the literature confirmed that we would be most likely to observe a letter-specific effect, if we chose a stimulus dimensions that are typically encountered in reading. For the local level we imposed a scale of stimuli of about 0.5° of visual angle, close to the critical threshold for fluent reading (Legge et al., 1985; Jordan and Martin, 1987). For the global level, we expected it to fall within the functional visual field (Sanders, 1970). These dimensions are consistent with previous observations on the GPE, which has been reported to disappear under those conditions. However, to our knowledge, we are the first to report for these specific dimensions a comparison between letters and non-letters, the choice of which is motivated by our theoretical assumptions about the role of letter-specific processing as a consequence of automatized reading skills.

In the present study, we obtained under these conditions a differentiation in the GPE between letters and non-letters: The GPE remained intact for non-letter stimuli but disappears for letters; for letters there is no general advantage for global stimuli (no global advantage effect) and the congruence effect is independent of local–global target level (no asymmetric congruence effect). Since the "forest before tree" effect vanished only for letters, we may consider it likely that a letter-specific strategy is applied to these stimuli.

The emergence of a letter-specific strategy is in accordance with earlier studies, in which skilled readers used a specific processing strategy for encoding letters (Lachmann and van Leeuwen, 2004, 2008a; van Leeuwen and Lachmann, 2004), while illiterates did not (Lachmann et al., 2012; see also Fernandes et al., 2014). This letter-specific processing strategy was described as more analytic than for non-letter shapes, for which processing may be called holistic. Consequently, the results suggest that the differentiation of holistic processing for non-letters versus analytic processing of letters can be extended to compound figures, as long as the stimulus dimensions invite a reading-specific strategy.

We do not wish to claim that our conditions closely resemble those of reading. The dimensions of our hierarchical letters are similar to single letters embedded in whole words, but the latter mostly involve different rather than uniform letters, and larger variety at the level of the whole, not to mention lexical, sentence and overall semantic context. Nevertheless, these results may be considered as a small but important step in extending our earlier results to contextually embedded letters.

Comparisons between letter and non-letter stimuli in Navon-local-global settings have rarely been made. For peripheral presentation, Dulaney and Marks (2007) found a GPE for both stimulus categories, as we would expect, since the analytic mode works only with central presentation. Peresotti et al. (1991) presented letter and non-letter stimuli both centrally within a variant of the Navon-local-global design, in order to investigate certain aspects of the time course of information processing (in particular, at what stage the GPE occurs, the perceptual or the decision level, Miller, 1981; Navon, 1981b). To this aim it was sufficient to have "letters vs. non-letters" as a variation only at the global level. Their study, therefore, did not involve a *systematic* comparison of the GPE in letters and non-letter shapes. For central presentation, this has, to our knowledge, only been done in a study by Poirel et al. (2008b) and an EEG follow-up (Beaucousin et al., 2011).

Their results seem to contrast with ours. The main distinction these authors obtained was between meaningful (both letters and non-letter objects) and meaningless material (random scribbles). They found that the global level of hierarchical stimuli was always processed faster than the local level (global advantage), irrespective of meaningfulness; however, the *asymmetric congruence* effect (exclusive global-to-local interference), was restricted to meaningful stimuli only. This latter category included both meaningful objects and letters.

However, Poirel et al. (2008b) used a relatively large visual angle: for local items $>1°$ (height) and for global items >11 (width). In the present study, local and global targets were approximately half those respective sizes. In other words, the local level letters are beyond the optimal size for reading (Legge et al., 1985) and thus for the analytic strategy, whereas the global level exceeds the functional visual field (Sanders, 1970; Motter and Simioni, 2008). In this respect, the results of Poirel et al. (2008b) do not contradict to our approach. Parts of their results do not fit, however, with the earlier studies in this field, which found no GPE for letters with the visual angles used by Poirel and his associates (Kinchla and Wolfe, 1979; Lamb and Robertson, 1990; Luna et al., 1995).

A possible reason for this discrepancy in the literature may be that, at least for letters, GPE effects also depend on the task. Poirel et al. (2008b) involved target detection; most tasks in the literature involved target discrimination. The latter may be more likely to elicit analytic processing. In our previous studies we observed task-dependency using a variety of target discrimination tasks. These tasks, however, used flankers (Eriksen and Eriksen, 1974): letters or non-letters were presented in isolation or surrounded with a non-target shape, which could either be similar (congruent) or different (incongruent) in form. Non-letters were classified faster if the target and its surrounding were form-congruent (e.g., a pseudo-A surrounded by a triangle) as compared to when they differed in shape, i.e., when both were form-incongruent (e.g., a pseudo-A surrounded by a square). We reasoned that non-letter shapes are processed in a holistic mode, in which the central target was perceptually bound to its surrounding. For letter targets no such effect was found in normally reading adults (Lachmann and van Leeuwen, 2004, 2008a). Thus, while non-letter processing generally benefits from surrounding flankers if their surrounding shapes are congruent, letters do not (see also Fernandes et al., 2014). This implies that the surroundings were perceived as separate from the letter target.

In the flanker tasks, in some cases an effect even opposite to congruence occurred with letters (van Leeuwen and Lachmann, 2004); letters are categorized faster when surrounded by an incongruent non-target (e.g., An "A" surrounded by a square) than when the non-target was congruent (e.g., An "A" surrounded by a triangle) – a *negative* congruence effect. This effect occurs because the surrounding context undermines the preferred mode of processing and is therefore actively suppressed; this, presumably, is harder when the surrounding is congruent to the target (Briand, 1994; van Leeuwen and Bakker, 1995; Bavelier et al., 2000). In van Leeuwen and Lachmann (2004), letters in *in*congruent surroundings were processed as efficiently as letters in isolation. Therefore the negative congruence effect suggests that congruency can selectively weaken the analytical processing mode; congruent configurations are, by definition, better Gestalts, and their processing as global wholes will therefore be more difficult to suppress. We may call this "overexpression" of the analytical processing mode: it may sometimes occur habitually, even if it is not optimal for the task.

Whereas in Fernandes et al. (2014), the differentiation in flanker effects was found to be underdeveloped in dyslexic children, in Lachmann and van Leeuwen (2007) it was overexpressed in a subgroup of dyslexics. As this illustrates, the symptom does not necessarily equal the underlying cognitive deficit (Frith, 2001). The observed emphasis on analytic processing may well be the result of a coping strategy; perhaps encouraged by their remedial teaching environment. In analogy to the acoustic domain, where deficient phonological awareness may be a symptom of an underlying, in this case, acoustic deficit (Vandermosten et al., 2010; Groth et al., 2011; Steinbrink et al., 2012), there may likewise be an underlying deficit for the visual domain. We suggest that this deficit is manifested in habitual less-than optimal usage of the analytic strategy.

The flanker studies, in which the visual angle was between 2.6 and 3.5 for the targets, and between 5.2 and 8° for their irrelevant surroundings (Lachmann and van Leeuwen, 2004, 2007, 2008a,b; van Leeuwen and Lachmann, 2004; Jincho et al., 2008), offer insight in the question why normal readers would adopt an analytic mode for letter discrimination in reading. In distinguishing letters, component features are important rather than their global shape distinctions. In van Leeuwen and Lachmann (2004) we varied the task in the following way: one version in which for instance, the response alternatives involved a decision on component features (Category 1 = "A" or "circle" versus Category 2 = "C" or "triangle") versus one in which response alternatives were based on global shape (Category 1 = "A" or "triangle" versus Category 2 = "C" or "circle"). Whereas the former reproduced the negative congruence effect for letters as opposed to a congruence effect for non-letters, congruence effects were obtained for both letters and non-letters in the latter condition. The upshot is that the preference for analytical strategies is functional and independent of the physical stimulus characteristics. It occurs if the task either requires or benefits from such a letter-specific processing mode and, sometimes, manifests itself even when it is not beneficial for the task, since reading has made this mode habitual for letters, such that it cannot always be suppressed (Lachmann and van Leeuwen, 2007). Thus, it is the reading-specific processing mode that makes the perception of letter special, not their configurational properties (e.g., symmetry) as such; neither their omnipresence, nor the fact that we are extensively trained to decode them.

The present results are consistent with our flanker studies, in suggesting that there is a strategic preference for analytic processing in letters, and that this preference may be context-sensitive and at the same time habitual. According to this reasoning, a notable discrepancy might seem to arise: in the flanker studies analytic processing leads to the decrease of congruence effects, or even their reversal; in compound stimuli it results in an increase in congruence effects, as these now occur both ways between the local and global levels. However, this discrepancy might be only apparent: the flanker congruency effects are clearly of perceptual origin (Boenke et al., 2009) and result from spurious feature binding. Whereas event-related potentials studies have found these processes to coincide with the GPE effect around 200 ms (Han et al., 2003), others have shown the GPE to arise earlier, i.e., around 100 ms, and thus to be of sensory origin (Proverbio et al., 1998). We may assume the latter without compromising our assumption that the effects of analytic processing of letters are context-dependent.

Context-dependency of analytic processing is not confined to letter studies only. When the task is to detect a part of a jigsaw puzzle piece that would prevent it to fit with another piece (Hogeboom and van Leeuwen, 1997), as long as the pieces are not too complex the global symmetry of the pieces influences the detectability of the target, meaning that perception is holistic. With increased complexity, the global symmetry is ignored, i.e., perception is analytic, and the parts of the figure are scanned in a serial manner (for a similar distinction, see Roelfsema and Houtkamp, 2011).

We believe it is not stimulus complexity per se that determines strategy. Task difficulty can be another factor. The Indian illiterates in Lachmann et al. (2012) performed the flanker task analytically for both letters and non-letters. They used analytic processing, in spite of having had minimal exposure to Western culture and education, known to promote context-free processing (Ventura et al., 2008b). This may illustrate our claim that analytic processing is a resident skill, not something acquired during training. The illiterates used analytic processing for both letters and non-letters because both are unfamiliar and the task, therefore, is rated to be difficult. This is reflected by very high RT of the illiterates as compared to skilled readers.

Task requirements can be another factor in whether perception is holistic or analytic. We discussed an example (van Leeuwen and Lachmann, 2004) where in the flanker experiment the task requirements invoked a shift from analytic to holistic processing in letters. Clearly, the ability to process letters holistically is not lost as a result of having learned to read (e.g., Borst et al., 2014). Likewise, switching to an analytic processing strategy for non-letters remains possible. With non-letter shapes only, in a part-whole detection task, presenting another part as preceding context can prime a certain configuration. This effect also depends on the task: when for the same figures the task is changed, such that no longer the part-whole structure but only a figural detail is relevant, the perceptual strategy becomes analytic and the preceding context is ignored (Stins and van Leeuwen, 1993). The observation that task requirements led to a shift between holistic and analytic processing may explain why the results by Poirel et al. (2008b) stand aside from the other studies in the literature: compared to their studies the latter may be seen as having a greater emphasis on analytic processing.

GENERAL CONCLUSION

Reading is a secondary process and its acquisition involves long-lasting and gradual procedural learning (Fawcett, 2002; Lachmann, 2002; Nicolson et al., 2010), during which already established visual and auditory functions are recruited and modified in a way to guarantee fast and accurate decoding of orthographic symbols. This involves the recruitment of processing strategies optimal for reading, and getting these optimally coordinated (Lachmann, 2002). Once functional coordination is optimized, the coordinated skill gets automatized (Fawcett, 2002; Lachmann, 2002). All this takes about 3–4 years (Rayner and Pollatsek, 1989; Lachmann and van Leeuwen, 2008b). As a result, letters are detected and processed automatically in a cross-modal fashion (Blomert, 2011); the specific set of fine-tuned processing strategies is habitual activated whenever it comes to situations of reading or to tasks where letter-specific processing makes sense. As a consequence, information processing in these situations is very fast and still accurate. Suboptimal functional coordination and its subsequent automatization, however, may lead to reading disability (Badian, 2005; Rusiak et al., 2007; Lachmann et al., 2009; Blomert, 2011; Perea et al., 2011; Perea and Panadero, 2014).

The automatization of letter-specific processing while learning to read seems not to result in losing any perceptual skills, but in acquiring habits that sometimes lead to suboptimal performance on certain tasks, for instance ones involving symmetry in letters (Lachmann and van Leeuwen, 2007). If reading involves the build-up of abstract or cross-modal letter codes, from which phonological information can readily be accessed, holistic information can interfere, and is therefore better ignored or, when needed, actively suppressed. For letters, the relevant context is not the level of graphemic representations of other letters, but their cross-modal encodings and the lexical items of which they are part.

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Developmental changes in reading do not alter the development of visual processing skills: an application of explanatory item response models in grades K-2

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Visual processing has been widely studied in regard to its impact on a students' ability to read. A less researched area is the role of reading in the development of visual processing skills. A cohort-sequential, accelerated-longitudinal design was utilized with 932 kindergarten, first, and second grade students to examine the impact of reading acquisition on the processing of various types of visual discrimination and visual motor test items. Students were assessed four times per year on a variety of reading measures and reading precursors and two popular measures of visual processing over a 3-year period. Explanatory item response models were used to examine the roles of person and item characteristics on changes in visual processing abilities and changes in item difficulties over time. Results showed different developmental patterns for five types of visual processing test items, but most importantly failed to show consistent effects of learning to read on changes in item difficulty. Thus, the present study failed to find support for the hypothesis that learning to read alters performance on measures of visual processing. Rather, visual processing and reading ability improved together over time with no evidence to suggest cross-domain influences from reading to visual processing. Results are discussed in the context of developmental theories of visual processing and brain-based research on the role of visual skills in learning to read.

Keywords: visual motor integration, visual processing, reading development, language based reading predictors, early reading skills

INTRODUCTION

Reading, an everyday task that is essential to success, is a complex developmental activity. Reading is interwoven with other developmental tasks such as attention, memory, and language. Researchers who focus on the cognitive aspects of learning to read have posited numerous theoretical models to describe the process. The simple view of reading (SVR: Gough and Tunmer, 1986) is one popular theoretical framework that stipulates that reading consists of two components: decoding and linguistic comprehension. The model is silent about the complex processes that enable decoding and linguistic comprehension, which together have been the focus of much reading research over the past 30 years. It is generally accepted that the decoding aspect of the model is itself developmental, building from foundational skills in the phonological code to more advanced reading skills that incorporate orthographic processes and automaticity in execution of decoding routines that together allow the reader to rapidly access word-level information encoded in print. The linguistic comprehension aspect of the model encompasses the reader's ability to rapidly retrieve the meanings of words and deduce both sentence- and discourse-level interpretations. The Construction-Integration model of van Dijk and Kintsch (1983) and the Landscape Model of van den Broek et al. (2005) are two of the most widely cited cognitive models for explaining how readers make sense of text, i.e., for elaborating the cognitive and linguistic processes involved in the linguistic comprehension component of the SVR. However, these models largely describe the process of skilled reading and are not generally recognized as developmental models of reading. That is, they do not attempt to capture the quantitative and qualitative changes that characterize reading as individuals develop from non-readers, to individuals learning to read, and ultimately to individuals reading to learn.

What we know about how children learn to read is well documented. Children must learn the alphabetic principal in order to become proficient readers (see Adams, 1994; Snow et al., 1998; National Institute of Child Health, and Human Development [NICHD], 2000 for a comprehensive review of the syntheses of the research). The skills consistently found essential for students to learn are often categorized into five main areas: phonemic awareness, phonics, vocabulary, fluency, and comprehension (National Institute of Child Health, and Human Development [NICHD], 2000). Several reports and books have compiled the research into easily accessible readings for educators, parents, and researchers. A review of three separate meta-analyses (Hammill, 2004) was conducted to determine the abilities most highly related to reading achievement. This review found that the three prior meta-analyses were consistent with the research reviewed by the National Research Council committee on early reading problems, which was headed by Snow, Burns, and Griffin, and the National Institute of Health's National Reading Panel. These reports are noteworthy for many reasons, but especially in the context of the present study for what they conclude about the relatively minor role played by visual processes in learning to read.

Peer reviewed research on the developmental trends relating reading ability to changes in visual processing as measured by tests of visual motor integration can be traced back to the 1960s. Much of this research has been correlational in nature and has found limited evidence of a role for visual processing in explaining individual differences in reading acquisition (Birch and Belmont, 1965; Beery, 1967; Busch, 1980; Wright and DeMers, 1982; Margolese and Kline, 1999). On balance these studies have reached similar conclusions which point to a limited role for visual motor skills in reading achievement, and a much stronger role for language based measures such as letter names and sounds, vocabulary, phonological skills, and language comprehension.

More recent research has found evidence that learning to read might alter individuals' processing of visual information. Research coming out of numerous laboratories engaged in functional magnetic resonance imaging (fMRI) has provided compelling evidence that the acquisition of reading may alter specific brain areas involved in the processing of visual information, including words and faces. For example, Olulade et al. (2013) investigated relationships between brain activity in area V5/MT during visual motion processing and reading ability by providing a group of dyslexic children with a phonologically based reading intervention. Using within-person controls, Olulade et al. (2013) found that exposing dyslexic children to the reading intervention resulted in better reading performance and greater activity in area V5/MT during visual motion perception. The authors concluded that reading acquisition has a positive influence on visual development, as demonstrated by the increase in right V5/MT activity after reading gains in children with dyslexia. In another similar study, using fMRI, Dehaene et al. (2010), measured the effect of reading performance on visual responses in the visual word form area (VWFA) – a specific brain site in left occipito-temporal cortex, which has been identified in numerous studies using fMRI and magneto encephalography to change following reading intervention in poor readers (see Pugh et al., 2000; Papanicolaou et al., 2003). Dehaene et al. (2010) reported that literacy enhanced left fusiform activation, and also broadly enhanced visual responses in fusiform and occipital cortex, extending to area V1. Simply put, these findings suggest that learning to read strengthens cortical networks for vision and language. Furthermore, the findings replicated other studies using brain neuroimaging in normal and dyslexic children to show that, with reading acquisition, the VWFA, starts to respond to orthographic stimuli in the learned script (Shaywitz et al., 2002; Maurer et al., 2006).

While these studies provide valuable insight into the relationship between reading and vision, there are several important features to these studies that must be kept in mind in considering whether learning to read affects visual processing skills. First, many studies that have examined brain related changes to learning to read have either compared dyslexic individuals to typical readers, have studied changes in dyslexic individuals following reading intervention, or have compared readers and non-readers. That is, none of these studies have examined, longitudinally, changes in the brains of typically developing individuals as they have learned to read over an extended developmental period. While it is compelling to generalize the changes seen in the brains of dyslexic children as they learn to read to changes in the brains of typically developing children as they learn to read, doing so requires that we ignore, or at least treat as immaterial, the differences between children with and without dyslexia that exist prior to the onset of reading intervention. Additionally, even if one accepts that the changes/differences observed in these studies generalize to typically developing individuals as they learn to read, the question remains whether these effects seen via brain imaging techniques have consequences at more macro levels of behavior. That is, do these changes that result from learning to read impact how individuals process visual information on educational and neuropsychological tests.

The current study attempts to answer this latter question. That is, the current study explores the impact of the development of early reading skills on the visual processing skills of children as measured on standard educational and neuropsychological tests of visual discrimination and visual-motor processing. To examine this question, we must take into account that both reading and visual processing skills evolve as children mature. The development of reading progresses from early manipulation of the sound structure of language to acquisition of the alphabetic principle (i.e., the bi-directional mapping of sound to print and print to sound), to the development of accurate and fluent decoding and comprehension. Likewise, visual discrimination and visual motor skills are not static, but develop throughout childhood.

THE SEQUENCE OF DEVELOPMENT OF VISUAL MOTOR SKILLS

Children acquire the ability to copy figures in a predictable order from circles to squares to triangles and diamonds at ages three, four, five, and seven, respectively (Rand, 1973). Other features of visual stimuli to which children develop sensitivity as their visual skills develop concern the orientation of stimuli, their visual complexity (i.e., their richness in detail), and their angularity (Beery, 1968a,b). These features have received varying degrees of attention in research on the development of visual, and visual-motor skills. For example, stimuli are known to be more difficult to process for children when they are presented at an oblique orientation, rather than vertically or horizontally (Gibson et al., 1962; Beery, 1968a; Appelle, 1972). Similarly, increasing the complexity of visual stimuli (i.e., increasing the number of sides and angles) increases the difficulty that children have in recognizing, reproducing, or matching them. Angularity also affects the difficulty of visual stimuli, with more acute angles creating greater difficulty for children (Graham et al., 1960), although Beery (1968a) has found that acute angles (especially 45°angles) are overestimated, whereas obtuse angles (especially 135°angles) are underestimated (Piaget, 1949). Moreover, Beery (1968a), has shown that these features interact in their effects on children's ability to process visual information.

Researchers have also used advanced psychometric modeling techniques, such as factor analysis, to investigate the development of visual motor skills (Polubinski et al., 1986; Brown et al., 2009). Unfortunately, neither of these studies examined differences in children's performance or differences in the factor structure of tests as children transitioned from being non-readers to readers, or from being beginning readers to skilled readers. If the development of reading affects the processing of visual information, it stands to reason that children's status as readers might affect how they approach items on a test of visual discrimination or visual-motor integration (VMI) such as the recognition–discrimination test or the Beery VMI. Whether this change in processing would manifest itself as differences in the factor structure/dimensionality of the test or as shifts in the difficulty of test items is not clear. Certainly, changes in the factor structure/dimensionality of a test as a function of changes in students status as readers cannot be explained as simple shifts in the ability distribution of the latent ability measured by the test of visual discrimination or visual-motor skill, whereas changes in item difficulties suggest that performance on test items is changing as a function of the change in status, but not necessarily the nature of the thing being measured.

The present study evaluated the role of reading in the development of visual processing skills using a large longitudinal data set and advances in psychometric/statistical modeling known as explanatory item response models (de Boeck and Wilson, 2004) to examine changes in visual processing associated with learning to read. Using explanatory item response models, discussed below, this study expects to show that phonological skills and the development of phonological awareness (PA), which anticipate the onset of reading acquisition, do not influence performance on test items measuring visual processing skill, either directly, or through interaction with item features that serve to explain item difficulties for visual processing items. It is also expected that measures of rapid naming, decoding, decoding fluency, and spelling, which is closely tied to the development of automated decoding skills, will be most influential in explaining item difficulties of visual processing items, and to predict changes in item difficulties over time, as well as to explain changes in the effects of item features on item difficulty that occur with development of reading. This paper will examine the role of reading acquisition on the development of visual processing skills in a unique and novel way on a rare longitudinal dataset. The use of explanatory item response models allows us to uniquely study the interplay of task demands, as measured by item features, and student characteristics, as measured by time varying covariates of reading and reading related skills, to understand how the development of reading affects the development of visual processing as measured by standard educational and neuropsychological tests.

THE EXPLANATORY ITEM RESPONSE MODELS

Application of explanatory item response models to analyze item level data has gained significant interest among psychometricians, statisticians, and educational researchers over the last decade. The models became popular because of their focus on explaining item responses on a test in terms of: (a) the effects of person characteristics on person abilities (θ_p – one's location on a latent trait continuum), as well as (b) the effects of item features on item difficulties (β_i – difficulty of an item designed to measure some latent ability; de Boeck and Wilson, 2004). In other words, these models attempt to jointly explain a person's position on the ability dimension as a function of person characteristics, and an item's position on the difficulty dimension as a function of item features. Consequently, external variables explain individual differences in responses to test items through their influence on ability and item difficulty. In many applications, one-parameter (1PL) variants of the explanatory item response models are preferable over other item response models [e.g., two-parameter (2PL) or three-parameter models (3PL)]. The 1PL model constrains the relationship between item performance and ability, referred to as item discrimination, to be the same for all test items and allows item difficulty to vary across items. Thus, items differ from one another only in terms of how difficult they are. Placing a constraint on the discriminability parameter carries important implications for interpretation of the unknown parameters and scoring of the test. Specifically, the restriction implies that the test is unidimensional, measuring a single latent ability, and further implies that the number of correct item responses is a sufficient statistic for person ability, that is, there is a one-to-one mapping between the number correct and person ability. The 1PL model also implies that the probability of correctly answering a more difficult item can never exceed the probability of correctly answering an easier item for individuals of any given ability level. The same is not true for the 2PL and 3PL.

Although the models are quite complex, they can be understood as a multivariate extension of multiple (logistic) regression with dichotomous outcomes. The multivariate extension allows us to capture variation across items within a test and time point as well as variation within and between items that occur in conjunction with development (i.e., change over time). In the current project, application of the 1PL explanatory item response models allowed us to model changes in responses to test items as a function of development and, particularly as a function of changes in person characteristics related to learning to read. That is, we used explanatory item response models to explain variability in item difficulties, in terms of item features, person characteristics, and their interactions over the developmental period where children learn to read from the beginning of kindergarten to the end of second grade in the U.S. If learning to read affects children's processing of visual information, then these effects should be evidenced by interactions between measures of reading and time in the explanation of item difficulties, that is, the influence of the reading measures on item difficulties will change over time.

MATERIALS AND METHODS

PARTICIPANTS

The sample of the current study was drawn from a longitudinal study of students' development of reading and reading precursor skills (Boscardin et al., 2008). The original project focused on developmental patterns of early reading skills and whether models of individual growth could identify children who were at-risk for the development of reading problems. The current study involved 932 students enrolled in regular educational programs at three elementary schools in the same district in a metropolitan area in Texas. Students were excluded from participation due to severe emotional problems, vision difficulties that were uncorrected, hearing loss, neurological disorders, and lack of proficiency in English as measured by the school district. Students were enrolled in the project beginning in Kindergarten, grade 1, or grade 2 and followed through the end of grade 2. Thus, children enrolled in Kindergarten were followed for 3 years whereas students enrolled in grade 2 were followed for 1 year. Each student was assessed on a variety of reading and reading precursors four times per year (October, December, February, and April) for the duration of their time in the study. Thus, students enrolled in kindergarten were tested as many as 12 times over the course of their participation, whereas children enrolled in grade 2 were tested up to four times on the reading precursors and reading measures. In addition, children were also administered a standardized achievement and intellectual assessment in May of each year at the end of Grade 1 and Grade 2. The mean ages of the students were 5.86 years (SD = 0.36) for the kindergartners, 6.92 years (SD = 0.38) for Grade 1, and 7.98 years (SD = 0.42) for Grade 2. **Table 1** provides the ethnicity and SES for the sample. Socioeconomic status (SES) was measured using the Hollingshead (1975) Four Factor Index of Social Status. This index combines information on mothers' and fathers' education and occupation status.

MEASURES

The measures assessed from October through April signified constructs thought to be important in the development of early reading skills, which was the focus of the original study that guided the design and data collection strategy. The measures used in this study can be categorized into: (a) visual motor and visual discrimination, (b) precursor and reading-related skills, and (c) norm referenced achievement and intelligence measures. Although in the original study these latter measures were included as possible predictors of reading acquisition and reading problems, in the present study they serve as the outcomes of interest.

VISUAL MOTOR AND VISUAL DISCRIMINATION

Visual-motor integration (VMI)

Visual-motor abilities (specifically VMI) were assessed using the Beery Test of Visual Motor Integration (VMI third edition; Beery, 1989). This instrument is a paper and pencil test, which required students to copy 24 geometric line drawings of increasing difficulty without using erasures. All students start with the first item and continue until a ceiling of three consecutive failures is reached. Inter-rater reliability has been reported at 0.93 with a median split-half reliability of 0.79. This measure was administered from kindergarten through Grade 2. The raw scores range from 0 to 24.

Table 1 | Demographic characteristics of the sample.

		N	%
Gender	Male	468	50.21
	Female	464	49.79
Ethnicity	Caucasian	469	50.32
	African American	161	17.27
	Hispanic	152	16.31
	Asian	141	15.13
	Other	9	00.97
SES	Lower	66	07.08
	Working	356	38.20
	Middle–upper	405	43.45
	Not provided	105	11.27

Recognition–Discrimination (RecDis)

Perceptual discrimination, measured by the Recognition–Discrimination Test (Satz and Fletcher, 1982), is a visual perceptual (matching) task. The students are required to identify a geometric stimulus design differing among a group of four figures, three of which were rotated and only one, the target, was similar in shape to the stimulus figure. The test is timed, and has three practice items and 21 test items. This instrument was included in this study as an additional non-linguistic measure since it is motor free, has good reliability (Kuder–Richardson coefficient of 0.94), and has demonstrated good predictive validity for reading group classification throughout elementary school (Satz et al., 1978). This measure was administered from kindergarten through Grade 2. The raw scores range from 0 to 21.

PRECURSOR AND READING-RELATED SKILLS

Phonological awareness (PA)

Phonological awareness was measured using a prepublication version of the Comprehensive test of phonological processes (CTOPP; Wagner et al., 1999). For this study, students' PA was estimated based on an item response theory (IRT) model involving six of the seven subtests in the battery. The seven subtests included *blending onset and rime*, *blending phonemes into words*, *blending phonemes into non-words*, *first-sound comparison*, *phoneme elision*, *phoneme segmentation, and sound categorization.* According to Schatschneider et al. (1999) the sound categorization subtest provided little information about PA since it did not discriminate well between students at different ability levels. Therefore, this subtest was excluded from the study when estimating students' PA scores. Internal consistency estimates for the subtests as reported by Wagner et al. (1993) ranged from 0.71 to 0.87 over the subtests, and estimates calculated in the present study ranged from 0.85 to 0.95. Instead of using raw total scores of phonological ability, scores were expressed as IRT-model-based estimates of each student's latent phonological ability to represent PA with a mean of 0 and SD of 1. These measures were administered from kindergarten through Grade 2.

Rapid serial naming (RAN)

Rapid naming was assessed through administration of Denckla and Rudel's (1976) Rapid Automatized Naming (RAN) tests for objects and letters. The task requires children to name familiar objects or letters within a set time. The Rapid Naming of Object (RNO) task consisted of line drawings of common objects (i.e., flag, drum, book, moon, and wagon); the Rapid Naming of Letters (RNLs) task consisted of high-frequency lower-case letters (i.e., a, d, o, s, and p). For each task, the stimuli consisted of two practice items and five test items repeated 10 times in random sequences. The child was asked to name each stimulus as quickly as possible.

The correct number of responses named within 60 s was recorded. Test–retest reliability was 0.57 for kindergarten (reflecting variability in true change over this age range) and 0.77 for Grades 1 and 2 (Wolf et al., 1986). Test–retest reliability was 0.87 for RNL and 0.76 for RNO when the test and retest were 2 months apart. In this study, RNO and RNL were administered from kindergarten through Grade 2.

Word reading (WR)

Students were presented a list of 50 words on 3 × 5 index cards. Words were presented one at a time and the student was asked to read each word as it was presented. This measure was administered four times per year, but only in first and second grade. There were 16 words that were included on both the first and second grade test forms. Thus, across the two forms, a total of 84 words were used, with 16 words in common and 34 words unique to grade one and 34 words unique to grade 2. The 50 words on either form included 36 single-syllable, 11 two-syllable, and 3 three-syllable real words. For the present study, word-reading ability was estimated using a 2PL model for the item responses (Hambleton et al., 1991). Scores were expressed as IRT model- based estimates of each student's latent ability and were scaled to have a mean of 0 and SD of 1 across grades 1 and 2. Internal consistency estimates calculated in the present study exceeded 0.90 on all occasions.

Spelling

Children in Grades 1 and 2 were presented the same list of 50 reading words and asked to write them on a sheet of paper. Of the 50 words, 32% had four letters, 40% had five letters, 18% had six letters, and 10% had seven letters. Half had predictable spelling patterns and half had unpredictable spelling patterns. Words were presented alone and in a sentence. The spelling test was administered in a group format in the students' regular classrooms. Words were presented in blocks of 10 over a period of 5 days. All other tests were individually administered. Scores were expressed as IRT-model-based estimates of each student's latent ability and were scaled to have a mean of 0 and SD of 1. Internal consistency estimates calculated in the present study exceeded 0.85 on all occasions for this subtest.

Word reading fluency (WRF)

In the pre-publication version of the Test of Word Reading Efficiency (TOWRE: Torgesen et al., 1999), students were presented with a word list containing 104 words divided equally into four columns. Students were directed to read the words as fast as they could and were given a short eight-item practice list first. Two items were recorded during this reading, the total number of words read and the total number of words read correctly within the 45 s time limit. In order to estimate students' word reading fluency, their total correct score from the word-reading test (WR) was divided by the total time (45 s).

Vocabulary (PPVT)

The Peabody Picture Vocabulary Test–Revised (PPVT-R; Dunn and Dunn, 1981) was administered to assess oral vocabulary levels of children from kindergarten through Grade 2. The PPVT-R is a well-established measure for receptive vocabulary. For this measure, the child is presented with a stimulus word and then shown a set of four pictures. The child is then asked to choose the picture that represents the word.

NORM REFERENCED ACHIEVEMENT AND INTELLIGENCE MEASURES

At the end of Grades 1 and 2, standardized measures of academic achievement and intelligence were administered. For the purposes of this study, the results of the Woodcock–Johnson-Revised subtests and the Hobby short form of the Wechsler Intelligence Scale for Children-Revised (WISC-R) are reported to provide information on the general abilities of the study sample. These measures are not otherwise used in the analyses.

Woodcock–Johnson psycho-educational test battery-revised

The Woodcock–Johnson battery includes several tests for measuring skills in reading, mathematics, and writing, as well as important oral language abilities and academic knowledge. However, only three of the subtests were used for the purpose of this study.

Woodcock letter word identification (WJR:WI)

This measure assesses the child's ability to decode isolated words of varying difficulty. In this subtest, students are required to first identify letters, which are presented in large type, and then to pronounce the presented words correctly (Woodcock and Johnson, 1989).

Woodcock word attack (WJR:WA)

This subtest measures grapheme-to-phoneme translation of pseudo words that are not contained in the lexicon. In this subtest students are required to provide sounds for single letters and to read combinations of letters that follow English orthographic rules but are either low frequency or non-sense words (Woodcock and Johnson, 1989).

Woodcock passage comprehension (WJR:PC)

This subtest consists of three item types and is a general measure of reading comprehension. The first item type has the student match a pictographic representation of the word with an actual picture of the object. The second type provides a multiple-choice format for which the student is asked to point to the picture represented by a phrase. Finally, the student reads a short passage and identifies a missing key word that fits within the context of the passage.

These measures are highly reliable with internal consistency estimates above 0.90 and extensive demonstrations of validity (Woodcock and Johnson, 1989). These subtests are normed to a mean of 100 and a SD of 15 in each grade.

Wechsler intelligence scale for children-revised (WISC-R)

Students were administered the Hobby short form (Hobby, 1982) of the WISC-R (Wechsler, 1974). The WISC-R was standardized on a large sample of children, ages 6.0–16.5 years, stratified for age, gender, race, and SES according to 1970 U.S. census information. Test–retest reliabilities for all tasks ranged from 0.73 to 0.95. The average correlations among Stanford-Binet IQ scores and WISC-R Verbal, Performance, and Full-Scale IQs were 0.71, 0.60, and 0.73, respectively.

Hobby short form

The Hobby short form (Hobby, 1982) was used because of the large number of children participating in the study. While the form contains all the subtests of the WISC-R, the administration is limited to every other item, with raw scores adjusted for the items that were omitted by design. The correlation between IQ scores from the full WISC-R and the Hobby short form are at 0.98 and above (Hobby, 1982; Sattler, 1993).

WISC-R performance IQ (WISCP)

This score reflects non-verbal intelligence as measured by five subtests: Picture Completion, Digit Symbol, Picture Arrangement, Block Design, and Object Assembly.

WISC verbal IQ (WISCV)

This test focuses on language-based skills and includes six subtests: information, similarities, arithmetic, vocabulary, comprehension, and digit span.

DATA ANALYSES

The cross-classified linear logistic test models with separate random intercepts for people and items were used to determine whether variation in item difficulties for test items from the two visual processing measures (VMI and RecDis) could be attributed to developmental growth in reading ability or due to maturation unrelated to reading as reflected simply by students' age. The models had a cross-classified random effects structure to deal with dependencies among the responses to items as these dependencies result from administering all items to all students with all students responding to all items. That is, item responses were cross-classified in persons and items. Specifically, (a) the first-level of the model included responses to items (dichotomous variables coded 0 or 1, where 1 = correct, 0 = incorrect), (b) the second-level included item and person parameters which are crossed in the design. In all models, person and item parameters were random (as reflected by random intercepts), whereas effects of person and item characteristics were fixed.

A hierarchical modeling approach was used to address the study hypotheses. At the first stage, a descriptive model of item difficulties for test items from the two visual processing tests was developed. After that, explanatory item response models were utilized to explain variation in item difficulties and the effects of item features on item difficulties through moderating effects of person characteristics, and changes in person characteristics over time. These interaction parameters that examine changes in the effects of person characteristics over time capture the effects of interest. Specifically, these interaction parameters test whether learning to read changes how children process visual motor and visual discrimination test items. Maximum likelihood estimation based on Laplace approximation was used to estimate all unknown model parameters. All models were estimated utilizing the *glmer* function of *lme4* package in *R* (Bates et al., 2008) as this function is suitable for estimating models with random effects and cross-classified structure.

RESULTS

Table 2 reports descriptive statistics including means and SDs for the achievement and intellectual measures among first and second graders as the standardized achievement and intelligence tests were not administered in kindergarten. **Tables 3** and **4** present descriptive statistics for reading and reading precursor measures with respect to different time points from the beginning of kindergarten through the end of second grade.

Figure 1 presents the pass rates (% correct) for the RecDis and VMI items in Panel A and B, respectively, as a function of item features and time from the beginning of kindergarten through the end of grade 2. The pass rates for VMI and RecDis items were estimated based on the frequencies of correct responses for each item at the 12 time points. Each point on the graph depicts the percentage of correct responses for a particular item at a particular wave of data collection. Also depicted on the figure is the average percent correct across all items, shown in each panel as a star at each time point. The panels show that, for both tests,

Table 2 | Descriptive statistics for achievement and intellectual measures.

Measure	Grade 1		Grade 2	
	M	SD	*M*	SD
Woodcock reading comprehension	105.70	14.84	107.04	14.97
Woodcock letter–word identification	106.83	16.66	107.21	17.09
Woodcock word attack	104.26	15.42	103.53	16.02
WICH performance IQ	111.83	14.60	113.78	14.18
WISC verbal IQ	104.48	14.20	106.66	14.75

A close analysis of the data shows that students' mean performance on all measures has increased across the different time points over a 3-year period. This pattern of finding suggests that students' reading and reading precursor skills develops as a function of age. A close analysis of the data suggests that students' mean performance, with the exception of WJWA, have increased across the grade levels.

Table 3 | Descriptive statistics for kindergarten data collected longitudinally.

Wave	0		1		2		3	
Measure	*M*	SD	*M*	SD	*M*	SD	*M*	SD
VMI	9.3	3.3	10.6	3.8	11.0	3.7	11.9	4.2
Recognition–Discrimination	12.5	3.9	13.8	3.5	14.7	3.2	15.2	3.1
Age in months	67.5	3.7	69.3	3.8	71.3	3.7	73.4	3.7
Phonological awareness	−1.2	0.6	−1.0	0.7	−0.8	0.7	−0.6	0.8
Rapid Naming of Letters	0.5	0.4	0.7	0.4	0.8	0.4	0.8	0.4
Rapid Naming of Objects	0.6	0.2	0.7	0.2	0.7	0.2	0.7	0.2
Vocabulary	55.9	15.0	57.7	14.8	62.0	15.1	64.4	14.6

VMI, Beery visual motor integration.

Table 4 | Descriptive statistics for grade 1 and 2 data collected longitudinally.

Wave	4		5		6		7		8		9		10		11	
Measure	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**
VMI	13.6	4.7	14.1	4.9	15.1	5.2	15.4	5.1	18.0	6.3	18.9	6.9	19.3	7.2	19.8	7.2
Recognition–Discrimination	15.8	2.8	16.6	2.8	17.1	2.7	17.5	2.5	17.6	2.4	18.3	2.1	18.4	2.1	18.8	1.9
Age in months	80.2	4.1	82.0	4.1	84.1	4.1	86.1	4.1	92.9	4.6	94.7	4.6	96.8	4.6	98.8	4.6
Phonological awareness	−0.2	0.7	0.1	0.7	0.3	0.7	0.5	0.7	0.5	0.6	0.7	0.6	0.8	0.7	1.0	0.7
Rapid Naming of Letters	1.1	0.4	1.2	0.4	1.3	0.4	1.4	0.4	1.6	0.4	1.7	0.4	1.7	0.4	1.8	0.4
Rapid Naming of Objects	0.8	0.2	0.9	0.2	0.9	0.2	0.9	0.2	1.0	0.2	1.0	0.2	1.0	0.2	1.0	0.2
Vocabulary	72.3	13.9	74.2	14.4	77.9	14.2	79.7	14.3	86.1	13.8	86.8	13.8	89.9	13.6	91.5	13.6
Word reading	−0.9	0.8	−0.6	0.9	−0.3	0.9	−0.1	0.9	0.3	0.7	0.5	0.7	0.7	0.7	0.8	0.7
Reading efficiency*	0.3	0.3	0.4	0.3	0.5	0.4	0.6	0.4	0.8	0.4	0.9	0.3	1.0	0.3	1.0	0.3
Spelling	−0.9	0.7	−0.6	0.8	−0.4	0.8	−0.1	0.8	0.3	0.6	0.6	0.6	0.7	0.7	0.8	0.7

*VMI, Beery visual-motor integration; *words per 45 s.*

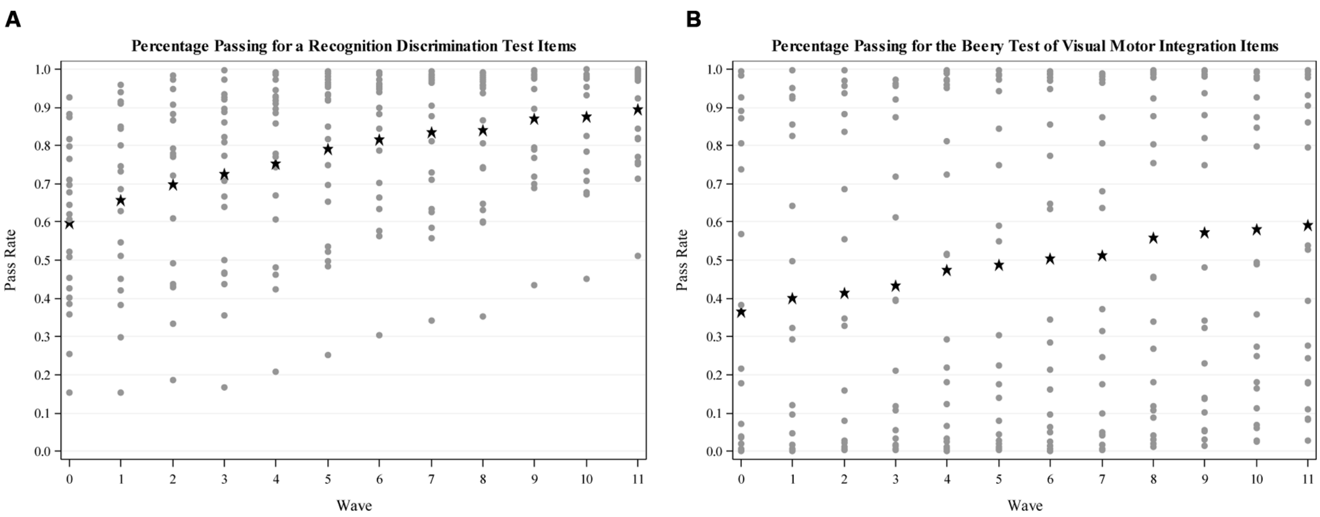

FIGURE 1 | Dot plots demonstrating the percent correct for the Recognition–Discrimination Test (A) and the Beery Test of Visual Motor Integration (B) over time. Dots were used to represent the percent correct for each item at any given point in time. The stars plotted in each panel represent the average percent correct across all items at each wave.

the pass rates were gradually increasing over time indicating the developmental trajectory of visual processing skills. The panels also show that, on average at any given point in time, VMI items were more difficult than RecDis items in that the average percent correct was lower and variation in test scores was greater for VMI items.

These initial findings were further explored using two explanatory item response models to further clarify the features of items that affect item difficulty. In the first model (model 1), wave, item type (VMI vs. RecDis), and the interaction of wave and item type were included as explanatory variables. In the second model (model 2), a more complete classification of item types was included. In particular, we classified items into five categories: (a) motor vs. non-motor, and then further distinguished among four types of motor item, (b) closed geometric designs, (c) closed designs comprised of simple horizontal and vertical lines, (d) open geometric designs with acute and oblique angles, and (e) closed geometric designs having three-dimensional features. This classification of the motor items was based on the theory underlying the development of visual processing skill in children, which undergirds the development of the VMI test. As in Model 1, wave, item type, as well as the interaction of wave and item type were used as explanatory variables.

Figure 2 presents the results for Model 1 and highlights the differential effects of time for the RecDis and VMI test items. The model was estimated to capture any difference in the developmental time course for motor and non-motor visual processing

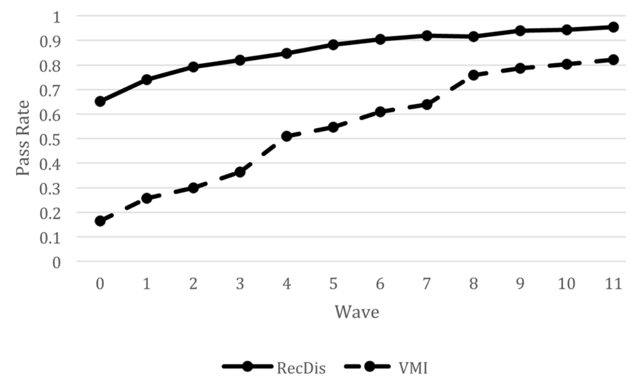

FIGURE 2 | A line plot demonstrating a pass rate for items with and without significant motor demands over time. RecDis, items without significant motor demands; VMI, items with significant motor demands.

items. This figure makes clear that differences between motor and non-motor items in the estimated percent correct from models 1 became smaller across the 12 time points. Although items without motor demands were easier at each wave and became easier over time, the difference between motor and non-motor items became smaller at each wave. That is, the average percent correct was increasing more rapidly for motor-based items than for items without significant motor demands, at least in part because of the overall higher performance on non-motor items. This pattern is not uncommon in learning data, namely that the rate of progress slows as the room for progress diminishes.

Figure 3 presents interactions between item type and wave for RecDis and VMI tests, with VMI items differentiated according to various item features. As mentioned above, we distinguished between motor and non-motor items and further distinguished among motor items representing closed geometric designs, closed designs comprised of simple horizontal and vertical lines, open geometric designs with acute and oblique angles, and closed geometric designs having three-dimensional features. These four distinguishing characteristics of the VMI items were related to increased item difficulty, as is evidenced clearly in **Figure 3**. Specifically, items representing closed geometric designs with acute and oblique angles, or having three-dimensional quality were the most difficult on average. At the same time, items representing closed geometric designs comprised of simple horizontal and vertical lines had a pass rate of nearly 100% indicating very low difficulty for these items. More importantly, the development of visual processing skills varied according to these structural features as evidenced by differences across time in estimated pass rates for items with different features. In particular, the developmental trajectory of visual processing skills was observed to be essentially flat and near 100% for VMI items consisting of closed figures comprised of vertical and horizontal lines. Similarly, the developmental trajectory for VMI items representing closed geometric figures of a three-dimensional nature was relatively flat, but in this case the percent passing for items of this type was essentially zero. The developmental trajectories for RecDis and VMI items comprised of closed designs with acute and oblique angles were almost identical, with slightly higher pass rates for the RecDis items in kindergarten (waves 0–3) and no difference between the two trajectories from wave 4 through 12. Finally, items on the VMI that represented closed geometric designs with acute and oblique angles showed a somewhat different pattern over the 12 waves. For these items, the pass rate increased steadily from about 5% at the end of kindergarten to between 20 and 30% by the end of grade 2.

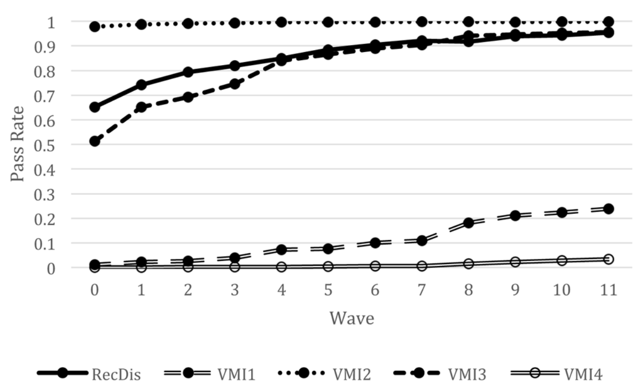

FIGURE 3 | A line plot demonstrating a pass rate for items with different structural features of design over time. RecDis, items representing rotated line drawings; VMI1, items representing closed geometric designs with acute and oblique angles; VMI2, items representing closed geometric designs comprised of simple horizontal and vertical lines; VMI3, items representing open geometric designs with acute and oblique angles; VMI4, items representing closed geometric designs having a three-dimensional quality.

These developmental differences in the pass rates across item types are interesting, but they do not, in and of themselves, indicate that item performance is changing because of the onset of learning to read. To test the primary hypotheses about developmental effects of reading acquisition on visual processing of test items, we ran a series of models looking at the effects of person characteristics on ability estimates, and most importantly, examining interactions between person characteristics, item features, and time. We began with estimating classes of models where reading measures were added to models 1 and 2. Specifically, each reading measure was added individually to the model along with IQ, wave, item type, the two-way interaction of wave and item type, as well as the three-way interaction of reading measure, wave, and item type. We ran models using each of the two ways of coding item type: (a) distinguishing motor (VMI) from non-motor (RecDis) items, and (b) differentiating among the five categories of item just described. These models were computed in order to explain variation in item difficulties and the effects of item features on item difficulties as a function of person characteristics, and changes in person characteristics over time.

Table 5 shows the estimated pass rates at the end of grades 1 and 2 from the set of models just described. These models were estimated using first and second grade data but not kindergarten data because word reading, spelling, and reading fluency were not administered during kindergarten. As can be seen from **Table 5**,

Table 5 | The influence of individual abilities on the probability of correctly answering an item of average difficulty.

Measure	End of grade 1 (Wave 7)		End of grade 2 (Wave 11)	
	PR-LA	PR-HA	PR-LA	PR-HA
Recognition–Discrimination Test				
Phonological awareness*	0.916	0.949	0.947	0.967
Rapid Naming of Letters*	0.930	0.940	0.956	0.966
Rapid Naming of Objects*	0.931	0.940	0.961	0.965
Vocabulary*	0.926	0.947	0.960	0.965
Word reading*	0.922	0.946	0.947	0.965
Reading efficiency*	0.931	0.952	0.955	0.969
Spelling*	0.926	0.946	0.948	0.965
Beery test of visual motor integration				
Phonological awareness*	0.627	0.742	0.732	0.820
Rapid Naming of Letters*	0.674	0.706	0.772	0.812
Rapid Naming of Objects*	0.677	0.708	0.793	0.810
Vocabulary*	0.658	0.735	0.787	0.811
Word reading*	0.652	0.736	0.738	0.815
Reading efficiency*	0.638	0.722	0.736	0.805
Spelling*	0.661	0.732	0.738	0.812

$p < 0.001$; PR-LA, pass rates for students with low ability; PR-HA, pass rates for students with high ability; N = 762. Pass rate is the estimated probability of a correct response on an item of average difficulty on a particular assessment. Models control for performance IQ, wave, item type, wave-item type interaction, and wave-item type-person characteristic interaction. Each model include only one person level characteristic.

these models revealed statistically significant main effects of PA, RNL and objects, vocabulary, word reading, reading efficiency, and spelling over and above other predictors. Most importantly, person characteristics did not interact with wave in a statistically significant way. Students with higher reading and reading related skills performed better on visual processing tests, but these effects did not change with time. In other words, there was a generalized ability related difference in performance on visual processing tests, but this difference did not vary with development, nor did it vary systematically as a function of item type and wave. This pattern of findings is inconsistent with the hypothesis that development of reading changes how students process visual information.

It is important to point out that the models reported in **Table 5** yielded identical findings in terms of estimated passing rates for specific person characteristics regardless of whether item type distinguished only motor items from non-motor items, or distinguished among the different item features depicted in **Figure 3**. This outcome was not surprising as person and item features were included in these models in a manner such that person characteristics explained person ability whereas item features explained item difficulty.

In looking at the effects of individual person characteristics in **Table 5**, it is important to also keep in mind that the models reported in **Table 5** examined the effects of person characteristics individually. Because these characteristics are correlated with one another, the possibility exists that these effects are overlapping and are not unique to the individual predictors listed in the table. To determine which person characteristics exert the largest independent influence on visual processing abilities, we next examined models that incorporated multiple person characteristics simultaneously. These models showed that several of the effects reported in **Table 5** are redundant. Specifically, we found that PA and spelling seemed to exert independent effects over and above the other predictors. That is, once PA ($b = 0.21$, $SE = 0.02$, $p < 0.001$), word reading ($b = 0.08$, SE = 0.04, $p < 0.05$) and reading efficiency were included in the same model, reading efficiency was no longer statistically significant ($b = 0.07$, SE = 0.04, $p = 0.07$). Additionally, the effect of word reading was negligible when spelling ($b = 0.08$, SE = 0.03, $p < 0.05$) was included along with PA ($b = 0.20$, SE = 0.02, $p < 0.001$), word reading ($b = 0.05$, SE = 0.04, $p = 0.13$) and reading efficiency ($b = 0.04$, SE = 0.04, $p = 0.33$). As such, PA and spelling were the most important, unique, predictors of performance on visual processing tests.

Most importantly, although these person characteristics related to visual processing abilities, there was no consistent evidence to suggest that abilities related to reading interacted with item type and wave in their effects on visual processing. Although individual interaction terms were occasionally statistically significant at a nominal alpha level of 0.05, they did not meet the adjusted alpha level set by the False Discovery Rate (FDR) of Benjamini and Hochberg (1995). Note, the FDR is generally regarded to be the most powerful approach to multiple comparisons when many hypotheses are being tested, and is thus preferred in this context over other multiple comparison procedures. It is also noteworthy that the significant interaction effects typically involved a single wave and item feature, and did not reflect a developmental pattern. For these reasons, we conclude that those interactions with significant nominal p-values and non-significant adjusted p-values constituted false rejections/false discoveries and should not be viewed as statistically significant. In that sense, we found no evidence to suggest that reader characteristics interacted with item-type and wave to differentially affect item difficulties as children acquired reading skills. In short, the findings support the idea that visual processing skills are related to the person abilities listed in **Table 5** and uniquely related to PA and spelling, but they are not consistent with the idea that learning to read changes how children process visual information as we found no consistent evidence for differential effects of person characteristics over time.

DISCUSSION

Interest in the role of visual processing in reading is not new and is not surprising. Reading is, at first glance, a visual task when performed by individuals with normal or corrected vision. However, the role of visual processing skills in reading have been found to be relatively minor, in so far as differences in visual processing skills do not explain variation in reading performance once skills related to the linguistic basis for reading have been taken into account. That is not to say that visual skills are unimportant in reading, but that individual differences in visual processing do not account for individual differences in reading performance. In learning to read, children must learn the process for transforming graphical inputs into spoken language. While the visual features of writing systems present some challenges to beginning readers, they pale in comparison to the challenge of abstracting the sound features of a spoken language from the writing system. Indeed, the importance of visual skills in reading has been shown experimentally through eye movement research and studies that control the flow of visual information to the reader (Rayner, 1998). It is without question that vision plays a crucial role in the cognitive processes involved in reading. However, it seems also to be the case that individual differences in visual processing explain little of the heterogeneity in reading acquisition (Fletcher et al., 1999). The present study contributes to research in the areas of visual processing and reading by taking a unique look at how reading contributes to the development of visual processing. The study made use of recent advances in the statistical modeling of item responses through cross-classified random effects models for binary outcomes. Specifically, we applied these models, known as explanatory item response models, in a developmental context during the early acquisition of reading skill to examine the characteristics of individuals that explain visual processing ability, the characteristics of test items that explain item difficulty, and most importantly, to investigate the presence of cross-level interactions between reader characteristics and item features which would signal that learning to read was altering the ways in which students relate to test items measuring visual processing ability. Despite finding significant and substantial effects of various item design features on item difficulty, as well as finding various subject characteristics that related to persons' ability to perform on test items, we found no consistent evidence for the presence of interactions which would have signaled that learning to read was differentially affecting the difficulty of tests items over time.

Rather than suggesting that learning to read altered the measurement of visual processing, results simply suggested that individuals' characteristics as readers explained some of the variability in visual processing abilities, but these relationships were not moderated by development or by item features. Study results were consistent with other research on the developmental sequence of visual motor (VMI) and motor-free (RecDis) visual processing skills in that item difficulty varied according to the type of figure presented. It was also the case that motor-free items (RecDic) were generally easier for students than visual motor (VMI) items. These results corroborate earlier research on the development of visual processes in children, and earlier factor analytic work on the VMI which showed that tests of visual motor performance are not, necessarily, one-dimensional (Polubinski et al., 1986; Brown et al., 2009).

Given that the research literature is sparse in either describing or explaining how phonological abilities and/or reading *per se* affect the processing of visual information, the results of the present study cannot be viewed as definitive. For one, a major limitation of the present study was the focus on operational tests of visual processes, rather than using carefully controlled or precise measures of visual processing that might tie more closely to the neural basis for visual processing skills. It is quite possible that measures of brain cortical activity, or precise measures of speed of processing of visual information might have revealed more subtle effects of learning to read on the processing of visual information, in much the way that research with neuroimaging techniques has found evidence of changes to visual processing areas following the onset of reading. At the same time, the current study employed a large sample and extensive longitudinal follow-up, so it is difficult to attribute the lack of findings to low power, imprecision in estimating item parameters, or limited change in individuals' reading and/or visual processing abilities. Both visual processing and reading/reading-related abilities changed substantially over the 3 years from the start of kindergarten through the end of grade 2. Indeed, students went from being non-readers at the start of kindergarten to being proficient beginning readers over this period, with marked variability across children. Similarly, **Figures 1–3** show that there was marked variability in item difficulty across this developmental period, and that much of this variability related to characteristics of the items.

That variation in item difficulty across waves was not related to variation in person abilities in reading and/or reading precursors over this period suggests that the relationships that have been reported in the literature may reflect a failure to adequately control other common sources of variability, such as maturation or increased efficiency/automaticity in reading and related skills. Work by Dehaene et al. (2010) found that the automatic processing of faces in visual association cortex is subject to competition following the acquisition of reading. However, their electrophysiological findings were not corroborated in that study by behavioral findings suggesting that cognitive performance was negatively impacted commensurate with the eletrophysiological evidence of competition.

Together results from neuroimaging studies are not incompatible with those from the present study and its placement within the broader literature on the potential effects of learning to read on visual processing. Rather, the current findings simply serve to highlight that subtle differences in measures of brain electrophysiology are not always consequential for cognition as measured at more macro levels of organization and execution. The history of neuropsychological assessment is rife with examples of behavioral measures failing to differentiate among individuals with gross brain anomalies. Although prior to the advent of non-invasive imaging, neuropsychological and behavioral assessment were the primary means of differentiating organic from functional disease origins, the challenge of showing behavioral correlates of brain electrophysiology remains substantial and prone to statistical artifacts (Vul et al., 2009). At one level, the problems identified by Vul et al. (2009) reflect a problem of sampling bias that inflates estimated relationships. At another level, the challenge of identifying such brain–behavior relationships is one of scale and the fact that true effect sizes in the behavioral and health sciences are often small, making replication an important, but too often neglected component of research (Ioannidis, 2013).

We fully expected that measures of rapid naming, decoding fluency, and spelling, would be most influential in explaining differences in item difficulties and, more importantly, in explaining changes in item difficulties over time. However, we found no such evidence for either prediction. We expected that, as students became proficient in distinguishing strings of graphemes, or words, with increased fluency, students would also become more proficient in discriminating more complex shapes from one another, and in analyzing and reproducing more complex visual stimuli. Contrary to expectations, higher student reading performance simply meant better performance on visual processing skills, and these effects were consistent over time.

Quite clearly, the study design was capable of detecting effects of person abilities on item parameters. We were able to show differences in item parameters over time as small as 0.09 on the logit scale, a difference of about 2.2% in the percentage of correct responses. Clearly, relatively small effects were discernible in the models given our relatively large sample of over 900 students and the extensive longitudinal follow-up of up to 12 observations per individual. That is not to say that all such differences that were small in size could be detected in the models, as effects in the models were correlated. However, it is clear that, for many item types, there was substantial power for detecting meaningful influences of learning to read on item difficulty over time. The failure to obtain such results consistently implies, at a minimum, that such effects on measures of this type must be small, indeed, if they exist at all.

Models involving PA and spelling as predictors found some evidence that these measures exerted unique effects on visual processing abilities. Although numerous predictors explained some of the variability in person ability, most of these effects were redundant with one another, with the exception of spelling and PA. Spelling may have been predictive of visual motor processing as spelling incorporated motor skills at a level of complexity that paralleled that found in the VMI. For instance, when writing words to dictation, stimuli differ substantially in the writing demands they impose on students. For example, writing the letter 'l' is easier than writing the letter 'm' which is easier than writing the letter 'q.' Importantly, both PA and spelling relate to the internal structure of words, which one might expect to relate more closely to visual processing of features. These two contributors to word recognition are known to contribute to the quality of lexical representations, which fuel efficient decoding processes as articulated in Perfetti's (2007) Lexical Quality Hypothesis (LQH). However, it must also be recognized that, although these measures related to visual processing abilities, they showed no evidence of interacting with item type or wave in affecting item difficulties. This latter point suggests that reading and visual processing abilities are both developing in related ways, but reading abilities do not appear to affect the way that students perform on measures of visual processing. That is to say, children who performed well on measures of reading and reading related skills also performed well on measures of visual processing, and these relations appear to be consistent across the developmental span from the beginning of kindergarten through the end of grade 2 with no indication that reading ability was changing the way in which children performed on the measures of visual processing.

This study set out to review the connection between reading skills as measured by instruments commonly used in academic settings to assess the development of visual motor skill. We did not find evidence that learning to read impacts how children approach these tests. However, it remains possible that findings might differ if alternate measures of visual processing had been used. Measures of sensitivity to information presented extra-foveally or measures of field sensitivity might be expected to show greater influence from learning to read. It is well known that readers process information visually that is outside the area of fixation while reading (Haber and Haber, 1981; Rayner, 1998). Thus, it might be expected that sensitivity to information presented outside the region of primary visual focus would change as children acquire reading. One might predict that while engaged in a reading task sensitivity to the visual features of linguistic information presented extra-foveally would improve as children acquire reading, whereas the same sensitivity might be absent when presented in a non-reading task. This difference would be expected to be smaller for non-readers, and no difference would be expected between readers and non-readers engaged in a non-reading task. Whether effects on visual processing could be obtained on standard paper and pencil tests of visual processing awaits further research, but it seems reasonable to speculate that effects would be more likely to emerge if the visual task more closely approximated reading than either of the current tasks. For example, a task that required individuals to process visually presented information quickly and serially from left to right, or right to left for readers of Arabic and Hebrew, might be more sensitive to learning to read. If such a task could be devised to record responses on a trial by trial basis, then application of the explanatory item response framework could again be used to examine the effects of reader and item features on item performance, and changes in item performance that occur with learning to read (see McBride-Chang et al., 2011). The implications that any such effects might have for teachers and students in school are unclear. However, absent negative effects of learning to read on the processing of visual information in standard educational assessments and tasks, any concern among students, parents, and teachers seems unwarranted.

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A cultural side effect: learning to read interferes with identity processing of familiar objects

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Based on the *neuronal recycling hypothesis* (Dehaene and Cohen, 2007), we examined whether reading acquisition has a cost for the recognition of non-linguistic visual materials. More specifically, we checked whether the ability to discriminate between mirror images, which develops through literacy acquisition, interferes with object identity judgments, and whether interference strength varies as a function of the nature of the non-linguistic material. To these aims we presented illiterate, late literate (who learned to read at adult age), and early literate adults with an orientation-independent, identity-based same-different comparison task in which they had to respond "same" to both physically identical and mirrored or plane-rotated images of pictures of familiar objects (Experiment 1) or of geometric shapes (Experiment 2). Interference from irrelevant orientation variations was stronger with plane rotations than with mirror images, and stronger with geometric shapes than with objects. Illiterates were the only participants almost immune to mirror variations, but only for familiar objects. Thus, the process of unlearning mirror-image generalization, necessary to acquire literacy in the Latin alphabet, has a cost for a basic function of the visual ventral object recognition stream, i.e., identification of familiar objects. This demonstrates that neural recycling is not just an adaptation to multi-use but a process of at least partial exaptation.

Keywords: visual object recognition, mirror images, enantiomorphy, literacy

INTRODUCTION

According to several theories concerning the functional organization of the brain, it is quite common for neural circuits established for one purpose to be *exapted* (Gould and Vrba, 1982) or *tinkered* (Jacob, 1977) during evolution (e.g., the *massive redeployment* hypothesis, Anderson, 2007a,b) or normal development (the *neuronal recycling* hypothesis, Dehaene and Cohen, 2007; Dehaene, 2009), so that they may come to serve a different purpose (see Anderson, 2010, for a review). The neuronal recycling hypothesis is specifically interested in the acquisition of cultural inventions such as reading or mathematics that have emerged too recently in mankind, precluding evolution to have engendered cortical circuits dedicated to these purposes. Consequently, these cognitive abilities have to be learned and must find their *neuronal niche*, namely pre-existing neural systems "that are sufficiently close to the required function and sufficiently plastic as to reorient a significant fraction of their neural resources to this novel use" (Dehaene and Cohen, 2007, p. 384).

Under this hypothesis, cultural learning is generally facilitated by pre-existing cortical properties. In the case of reading acquisition, several characteristics of the ventral visual pathway, including the general properties for invariant object recognition (e.g., Serre et al., 2007; Ullman, 2007), may explain why a subpart of the left ventral visual system, termed the visual word form area (*VWFA*, e.g., Cohen et al., 2000), has been partially co-opted or *recycled* for recognizing the visual shapes of written symbols.

However, it is quite unlikely that all pre-existing cortical properties suit the new, target function. In some cases the acquisition of cultural inventions may require the overcoming of properties that were useful for the original function, but are deleterious for the new one. An example of such an undesirable property for reading acquisition is *mirror-image generalization*, also called *mirror invariance*, namely the tendency to confuse lateral reflections.

Difficulties in differentiating and remembering lateral reflections or *enantiomorphs* have been reported in infants (e.g., Bornstein et al., 1978; Bornstein, 1982), children (e.g., Gibson et al., 1962; Rudel and Teuber, 1963; Cronin, 1967; Gibson, 1969; Casey, 1984; Shepp et al., 1987; de Kuijer et al., 2004), and even adults (e.g., Butler, 1964; Sekuler and Houlihan, 1968; Standing et al., 1970; Wolf, 1971; Farrell, 1979; Nickerson and Adams, 1979; Martin and Jones, 1997; de Kuijer et al., 2004; Rentschler and Jüttner, 2007), for whom long-term priming (with primes and probes separated by several minutes) is unaffected by left-right reflection (e.g., Biederman and Cooper, 1991; Stankiewicz et al., 1998; Fiser and Biederman, 2001). Mirror invariance seems to have been deeply rooted by evolution into the visual system: many animals (e.g., fishes, octopuses, rodents, and monkeys) are also confused by enantiomorphs (e.g., Sutherland, 1960; see a review in, e.g., Corballis and Beale, 1976), and neurons in the monkeys' inferotemporal cortex generalize over mirror reversal (Logothetis and Pauls, 1995; Logothetis et al., 1995; Rollenhagen and Olson, 2000; Baylis and Driver, 2001).

This characteristic of the visual system presumably arose in the course of evolution because most natural visual categories are invariant across enantiomorphic changes (Corballis and Beale, 1976; Gross and Bornstein, 1978), and hence, lateral reversals convey little information about the object viewed: "a tiger is equally threatening when seen in right or left profile" (Rollenhagen and Olson, 2000, p. 1506). However, whereas useful for the recognition of natural objects, mirror invariance is deleterious for reading in the Latin alphabet. As this script includes minimal mirror pairs such as *b* and *d*, mirror generalization would impede reading acquisition, leading to confusions between mirrored letters. Mirror invariance is an intrinsic property of a subpart of the visual cortex that has thus to be unlearned or at least suppressed so that one can become a fluent reader.

Consistently, in fluent adult readers the VWFA simultaneously shows a maximal effect of mirror priming for pictures of familiar objects, fruits, or animals and an absence of mirror priming for words (Dehaene et al., 2010a) and letters (Pegado et al., 2011). In an orientation-independent task in which participants had to judge either whether a target was larger or smaller in real-life than a standard computer screen (Dehaene et al., 2010a) or whether it stayed (or not) within a central frame (Pegado et al., 2011), each target being preceded by either the same or a different prime that appeared either in the same orientation or mirrored, repetition suppression (i.e., decreased fMRI activation due to processing subsequent stimuli with identical attributes) was observed in the VWFA only for mirrored pictures, not for mirrored words or letters. In addition, in Dehaene et al. (2010a), the size judgments were accelerated by mirrored primes much more for pictures than for words.

At the behavioral level, there is considerable evidence for a progressive unlearning of mirror invariance in children, and this process, crucial for linguistic materials, generalizes to non-linguistic stimuli (e.g., Gibson et al., 1962; Rudel and Teuber, 1963; Cronin, 1967; Gibson, 1969; Serpell, 1971; Casey, 1984). These developmental studies confounded age with literacy level, leading to the view that the ability to discriminate mirror images would mainly depend on neural maturation (e.g., Orton, 1937; Corballis and Beale, 1976; Casey, 1984). However, more recent work on adults disentangled the influence of literacy from that of neural maturation. In these studies, adults who remained illiterate for strictly socioeconomic reasons were far poorer at discriminating between non-linguistic enantiomorphs (of geometric or blob-like shapes, as well as of pictures of familiar objects like tools, furniture, and clothes) than both *early literates*, who learned to read at school in childhood, and *late literates*, who never attended school in childhood but learned to read in adulthood in special literacy classes (Kolinsky and Verhaeghe, 2011; Kolinsky et al., 2011; Fernandes and Kolinsky, 2013). Therefore, it is not neural maturation, but the need to take enantiomorphic contrasts into account when learning a script that includes mirrored symbols that pushes one to unlearn (Dehaene et al., 2010a) or at least partly inhibit (Duñabeitia et al., 2011; Perea et al., 2011) mirror-image generalization during explicit, conscious processing of both linguistic and non-linguistic materials.

In readers, this unlearning process may have adverse consequences for object recognition if objects vary by orientation in a way irrelevant to the task. Consistent with this idea are the priming effects observed by Dehaene et al. (2010a) in the size judgment task: for pictures of objects, behavioral priming effects were smaller for mirrored than for identical primes. Similarly, in a behavioral orientation-independent, identity-based same-different comparison task in which participants had to respond "same" to both physically identical and mirror images, Dehaene et al. reported that participants showed interference from irrelevant mirror variations (henceforth, *mirror interference*): they were faster to respond to identical than to mirrored images of non-linguistic objects. Using a similar identity-based task, Pegado et al. (2014) provided direct evidence supporting the idea that such mirror interference is a side effect of literacy acquisition: both early and late literate adults presented slowed responses and increased error rates when letters strings, false-fonts, and pictures of familiar objects were mirrored rather than strictly identical, whereas illiterate adults did not present any cost for mirrored pairs.

In the present study, we also compared illiterate, late literate and early literate adults, using an identity-based same-different comparison task similar to the one used by Dehaene et al. (2010a) and Pegado et al. (2014): in two experiments, on each trial participants were asked to decide whether the second stimulus (*S2*) was the same or not as the first one (*S1*), independently of its orientation. Our aim was two-fold.

First, we checked for the specificity of the literacy effect reported by Pegado et al. (2014) by comparing the mirror interference effect to the interference caused by another orientation contrast, i.e., rotations in the image plane or *plane rotations* (henceforth, *rotation interference*). As already noted by Gibson et al. (1962), both mirror images and plane rotations distinguish graphic forms in the Latin alphabet (e.g., d—b, and d—p, respectively). Literacy would thus impact on the ability to discriminate both types of orientation contrasts. Yet, according to the neuronal recycling hypothesis (Dehaene, 2009), the impact of reading acquisition should be stronger on enantiomorphy, as the ventral visual pathway is originally sensitive to plane rotations but not to mirror images (e.g., Logothetis and Pauls, 1995; Logothetis et al., 1995). Consistently, in orientation-dependent tasks, both illiterate and literate adults explicitly discriminate plane rotations far more easily than enantiomorphs (Kolinsky et al., 2011; Fernandes and Kolinsky, 2013). It is thus probable that in an identity-based task, (irrelevant) plane-rotation contrasts would be more automatically activated than (irrelevant) mirror-image contrasts. Although this difference might hold true for all participants, whatever their literacy level, it might be particularly strong for illiterates, as they display very poor enantiomorphic discrimination (Kolinsky and Verhaeghe, 2011; Kolinsky et al., 2011; Fernandes and Kolinsky, 2013). Here, we thus predicted that the interference effect would be stronger with plane rotations than with mirror images for all participants, and that rotation interference would be less modulated by literacy than mirror interference, which was expected to be far stronger in literate than illiterate participants, as was the case in Pegado et al. (2014).

Second, we checked whether the strength of the interference displayed by the participants would vary as a function of the nature of the non-linguistic material. Across the two experiments, we examined the impact of familiarity of the material. In Experiment 1, on familiar objects, we also examined the role of graspability, namely of the degree by which visuomotor information is critical to the representation of the object, by comparing identity-based judgments for *non-graspable* and *graspable* objects; for the latter (e.g., a hammer), there is a strong relationship between shape and manner of being grasped or manipulated.

The impact of familiarity of the material was examined by comparing pictures of familiar objects (Experiment 1) to geometric shapes (Experiment 2). We predicted that interference from irrelevant orientation variations would be stronger with geometric shapes than with familiar objects (at least with non-graspable ones), for both mirror images and plane rotations. This prediction is based on three non-mutually exclusive reasons. First, simple geometric shapes may be more similar to letters than familiar objects, and there seems to be an early bias in the VWFA for processing visual features of symbol-like shapes. In support of this idea, Szwed et al. (2011) found that configurations of line junctions, which seem universally used in writing systems worldwide (Changizi et al., 2006; but see discussions in Coltheart, 2014; Dehaene, 2014; Downey, 2014), specifically promote activation in the ventral fusiform part of the visual system. As mirrored letters or words are much more differentiated in the VWFA than mirrored pictures (Dehaene et al., 2010a; Pegado et al., 2011), if geometric shapes were treated as visual features of symbol-like shapes, then their mirror images would also be more differentiated than mirrored familiar objects, hence leading to stronger mirror interference for geometric shapes in an identity-based task. An early bias to the processing of this kind of material might also explain that even in for 4-year-old preliterates, letter-like shapes already activate the VWFA (Cantlon et al., 2011). In addition, even young preliterate children and illiterate adults may benefit from minimal exposure to letters and other symbols. Consistently, illiterate adults with some knowledge of letters already process letters differently than non-letter stimuli (Fernandes et al., 2014). Finally, according to some visual models, novel shapes are coded in a viewpoint-dependent, orientation-specific way, whereas familiar objects (especially non-graspable ones) benefit from viewpoint-independent, object-centered representations (e.g., Tarr and Bülthoff, 1995). The enantiomorphic performance of illiterate adults is consistent with all these views: in an orientation-dependent task requiring explicit discrimination of mirror images, their performance was facilitated for geometric shapes compared to (non-graspable) familiar objects (Fernandes and Kolinsky, 2013). Here, we thus expected all groups to present more mirror and rotation interference with geometric shapes than with familiar objects.

Our former work using an orientation-dependent task also showed that enantiomorphic performance was modulated by the graspability of familiar objects (Fernandes and Kolinsky, 2013). Action-related information seems to be automatically invoked by graspable objects like tools, even when there is no action on the object, as in passive viewing or perceptual tasks (e.g., Tucker and Ellis, 1998; Creem-Regehr and Lee, 2005). Fernandes and Kolinsky (2013) manipulated specifically whether the position of the object in the picture signaled the use of one particular hand if one would want to grasp it. Although no overt grasping response was required, enantiomorphic performance was facilitated for graspable compared to non-graspable objects, i.e., those for which the position of the object does not signal the use of one particular hand. This was the case in all groups (illiterate, late and early literate adults) and probably reflects that orientation signals the visuomotor properties of graspable objects, for which these properties are critical but not to non-graspable ones (Murata et al., 2000; Valyear et al., 2006; Rice et al., 2007). Therefore, in Experiment 1, we compared graspable to non-graspable familiar objects, predicting that mirror interference would be stronger with graspable than non-graspable objects.

Since the identity judgment used in the present study is an easy task, even for unschooled illiterates (cf. Pegado et al., 2014), instructions emphasized both accuracy and speed, with the latter being the principal measure of interest. For both accuracy and response times (*RTs*), we compared performance on physically identical trials, in which both object identity and orientation were the same, to performance on different-orientations trials, in which object identity was also the same but S2 was either a mirror image or a plane rotation of S1. Yet, since we know that illiterates have difficulties at speeded responses, to which they are not used to (e.g., Morais and Kolinsky, 2002; Ventura et al., 2007; Kolinsky et al., 2011), and since they often present quite variable performance (e.g., Kolinsky et al., 2011), we expected them to display slower and perhaps less accurate responses than literates. To control for this overall between-group difference, as in Pegado et al. (2014) we used a normalized *interference index* computed, separately for mirror and for plane-rotation variations, as the ratio between the RT (or accuracy) difference between different-orientation and identical trials, using as denominator the sum of RTs (or accuracy) on different-orientation and identical trials. We predicted that both late and early literates would present stronger interference from irrelevant orientation variations than illiterates, especially with enantiomorphs.

EXPERIMENT 1: IDENTITY JUDGMENTS ON FAMILIAR OBJECTS

METHOD

Participants

Forty-nine adults were paid for their participation to a larger battery of tests, including orientation-dependent tasks using the same materials (see below). According to their schooling and literacy levels (see below), they were assigned to three groups: unschooled illiterates, unschooled late literates, and schooled early literates. The ethical committee of the Psychological and Educational Sciences Faculty at Université Libre de Bruxelles approved the study protocol; all participants provided oral informed consent.

To check for task commitment, we first examined the *Signal Detection Theory* (SDT) d' statistic adapted for same-different comparison tasks (Macmillan and Creelman, 2005), considering as *hits* the correct "different" responses on trials in which both object identity and orientation were different, and as *false alarms* the incorrect "different" responses on identical trials, in which both object identity and orientation were the same (see mean correct scores in **Table 1**, separately for each group). Two illiterates were excluded from further analyses because they probably have not understood the task: both presented a d' of zero, while all other participants were quite able to perform the task with mean d' scores of 4.36 ($SD = 1.56$), 5.74 ($SD = 1.11$), and 6.01 ($SD = 0.67$) for illiterates, late literates and early literates, respectively.

The final samples included 17 illiterates (12 women), aged 31–74 years ($M = 56.6$), 15 late literates (11 women), aged 19–71 years ($M = 49.3$), and 15 early literates (10 women), aged 27–68 years ($M = 52.5$). Early literates had on average 8 years of schooling ($SD = 3.1$). Illiterates were either recruited through non-governmental agencies or were attending the first lessons (first 2 weeks) of literacy classes, during which they received only information about civil rights and possible courses. Late literates were engaged in or already had finished the fourth (final) level of the literacy course. The three groups were from the same socioeconomic and residential backgrounds and had similar ages, $F < 1$.

All participants were first presented with letter recognition and reading (6 words and 6 pseudowords) tests. Illiterates were able to identify, on average, 8.65 letters out of the 23 letters of the Portuguese alphabet, and only one of them was able to read a single word ($M = 0.49\%$). Almost all late literates correctly identified the 23 letters ($M = 22.67$) and reached at least 83.3% correct in the reading test ($M = 95.6\%$). Except for one participant who did not recognize one letter, all early literates were perfect in both the letter recognition ($M = 22.93$) and the reading ($M = 100\%$) tests. In the analyses of variance (*ANOVA*) on these scores, the main effect of group was significant on both letter recognition and reading performance, $F_{(2,\ 44)} = 88.88$ and $= 3052.46$, respectively, both $p < 0.0001$[1]. *Post-hoc* tests[2] showed that late and early literate adults presented the same level of performance on letter recognition, both differing from illiterates, both $p < 0.01$. In the reading test, all groups differed from each other, $p < 0.05$ in all cases.

In order to evaluate potential cognitive differences, all participants were tested with the Mini-Mental State Examination (*MMSE*, Folstein et al., 1975). Because this test is known to be sensitive to educational and (correlated) literacy level (e.g., Crum et al., 1993), we used MMSE revised scores, recalculating individual scores after discarding the three items that examine reading, writing, and arithmetic abilities. This led to similar mean scores of 23.47 ($SD = 3.02$), 22.47 ($SD = 1.77$), and 23.33 ($SD = 1.68$) by illiterates, late literates and early literates, respectively, $F < 1$.[3]

[1]As usual, for all inferential statistics presented in this study, $p < 0.05$ is interpreted as a statistically significant result.

[2]All *post-hoc* between-group tests reported in the present study correspond to unequal N HSD tests.

[3]As expected, when the items examining reading and writing abilities were also taken into account, the group effect became significant, $F(2,\ 44) = 20.97$, $p < 0.0001$, with illiterates differing from both late and early literates ($M = 23.47$, 27.47, and 28.33, respectively), both $p < 0.001$.

After the orientation-independent tasks presented here, 38 participants (12 illiterates, 13 late literates, and 13 early literates) were also tested on orientation-dependent tasks using either pictures of familiar objects or geometric shapes (for detailed method and results, see Fernandes and Kolinsky, 2013). In the orientation-dependent task, the illiterates who were presented with both types of tasks showed difficulties especially in discriminating mirror images, obtaining 64.8% correct on "different" trials involving mirror images (64.17% for familiar objects, 65.5% for geometric shapes) vs. more than 80% correct on "different" trials involving plane rotations (82.1% for familiar objects, 80.3% for geometric shapes) and more than 85% correct on "same" trials (85.8% for familiar objects, 86.8% for geometric shapes).

Material and procedure

Stimuli were black and white pictures of asymmetric real objects. As explained in detail in Fernandes and Kolinsky (2013), most were from Snodgrass and Vanderwart (1980), the others were from Bonin et al. (2003). Examples are presented in **Figure 1**.

A total of 36 different objects (see the Appendix in Fernandes and Kolinsky, 2013) was used, half being graspable, the others non-graspable, as assessed by an independent group of participants (see Fernandes and Kolinsky, 2013). According to the norms collected by Ventura (2003), the two categories were matched on visual ambiguity, complexity, and familiarity, all $t < 1$.

For each object, a standard position, corresponding always to S1, was defined, and for the S2 a mirror image (lateral reflection) as well as a plane rotation were created, both differing from the standard by 180°.

Each trial started with a fixation cross presented in the center of the screen for 250 ms, after which S1 was presented during 2000 ms, then a 500 ms mask comprising random lines separated the presentation of S2 from the presentation S1 in order to guarantee no involvement of iconic memory in performance. On each trial, participants were asked to decide as quickly and as accurately as possible whether the second object was the same or not as the first, independently of its orientation. They thus had to answer "same" if S2 had the same identity as S1, independently of whether it had the same orientation (identical trials) or not, and to answer "different" if S2 had a different identity compared to S1, also independently of their orientation. As illustrated in **Figure 1**, on different-orientation trials, S2 could be either a mirrored or plane-rotated version of S1. RTs were measured from the onset of S2 to response onset. Immediately after participants gave their response another trial began, or if no response was provided the next trial began after 4750 ms.

Participants were presented with 864 trials, half "same," half "different." Each of the six possible pairs used for a particular object (see **Figure 1**) was presented twice, in different blocks. Participants were first presented with six practice trials to familiarize them with the task. They received feedback on the correctness of their response only for these trials.

RESULTS

Accuracy and RTs for correct responses were analyzed separately. For each participant, correct RTs longer or shorter than the grand

Table 1 | Experiment 1: Mean performance in the identity-based same-different comparison task for familiar objects, presented by object type, trial type, and group of participants.

	Trial type		Graspable objects			Non-graspable objects		
	Expected response	**Orientation**	**Illiterates**	**Late literates**	**Early literates**	**Illiterates**	**Late literates**	**Early literates**
Accuracy (%)	Different		84.57 [13.86]	94.49 [5.83]	96.09 [4.33]	86.67 [13.71]	95.42 [5.26]	97.02 [2.83]
	Same	Identical	87.18 [10.01]	95.93 [4.56]	96.67 [3.37]	86.06 [10.81]	94.27 [7.14]	97.13 [2.53]
	Same	Mirror	86.82 [9.01]	95.47 [4.00]	96.67 [2.74]	87.18 [8.82]	95.27 [4.08]	96.40 [3.11]
	Same	Rotation	89.00 [7.78]	94.53 [5.90]	97.00 [2.17]	87.24 [10.16]	94.47 [4.60]	94.47 [3.76]
RTs (ms)	Different		1022 [243]	844 [277]	714 [129]	1031 [254]	847 [271]	709 [138]
	Same	Identical	826 [269]	677 [213]	591 [77]	828 [227]	680 [207]	607 [86]
	Same	Mirror	826 [216]	705 [230]	625 [86]	807 [195]	707 [233]	620 [79]
	Same	Rotation	837 [179]	741 [236]	641 [80]	850 [191]	752 [260]	632 [71]

Standard deviations in brackets.

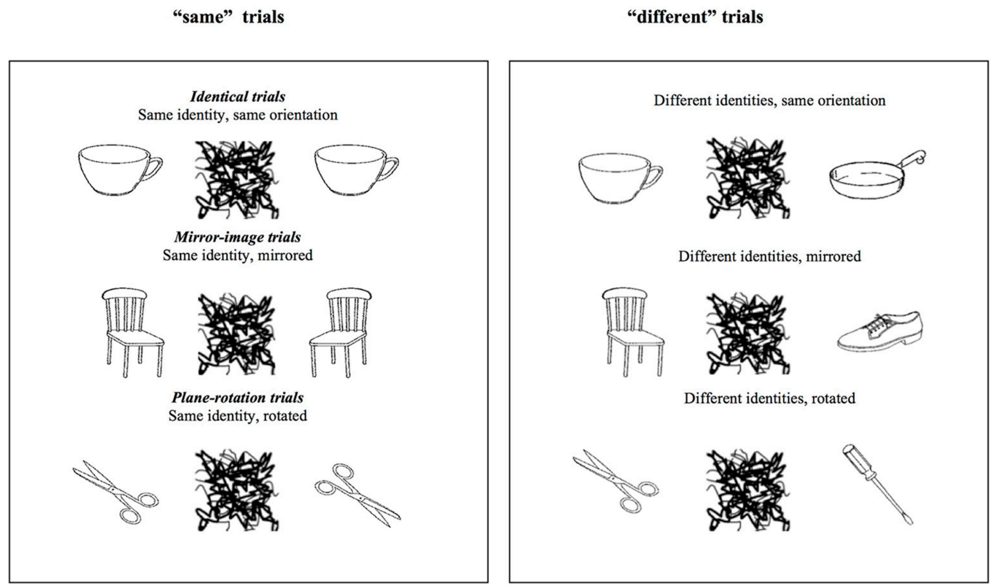

FIGURE 1 | Examples of the stimuli used in the "same" and "different" trials of Experiment 1. The critical trials are the three types of "same" trials.

mean plus or less 2.5 SD were removed from further analyses (less than 3% of the data excluded). In all analyses, RTs for correct responses were logarithmically transformed and accuracy was arcsine transformed[4]. Still, for the sake of clarity tables and figures present RTs in ms and accuracy in percentages.

Table 1 presents the mean scores for all trial types, separately for each group. Only the trials in which object identity was the same were considered in the following analyses. For both RTs and accuracy, we compared performance on physically identical trials to performance on trials in which object identity was also the same but where S2 was either a mirror image or a plane rotation of S1.

[4]Given that proportions usually follow a binomial distribution in which the variance is a direct function of the mean, the arcsine transformation allowed guaranteeing no violation of the normality assumption necessary for conducting parametric analyses (e.g., Howell, 2010).

In a first step, we performed two separate ANOVAs, one on RTs, the other on accuracy, each with group (illiterates; late literates; early literates) as a between-participants variable and orientation (identical; mirror; rotation) and graspability (graspable vs. non-graspable objects) as within-participants variables.

There was a main effect of group for both RTs, $F_{(2,\ 44)} = 6.79$, $p = 0.003$, $\eta_p^2 = 0.236$, and accuracy, $F_{(2,\ 44)} = 11.16$, $p < 0.001$, $\eta_p^2 = 0.337$. *Post-hoc* comparisons showed that illiterates were significantly less accurate and slower than early literates, both $p < 0.005$, and less accurate, $p = 0.003$, but not slower, $p = 0.10$, than late literates, whereas late and early literates did not differ from each other in either analysis, both $p > 0.30$.

No other significant effect was found in the accuracy analysis, all other $F < 1$, including the main effects of orientation and of graspability, and the orientation by group interaction. Graspability did not affect performance on RTs either, $F < 1$.

Yet, orientation strongly affected performance in the RTs analysis, $F_{(2, 88)} = 27.31$, $p < 0.001$, $\eta_p^2 = 0.383$, in which its effect was modulated by group, $F_{(4, 88)} = 2.48$, $p < 0.05$, $\eta_p^2 = 0.101$. Orientation of the stimulus strongly affected the response speed of both late literate, $F_{(2, 28)} = 35.27$, $p < 0.001$, $\eta_p^2 = 0.716$, and early literate adults, $F_{(2, 28)} = 13.48$, $p < 0.001$, $\eta_p^2 = 490$. In contrast, it only slightly and non-significantly modulated the illiterates' response latencies, $F_{(2, 32)} = 2.35$, $p = 0.11$, $\eta_p^2 = 0.111$. Whereas illiterates' responses to mirrored trials were as fast as those to identical trials, $F < 1$, in the two literate groups, performance was slower for mirror images compared to identical trials [late literates: $F_{(1, 28)} = 9.83$, $p = 0.004$; early literates: $F_{(1, 28)} = 10.56$, $p = 0.003$]. For rotations, all groups presented slower responses compared to both identical trials [illiterates: $F_{(1, 44)} = 3.95$, $p = 0.\ 05$; late literates: $F_{(1, 28)} = 49.95$, $p < 0.001$; early literates: $F_{(1, 28)} = 22.89$, $p < 0.001$] and mirror images [illiterates: $F_{(1, 44)} = 15.32$, $p < 0.005$; late literates: $F_{(1, 28)} = 32.26$, $p < 0.001$; early literates: $F_{(1, 28)} = 6.15$, $p = 0.019$].

The analyses of the interference indexes (performed without taking graspability into account, as this factor did not affect performance) showed, in addition, that illiterates were less susceptible to irrelevant orientation variations than literates for both mirror images and (although to a lesser extent) for rotations. As illustrated in **Figure 2**, on the RT interference index, only illiterates were unaffected by orientation variations, with both mirror interference and rotation interference not differing from zero, $t < 1$ and $t_{(16)} = 1.39$, $p = 0.18$, respectively. In contrast, both literate groups presented significant mirror interference [late literates: $t_{(14)} = 3.00$, $p = 0.009$; early literates, $t_{(14)} = 3.41$, $p = 0.004$] and rotation interference [late literates: $t_{(14)} = 6.63$, $p < 0.001$; early literates: $t_{(14)} = 5.16$, $p < 0.001$]. On the accuracy interference index, only early literates showed significant rotation interference, $t_{(14)} = 2.33$, $p = 0.035$, all other $p > 0.20$.

Since the size of interference was similar for late and early literates for both mirror images, $t < 1$, and plane rotations, $t_{(28)} = 1.61$, $p = 0.12$, we contrasted the illiterate group to these literate participants. Compared to them, illiterate adults clearly presented weaker mirror interference, $t_{(45)} = -2.27$, $p = 0.028$, and somewhat weaker rotation interference, $t_{(45)} = -1.96$, $p = 0.056$.

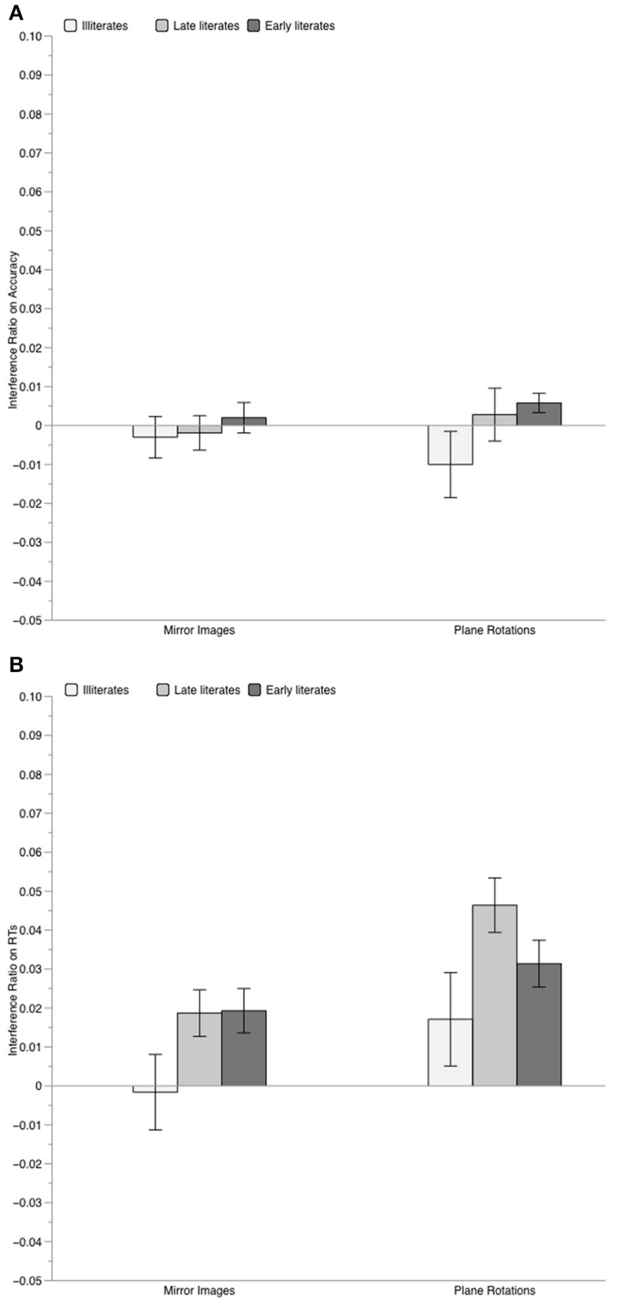

FIGURE 2 | Mean value of the interference index for familiar objects, computed on accuracy scores (Panel A) and on RTs (Panel B), separately for each group of participants. Error bars represent standard error of the mean.

DISCUSSION

Our previous work had shown that breaking mirror generalization depends on literacy acquisition in the Latin alphabet (Kolinsky and Verhaeghe, 2011; Kolinsky et al., 2011; Fernandes and Kolinsky, 2013). Here, similarly to former studies (Dehaene et al., 2010a; Pegado et al., 2011), we demonstrated that in adult readers enantiomorphy is automatically evoked during object recognition. In addition, confirming the results reported by Pegado et al. (2014), we showed that this process is a consequence of literacy acquisition: in an identity-based same-different comparison task in which participants had to respond "same" to both physically identical and differently oriented pictures of the same object, only literate but not illiterate adults were affected by irrelevant enantiomorphic variations. Thus, in literates, breaking mirror invariance interferes with a non-linguistic object recognition task when orientation is neither relevant nor useful for it. Furthermore, as predicted by the neuronal recycling hypothesis (Dehaene and Cohen, 2007; Dehaene, 2009), rotation interference was stronger than mirror interference, at least in literates. Mirror-image contrasts thus remain less salient or less automatically evoked than plane rotations, when processing the identity of familiar objects, probably because enantiomorphy is learned in the course of literacy acquisition. However, contrary to our prediction, no effect of graspability was observed.

EXPERIMENT 2—IDENTITY JUDGMENTS ON GEOMETRIC SHAPES

METHOD

Participants

Among the participants of Experiment 1, 46 participated in this experiment: 16 illiterates, and all the late and early literates. As in Experiment 1, we first checked for task commitment, examining the SDT d' scores in the same-different comparison task. One illiterate who presented a $d' \sim 0$ was excluded from further analyses. All other participants were able to correctly perform the task with mean d' scores of 3.95 ($SD = 1.93$), 4.92 ($SD = 0.99$), and 5.17 ($SD = 0.92$) by illiterates, late and early literates, respectively.

The final illiterate sample thus included 15 participants (10 women), aged 31–74 years ($M = 56.0$). They were able to identify, on average, 8.3 letters out of the 23 letters of the Portuguese alphabet, and none was able to read a single word of the reading test. Their mean revised MMSE score was 23.80 (SD: 3.14; same score as the unrevised one).

Material and procedure

Nine asymmetric geometric shapes were used as S1 (see examples in **Figure 3**).

Construction of the pairs and trial types were identical to Experiment 1 (see **Figure 3**). Participants were presented with a total of 216 trials, half "same," half "different." Each S1 shape was paired four times with a replica and four times with its mirror image and with its plane rotation. For "different" trials, each S1 shape was paired four times with a different geometric shape, with a mirror image, and with a plane rotation of that shape.

Procedure was the same as in Experiment 1.

RESULTS

Data were trimmed (<3% of data excluded) and analyzed as in Experiment 1. **Table 2** present the mean scores for all trial types, separately for each group.

In the ANOVA on accuracy, only the main effect of orientation was significant, $F_{(2, 84)} = 14.83$, $p < 0.001$, $\eta_p^2 = 0.261$, with identical trials leading to better performance than both mirror images, $F_{(1, 42)} = 12.43$, and rotations, $F_{(1, 42)} = 25.59$, both $p \leq 0.001$ (mirror images vs. rotations: $F = 3.79$, $p = 0.058$). The group effect only tended toward significance, $F_{(2, 42)} = 2.87$, $p = 0.068$, $\eta_p^2 = 0.120$. Although the interaction between group and orientation was not significant, $F = 1.2$, we further examined the effect of orientation on performance of each group, considering both the results of Experiment 1 and prior results on literate participants showing that they are more sensitive to orientation variations than illiterates (Pegado et al., 2014). In fact, whereas no effect of orientation was found in illiterates, $F_{(2, 28)} = 1.76$, $p = 0.19$, the effect of orientation was significant for both late literates, $F_{(2, 28)} = 6.82$, $p = 0.003$, and early literates, $F_{(2, 28)} = 9.17$, $p < 0.001$. In the two literate groups, relative to identical trials, performance was worse for mirror images [late literates: $F_{(1, 14)} = 5.32$, $p = 0.036$; early literates, $F_{(1, 14)} = 12.36$, $p = 0.003$], and for plane rotations [late literates: $F_{(1, 14)} = 10.36$, $p = 0.006$; early literates: $F_{(1, 14)} = 12.11$, $p = 0.001$]. Consistently, the analyses of the accuracy interference indexes (see **Figure 4A**) showed that only the literates were penalized by orientation variations, with significant mirror interference [late literates: $t_{(14)} = 2.22$, $p = 0.043$; early literates: $t_{(14)} = 2.14$, $p = 0.049$] and rotation interference [late literates: $t_{(14)} = 2.77$, $p = 0.015$; early literates: $t_{(14)} = 2.94$, $p = 0.010$]. In contrast, illiterates exhibited no mirror interference, $t < 1$, nor rotation interference, $t_{(14)} = 1.40$, $p = 0.18$. Since the amount of mirror and rotation interference was similar for late and early literates, both $t < 1$, we tested whether illiterates presented weaker interference than the literate participants. This was the case for mirror interference, $t_{(42)} = -1.80$, $p = 0.038$, but not for rotation interference, $t_{(42)} = -1.18$, $p = 0.122$.

Yet, the RT analysis suggested that even illiterates were somewhat sensitive to irrelevant mirror images of geometric shapes: both the main effect of group, $F_{(2, 42)} = 5.02$, $p = 0.01$, $\eta_p^2 = 0.193$ (with illiterates overall slower than late and early literates, $p < 0.05$, and $p = 0.01$, respectively), and of orientation, $F_{(2, 84)} = 26.8$, $p < 0.001$, $\eta_p^2 = 0.389$, were significant, but not their interaction, $F < 1$. Contrary to what was observed on accuracy, the effect of orientation was significant in all groups [illiterates: $F_{(2, 28)} = 4.56$, $p = 0.02$; late literates: $F_{(2, 28)} = 14.45$, $p < 0.001$; early literates: $F_{(2, 28)} = 24.83$, $p < 0.001$]. Across groups, performance was the slowest for rotations compared to identical trials, $F_{(1, 42)} = 36.54$, and to mirror images, $F_{(1, 42)} = 13.14$, both $ps < 0.001$, and was also slower for mirror images than for identical trials, $F_{(1, 42)} = 24.80$, $p < 0.001$. Thus, in terms of latency both illiterate and literate participants displayed mirror and rotation interference. The same conclusion can be drawn from the analysis of the RT interference index: as illustrated in **Figure 4B**, mirror and rotation interference effects were significant in all three groups (all $p \leq 0.03$). No difference between illiterate and literate participants was observed, neither for mirror interference, $t_{(43)} = 1.05$, $p = 0.300$, nor for rotation interference, $t_{(43)} = -0.25$, $p = 0.803$.

DISCUSSION AND CROSS-EXPERIMENTS ANALYSES

Contrary to what was observed in Experiment 1 with familiar objects, here with geometric shapes all participants, whatever their literacy level, were sensitive to the irrelevant orientation variations, at least on response latencies and mostly for plane rotations.

To check for the robustness of this material difference, we performed cross-experiment analyses on the accuracy and RT interference indexes of the 43 participants (13 illiterates, 15 late literates, 15 early literates) who were presented with both materials and adequately performed the identity-based task. There was a significant main effect of material in both analyses, accuracy, $F_{(1, 40)} = 10.31$, $p = 0.003$, $\eta_p^2 = 0.205$, RT, $F_{(1, 40)} = 8.37$, $p = 0.006$, $\eta_p^2 = 0.173$, with an overall stronger interference effect with geometric shapes than with familiar objects. The main effect of orientation was also significant in both analyses, accuracy, $F_{(1, 40)} = 7.04$, $p = 0.01$, $\eta_p^2 = 0.150$, and RT, $F_{(1, 40)} = 24.42$, $p < 0.001$, $\eta_p^2 = 0.379$, with overall stronger rotation than mirror interference. The interaction between material and orientation was only significant in accuracy, $F_{(1, 40)} = 7.68$, $p = 0.008$, $\eta_p^2 = 0.161$, not on RTs, $F < 1$: rotation interference was stronger with geometric shapes than with familiar objects, $F_{(1, 40)} = 17.64$, $p < 0.001$, whereas mirror interference was similar with both

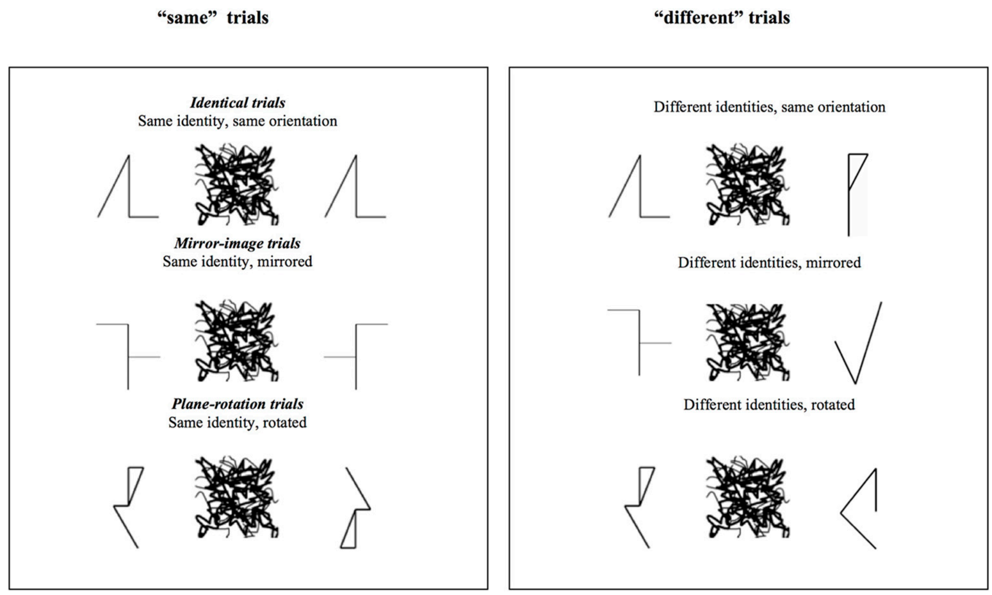

FIGURE 3 | Examples of the stimuli used in the "same" and "different" trials of Experiment 2. The critical trials are the three types of "same" trials.

Table 2 | Experiment 2: Mean performance in the identity-based same-different comparison task for geometric shapes, presented by trial type and group of participants.

	Trial type		Illiterates	Late literates	Early literates
	Expected response	**Orientation**			
Accuracy (%)	Different		80.17 [20.08]	92.09 [7.56]	94.13 [4.68]
	Same	Identical	83.67[19.63]	95.00 [5.24]	95.80 [7.16]
	Same	Mirror	83.67 [15.67]	91.53 [7.69]	92.27 [6.24]
	Same	Rotation	80.87 [19.14]	88.53 [10.12]	90.67 [9.62]
RTs (ms)	Different		1194 [301]	960 [232]	836 [218]
	Same	Identical	941 [322]	734 [138]	723 [136]
	Same	Mirror	1034 [375]	800 [155]	747 [155]
	Same	Rotation	1055 [304]	863 [211]	815 [168]

Standard deviations in brackets.

materials, $F_{(1, 40)} = 1.77, p = 0.191$. In neither analysis did group interact with any other factor, all $ps > 0.10$. Thus, in comparison to familiar objects, identity-based judgments on geometric shapes were more strongly affected by irrelevant plane rotations, whatever the literacy level of the participant.

Given that 38 of the participants of the present study had also performed orientation-dependent tasks with the same materials (Fernandes and Kolinsky, 2013), we next examined whether there was any association between the interference effects reported here and the performance level observed for either mirrored or rotated trials in the orientation-dependent tasks by Fernandes and Kolinsky (2013). Across materials, no correlation was observed between this performance and the RT interference index, all $rs < 0.195$, $ps > 0.24$, but when accuracy was considered, there was a significant correlation between enantiomorphic performance and mirror interference, $r_{(36)} = 0.387$, $p = 0.016$, but not between plane rotation discrimination and rotation interference, $r_{(36)} = -0.176$, $p = 0.289$. Thus, the better the participants discriminated mirror images, the stronger these interfered on their identity-based judgments.

GENERAL DISCUSSION

Literacy is an acculturation process that enables massive cognitive gains. However, according to the neuronal recycling hypothesis (Dehaene and Cohen, 2007; Dehaene, 2009), this new cultural ability may compete with evolutionary older functions, leading to collateral effects. As a matter of fact, enantiomorphy, namely the ability to discriminate between mirror images that develops through reading acquisition (Kolinsky and Verhaeghe,

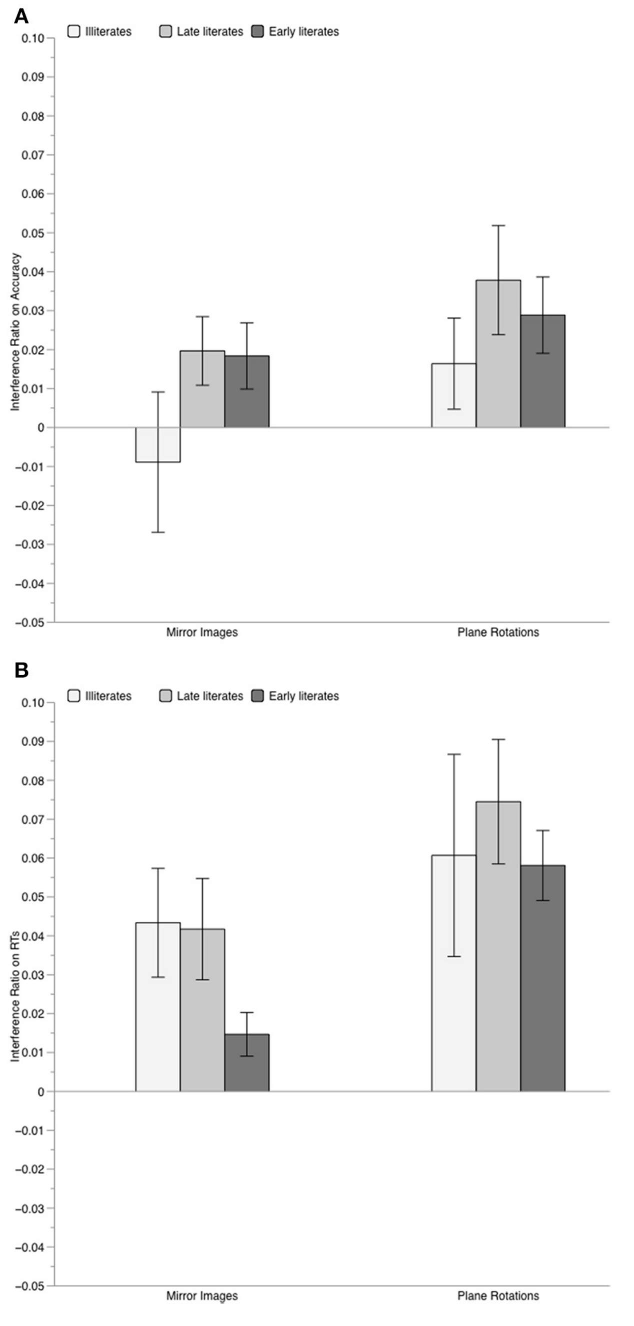

FIGURE 4 | Mean value of the interference index for geometric shapes, computed on accuracy scores (Panel A) and on RTs (Panel B), separately for each group of participants. Errors bars represent standard error of the mean.

2011; Kolinsky et al., 2011; Fernandes and Kolinsky, 2013), collides with the original mirror invariance property of the ventral visual system. Therefore, in the present study we investigated whether enantiomorphy interferes with object identity judgments, as suggested by former work (Dehaene et al., 2010a; Pegado et al., 2011, 2014). In particular, we examined whether the expected mirror interference reflects a specific impact of literacy on enantiomorphy rather than a general impact on orientation processing during object recognition. Furthermore, we also checked whether the strength of the interference displayed by illiterate and literate adults would be modulated by the familiarity of the material and, for familiar objects, by their graspability (Fernandes and Kolinsky, 2013). To these aims we presented illiterate, late literate (who learned to read at adult age) and early literate adults with an identity-based same-different comparison task in which they had to respond "same" to physically identical, mirrored, and plane-rotated images of either pictures of familiar objects (Experiment 1) or geometric shapes (Experiment 2). We examined the interference from irrelevant orientation variations separately for mirror images and plane rotations.

With pictures of familiar objects, contrary to literate adults, illiterates did not display any mirror interference. As expected, for all groups, interference was stronger with geometric shapes than with familiar objects. With geometric shapes, both plane rotations and enantiomorphic variations affected response latencies, irrespective of the participants' literacy level. Still, in terms of accuracy, contrary to literates, illiterates did not display mirror interference with geometric shapes, whereas they did show rotation interference.

In what regards familiar objects' graspability, namely the degree by which visuomotor information is critical to the representation of the object, in contrast to our prediction, this property had no impact on identity-based judgments. This result pattern stands in sharp contrast to that found by Fernandes and Kolinsky (2013) in an orientation-dependent task. There, the explicit discrimination of orientation variations, either mirror images or plane rotations, was facilitated for graspable objects. Note, however, that the orientation variations that could have invoked action-related information of graspable objects were in the present study irrelevant to the task. Prior studies have shown that the visuomotor properties of objects are especially processed by the dorsal, vision-for-action stream (e.g., Valyear et al., 2006; Rice et al., 2007). In particular, parietal regions, part of the dorsal stream, have been shown to be critical for processing spatial attributes of objects in orientation-based tasks, but not their identity (Harris et al., 2008). Therefore, although both ventral and dorsal streams operate simultaneously during visual processing, their relative involvement depends on the specific task. Task specificities might thus explain the apparent discrepancy between the graspability effects found in the orientation-based task used by Fernandes and Kolinsky and their absence in the identity-based task of the present study. Further brain-imaging studies could test this possibility.

More importantly, the present result pattern is in line with prior studies showing that the discrimination of mirror images and of plane rotations are supported by at least partially different mechanisms (e.g., Turnbull et al., 1997; Turnbull and McCarthy, 1997), and that the ventral visual pathway is originally sensitive to plane rotations but not to mirror images (e.g., Logothetis and Pauls, 1995). In this vein and in line with our prediction, across groups and experiments, plane rotations interfered more on identity judgments than mirror images. Furthermore, it was only for mirror images that the size of the interference effect was linked to the participants' enantiomorphic performance in an orientation-dependent task (cf. Fernandes and Kolinsky, 2013): the better they could discriminate mirror images, the stronger the mirror interference on their identity-based judgments.

The process of unlearning mirror invariance, necessary to acquire literacy in the Latin alphabet, has thus a cost for object identification, a basic function of the visual ventral stream. The observation of a negative side effect of a literacy-related ability, namely enantiomorphy, was expected under the neuronal recycling hypothesis (Dehaene and Cohen, 2007; Dehaene, 2009), which proposes that reading, as other recent cultural inventions, capitalizes on evolutionary older functions, with which they may compete. Brain-imaging data had already shown that literacy induces a profound reorganization of the cortical networks for vision and language, and that this process involves competition for neural space in the left fusiform gyrus, especially between written strings and faces (Dehaene et al., 2010b).

A functional cost like the one reported here is also expected if some properties that were useful for the original function are deleterious for the new function, and hence, should be unlearned. As a direct consequence, this unlearning process would benefit the new function (here, reading) but harm the older one. Effects of both neural competition (Dehaene et al., 2010b) and functional competition as shown here, as well by Dehaene et al. (2010a) and Pegado et al. (2011, 2014), thus demonstrate that neural recycling is not just an adaptation to multi-use (see discussion in, e.g., Jungé and Dennett, 2010) but a process of at least partial exaptation. More generally, as noted by Dehaene (2013), the presence of mirror invariance prior to literacy and its reduction during reading acquisition show that learning to read involves the recycling of a preexisting circuit that did not evolved purposely for reading, but adapts to this novel task.

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Mirror-image discrimination in the literate brain: a causal role for the left occpitotemporal cortex

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Previous studies show that the primate and human visual system automatically generates a common and invariant representation from a visual object image and its mirror reflection. For humans, however, this mirror-image generalization seems to be partially suppressed through literacy acquisition, since literate adults have greater difficulty in recognizing mirror images of letters than those of other visual objects. At the neural level, such category-specific effect on mirror-image processing has been associated with the left occpitotemporal cortex (L-OTC), but it remains unclear whether the apparent "inhibition" on mirror letters is mediated by suppressing mirror-image representations covertly generated from normal letter stimuli. Using transcranial magnetic stimulation (TMS), we examined how transient disruption of the L-OTC affects mirror-image recognition during a same-different judgment task, while varying the semantic category (letters and non-letter objects), identity (same or different), and orientation (same or mirror-reversed) of the first and second stimuli. We found that magnetic stimulation of the L-OTC produced a significant delay in mirror-image recognition for letter-strings but not for other objects. By contrast, this category specific impact was not observed when TMS was applied to other control sites, including the right homologous area and vertex. These results thus demonstrate a causal link between the L-OTC and mirror-image discrimination in literate people. We further suggest that left-right sensitivity for letters is not achieved by a local inhibitory mechanism in the L-OTC but probably relies on the inter-regional coupling with other orientation-sensitive occipito-parietal regions.

Keywords: mirror-image discrimination, transcranial magnetic stimulation, visual orientation invariance, occipitotemporal cortex, visual word-form area

INTRODUCTION

The human and primate ventral visual system is known to spontaneously generate a common and invariant representation from a visual object image and its mirror reflection, irrespective of their left-right orientation (Eger et al., 2004; Vuilleumier et al., 2005; Dehaene et al., 2010b; Freiwald and Tsao, 2010). For humans, this mirror-image generalization probably relies on a fast neural process occurring at ~200 ms after stimulus onset (Eddy and Holcomb, 2009), but seems to be partially "suppressed" through literacy acquisition. That is, literate adults are known to have greater difficulty in recognizing mirror images of letters than those of other objects, whereas this is not the case for illiterate people (Kolinsky et al., 2011; Pegado et al., 2014). Recent functional magnetic resonance imaging (fMRI) data show that such category-specific sensitivity in mirror-image processing relies on the left visual word-form area (VWFA) in the left fusiform gyrus (Dehaene et al., 2010a,b; Pegado et al., 2011).

However, it remains unclear how the strong behavioral sensitivity to letter/word orientation is achieved in this and adjacent left occpitotemporal cortex (L-OTC). More specifically, while this region is thought to represent abstract shape-invariant identities of letters (see Dehaene et al., 2005 for review, and see also Rothlein and Rapp, 2014), it is unknown whether the same region comprises a local inhibitory circuit for suppressing mirror-image generalization only for letters and words. More specifically, it is possible that mirror-image representations are covertly generated even from letter stimuli and then suppressed via a local feedback circuit in the L-OTC. This is expected because (1) a recent event-related study has shown that early neural responses to masked letters/words (i.e., ~250 ms after stimulus onset) do not differ between normal-oriented and mirror-reversed stimuli (Dunabeitia et al., 2011), and (2) such lateral inhibition of non-canonical inputs seems to reflect an ubiquitous feature of the neural mechanism involved in early sensory processing (Srinivasan et al., 1982) and play a role in shaping response tuning of higher-order sensory pathways (Carandini and Heeger, 2012). Indeed, human extrastriate cortex may comprise a lateral inhibition mechanism in which neuronal populations responsive to one stimulus category suppress those responsive to another category (Allison et al., 2002). It is therefore plausible that a category-specific inhibitory circuit for mirror-reversed letters develops within the L-OTC through literacy training.

On the other hand, it is also possible that the L-OTC comprises no such orientation-sensitive inhibitory mechanism for mirror-image discrimination. This is because this region *per se* has been associated with abstract, shape- and orientation-invariant representations of visual stimuli (Dehaene et al., 2005) and thus might be unable to differentiate their left-right orientations. If this is the case, mirror-image discrimination during visual word perception may not occur inside the L-OTC, but rather rely on input signals from other orientation-sensitive regions, such as the lateral occipital cortex (LOC) (Eger et al., 2004; Vuilleumier et al., 2005; Dilks et al., 2011) and posterior parietal cortex (PPC) involved in spatial recognition (Poldrack and Gabrieli, 2001).

In the present study, we examined these two possibilities by applying transcranial magnetic stimulation (TMS) to the left and right OTC during a same-different judgment task (**Figure 1A**). We measured a behavioral impact of TMS on mirror-image recognition by varying the semantic category (letters and non-letter objects), identity (same or different) and orientation (same or mirror-reversed) of the first and second stimuli. Crucially, the two different models described above should predict different patterns of TMS-induced interference during mirror-image processing. On one hand, if the L-OTC comprises a category-specific inhibitory circuit for left-right discrimination, the visual recognition of mirror-reversed words should be facilitated when this region is disrupted by TMS. That is, a transient reduction of inhibitory signals is likely to accelerate the otherwise suppressed mirror-image processing for letter-strings, since mirror generalization is known to occur in both hemispheres (Eger et al., 2004; Vuilleumier et al., 2005; Freiwald and Tsao, 2010). On the other hand, if such local inhibition is not operating in the L-OTC, no behavioral facilitation should occur during mirror-image recognition when TMS is applied to this region. Rather, magnetic stimulation of the region would disrupt the orientation-invariant representations of stimulus identity, and thereby induce a delay in same-different judgment about mirror images. These effects should be strictly category-specific, i.e., detectable only for word stimuli and not for other visual objects.

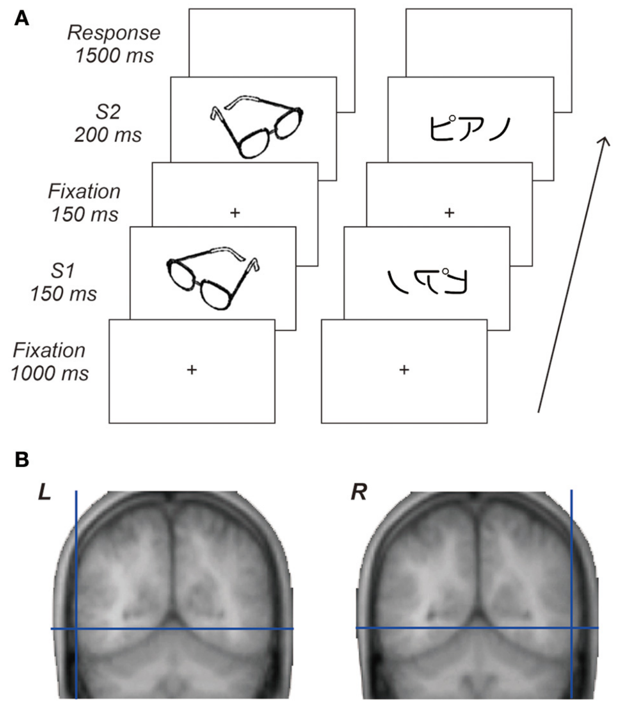

FIGURE 1 | Behavioral task and cortical target regions. (A) Sequence of visual stimuli. Each trial comprised central fixation, a first stimulus (S1), central fixation, a second stimulus (S2) followed by a response period. Visual stimuli for S1 and S2 were either identical or different images taken from the same category and presented either in the same or mirror reversed orientation. Participants responded by key-press as quickly and accurately as possible to decide whether or not paired stimuli were identical regardless of their orientation. **(B)** Locations of the cortical target structures in the occipitotemporal areas. The average coordinates of these cortical targets across participants were $x = -62$, $y = -60$, $z = -5$ for the L-OTC and $x = 61$, $y = -57$, $z = -5$ for the R-OTC.

MATERIALS AND METHODS

PARTICIPANTS

Twelve right-handed Japanese speakers participated in the present TMS experiment (age range 20–38 years, six females). All of them gave written informed consent prior to the TMS experiment. We additionally recruited a separate group of 18 Japanese participants (age range 19–45 years, seven females) for a control experiment without TMS (see Results). The protocol of this study was approved by the institutional ethical committee at the National Rehabilitation Center for Persons with Disabilities.

MATERIALS AND PROCEDURES

Visual stimuli consisted of 48 Japanese words written in a syllabic script (katakana) and 96 black-and white drawings of objects (e.g., animals, clothes, faces, tools). Since printed words and other drawings greatly differ in physical features, it is possible that they also depart from each other in the degree of asymmetry. We therefore assessed the degree of asymmetry for the present stimuli using a pixel-based analysis. That is, visual images were binarized to remove white background pixels and then edge-detected using the Matlab image processing toolbox (Mathworks, USA), For each item, we determined the number of overlapping pixels shared by the filtered image and its left-right reversal, and computed the ratio of overlap against the whole filtered image. This analysis revealed that mean percentage overlap (*SD*) was 11.6 (5.7)% for words and 9.52 (3.99)% for objects, respectively, and did not differ from each other ($p > 0.2$, Wilcoxon rank-sum test). In addition, faces tended to be slightly more symmetrical than other non-face objects (10.1 (3.8) and 8.9 (4.1)%, respectively), but this difference neither reached significance ($p = 0.18$). These results thus confirmed no significant difference in the degree of asymmetry between words and other objects.

Each trial comprised central fixation, a first stimulus (S1), central fixation, a second stimulus (S2) followed by a response period (**Figure 1A**). Visual stimuli for S1 and S2 were either identical or different images taken from the same category and presented either in the same or mirror reversed orientation. Participants responded by key-press as quickly and accurately as possible to decide whether or not paired stimuli were identical regardless of their orientation (thus they should make a "same" response when S2 was a mirror image of S1). Each participant received two sessions of 240 randomly ordered trials. The order of the stimulation site was counterbalanced across participants. The experiment was therefore arranged in a 2 × 2 × 2 × 2 factorial design, treating

S1–S2 stimulus identity (same vs. different), orientation (same vs. mirror-flipped), category (words vs. objects), and magnetic stimulation site (L-OTC vs. R-OTC) as within-participant factors. In addition, we performed a third 240-trial session in nine of the 12 participants to assess a non-specific, global impact of TMS by applying the same level of magnetic pulse to a distant control region, i.e., the vertex (Vx, see Results).

TMS PROCEDURES

A high-resolution anatomical MRI was obtained for each participant prior to the TMS experiment. We selected the left and right OTC as target structures to assess the regional specific effects of TMS on mirror-image recognition. For the L-OTC stimulation, we targeted a posterior part of the left inferolateral temporal region ∼25 mm posterior to the lateral edge of the transverse temporal gyrus, which overlaps the a subpart of the L-OTC known as the VWFA (Dehaene et al., 2005). On each participant's MRI, a right homologous region was identified as a target structure in the R-OTC. The average coordinates of these cortical targets across participants were $x = -62$, $y = -60$, $z = -5$ for the L-OTC and $x = 61$, $y = -57$, $z = -5$ for the R-OTC (**Figure 1B**) according to the standardized brain space defined by the Montreal Neurological Institute. In addition, the Vx was selected as an active cortical control site for each participant.

A single-pulse TMS was generated using two MagStim 200 magnetic stimulators connected to a 70 mm figure-of eight coil through a BiStim module (Magstim, UK). The coil was kept tangential to the skull for stimulating the OTC and Vx with the handle pointing backward parallel to the midline. TMS pulse was applied 100 ms prior to the onset of S2 at an intensity of 60% of the stimulator power output, which corresponded to 80∼120% of the motor threshold of resting hand muscles. A single magnetic pulse at this stimulus intensity is estimated to suppress the local neuronal activity for approximately 100 ∼ 200 ms (Moliadze et al., 2003). Using a 3D-navigation system (Nexstim, Finland), we tracked the position and orientation of the coil relative to the head at the rate of ∼20 Hz to minimize their mutual displacement during the TMS session using our standard TMS procedures (see Nakamura et al., 2006, 2010).

RESULTS

EFFECTS OF TMS ON THE LEFT AND RIGHT OCCIPITOTEMPORAL REGION

Participants made only few errors during the same-different judgment task [mean error rate (*SD*) = 2.81 (1.91)%]. We assessed reaction time data for correct responses (**Figure 2**) using 2 × 2 × 2 × 2 ANOVA treating site (L-OTC vs. R-OTC), category (words vs. objects), orientation (same vs. mirror-reversed) and identity (same vs. different) as within-participant factors (outliers > 3 *SD* above the mean were excluded from this and all subsequent analyses). First, overall latency did not differ between words and objects ($F < 1$). However, participants responded 28 ms more slowly in L-OTC stimulation than in R-OTC stimulation, whereas this left-right difference in TMS was significant ($p = 0.003$). These effects interacted with each other ($p < 0.02$), suggesting that the left-right asymmetry in TMS effects was greater for words (35 ms) than for objects (20 ms).

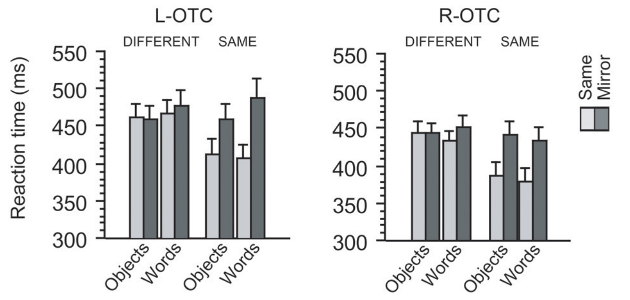

FIGURE 2 | Behavioral effects induced by the TMS of the left and right OTC. For each TMS site, mean reaction times during same-different judgment are illustrated with respect to the identity, category, and orientation of visual stimuli. For each site, participants responded similarly when S1 and S2 differed in identity from each other (i.e., "different" trials) irrespective of their category and orientation. In same-identity trials, however, participants responded more slowly when S1 and S2 were mirror images than when they were identical. Moreover, this mirror recognition cost was greater for words than for objects when TMS was applied to the L-OTC, whereas no such category-specific effect emerged when TMS was applied to the R-OTC.

On the other hand, participants responded 33 ms more slowly in mirror trials than in same trials. This effect of orientation was highly significant ($p < 0.001$), but interacted with the effect of category ($p < 0.02$), suggesting that the behavioral cost of mirror recognition was greater for words (41 ms) than for objects (25 ms). Furthermore, the main effect of identity was also significant ($p = 0.004$) and interacted with that of orientation ($p < 0.001$), suggesting a net component of cognitive processing cost for recognizing mirror images as being identical. Indeed, the effect-size of identity was much greater when paired stimuli were in the same orientation (56 ms) than in mirror-flipped orientation (3 ms). This finding was expected because the orientation difference between S1 and S2 should yield a recognition cost in making "same" responses only when the stimuli are mirror images, whereas the orientation of stimuli is not important in making "different" responses when S1 and S2 are totally different images (we therefore performed further analysis restricted to same identity trials, as described below). These effects of identity and orientation produced no triple interaction, either with site ($p > 0.1$) or with category ($F < 1$), but showed a significant quadruple interaction with site and category ($p = 0.04$). This last finding suggests that the recognition cost for assimilating mirror images increases for words relative to objects when TMS was applied to the L-OTC (see below). Other interactions were all non-significant ($p > 0.1$).

We then assessed the effects of site, category, and orientation by restricting the analysis to "same identity" trials. This analysis revealed significant effects of site ($p = 0.001$) and orientation ($p < 0.001$) but not that of category ($F < 1$). Participants responded to objects 10 ms faster than to words in L-OTC stimulation, whereas this trend was reversed in R-OTC stimulation (i.e., ∼7 ms faster to words than to objects), resulting in a significant cross-over interaction between site and category ($p = 0.01$). Response latency to objects was 51 ms slower in mirror trials than in same-orientation trials, whereas this "mirror recognition cost" (Pegado et al., 2014) was even greater for words (68 ms). Indeed, the effect of category on mirror recognition cost was marginally significant ($p = 0.06$). More importantly, there was a significant triple interaction between site, category and orientation ($p = 0.01$), suggesting that the between-category difference in mirror recognition cost was enhanced by the disruption of the L-OTC relative to that of the R-OTC.

EFFECTS OF TMS ON THE VERTEX

We then performed a third session with 240 trials in which TMS was delivered to a distant control region (Vx). The behavioral paradigm and TMS procedure were the same as those in the main experiment. This control experiment is required because magnetic stimulation of the R-OTC might change the activation level of the L-OTC via callosal connections between the left and right hemispheres. That is, neuropsychological and neuroimaging data show that these homotopic regions may exert a mutually inhibitory influence on each other (Forss et al., 1999; Fink et al., 2000; Ueki et al., 2006; Koch et al., 2008; Nakamura et al., 2012b).

Again, participants made few errors during the same-different judgment task [mean error rate (SD) = 4.52 (4.92)%]. Reaction time data for correct responses are presented in **Figure 3**. Since our main interest was to compare the behavioral effects of Vx stimulation with those of L-OTC and R-OTC, we ran a $2 \times 2 \times 2 \times 2$ ANOVA separately for each of the left and right OTC, treating site (OTC vs. vertex), category (words vs. objects), orientation (same vs. mirror-reversed), and identity (same vs. different) as within-participant factors. Therefore the critical comparison here is the main effect of site and its interaction with other factors.

First, the R-OTC vs. Vx comparison revealed that the main effect of site never approached significance (422 vs. 420 ms, $p > 0.5$). Moreover, this effect did not interact with any other factors ($p > 0.2$ for all interactions). Thus, these findings suggest that the behavioral effects induced by Vx stimulation did not differ significantly from those induced by R-OTC stimulation.

Next, the L-OTC vs. Vx comparison revealed that overall latency was slower in L-OTC stimulation (442 ms) than in Vx stimulation (420 ms), although this ∼22 ms difference did not reach significance ($p = 0.20$). The effect of identity was significant ($p = 0.003$) and produced a trend of interaction with the effect of site ($p = 0.1$). The effect of site interacted neither with that of orientation nor with that of category ($p > 0.2$ for both). These four factors (site, category, orientation, and identity) produced no significant triple interactions ($p > 0.2$ for all). Lastly, however, there was a significant quadruple interaction ($p = 0.01$), similarly to the comparison between L-OTC and R-OTC in the main experiment (see above). Thus, these results additionally support the previous finding that L-OTC stimulation produces a regional specific impact on the mirror recognition process.

COMPARISONS WITH A NON-TMS BASELINE

We further conducted a behavioral experiment without TMS with a separate group of 18 participants to determine the baseline pattern of mirror-image recognition during the same-different judgment task. These participants also made few errors during the same-different judgment task [mean error rate (SD) = 2.69 (1.88)%]. On the other hand, overall responses were >50 ms slower in this non-TMS experiment compared to the TMS experiment (see **Figure 3**). Probably, this large between-group difference should be attributed to some non-specific behavioral facilitation effects of TMS, known as "inter-sensory facilitation" (e.g., Terao et al., 1997). We therefore transformed reaction time data into a logarithmic scale to compare the mirror recognition cost between different sessions. The behavioral index for mirror recognition cost (**Figure 4**) was obtained by selecting only same-identity trials and then calculating log RT differences between same orientation trials and mirror trials for each category for each session.

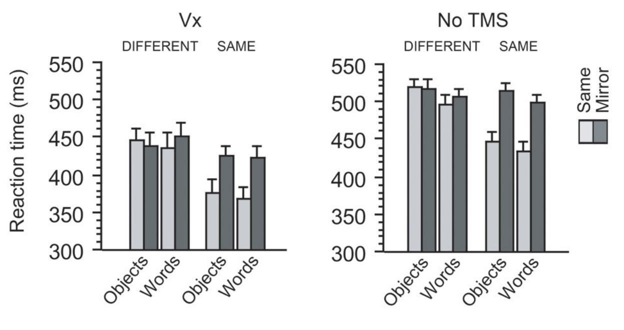

FIGURE 3 | Behavioral results in two control experiments. When TMS was applied to a control site (Vx) distant from occipitotemporal regions, participants showed the similar amount of mirror recognition cost between words and objects. This pattern of behavioral cost during mirror image processing was also observed when no TMS was applied during the same behavioral task. Thus, the effects of category, orientation, and identity overall produced the similar patterns of impact on reaction times between the two experiments (see Results).

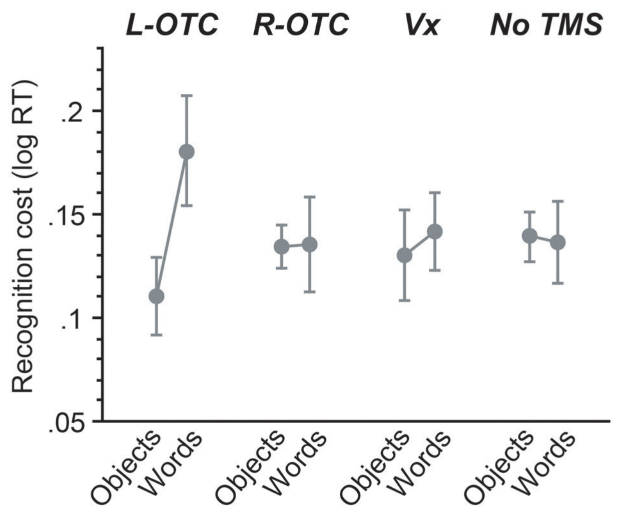

FIGURE 4 | Across-session comparisons for mirror recognition cost. For each session, the magnitude of mirror recognition cost was calculated by subtracting log-transformed reaction times for mirror trials from those for same-orientation trials. Magnetic stimulation of the L-OTC produced a large impact on mirror-image recognition for words but not objects, whereas all other sessions showed the similar pattern of behavioral effects without significant between-category differences (see Results).

For this mirror recognition cost, we then examined the effect of TMS and its interactions with other factors by contrasting each of the three TMS sites with the non-TMS control. First, the L-OTC vs. non-TMS comparison revealed no significant effect of TMS on mirror recognition cost ($F < 1$). However, there was a marginally significant effect of category ($p = 0.05$), suggesting that the magnitude of mirror-recognition cost was greater for words than for objects. Importantly, there was a significant interaction between TMS and category ($p = 0.03$), suggesting that the category-specific impact on recognition cost was greater for L-OTC relative to the non-TMS. On the other hand, both the R-OTC vs. non-TMS and the Vx vs. non-TMS comparisons revealed that the effects of TMS and category and their interaction were all non-significant ($p > 0.5$ for all). These findings suggest that the overall pattern of mirror recognition cost did not differ between R-OTC, Vx, and non-TMS sessions.

DISCUSSION

Recent brain imaging studies suggest that fluent reading rests on a distributed bilateral network extending from the lateral frontal region to ventral and dorsal visual areas (Dehaene et al., 2005; Cohen et al., 2008; Nakamura et al., 2012a). Since written language is a recent cultural invention dating back only ∼5000 years, this extensive reading network should be shaped by imposing learning-related plastic changes upon evolutionarily older neural systems as a function of cognitive processing demands of reading (see e.g., Szwed et al., 2014). In particular, mirror-image discrimination is likely to rely on such experience-dependent process occurring in the higher-order visual system during literacy development. That is, whereas the human ventral visual area involved in object recognition is generally known to represent visual objects and their mirror reversals as being the same (Eger et al., 2004; Vuilleumier et al., 2005; Dehaene et al., 2010b), the intrinsic propensity for mirror-image generalization should be partially suppressed through literacy training, since many writing systems include minimal pairs of mirror-image letters, such as "b" vs. "d" and "p" vs."q" (Dehaene et al., 2005). Literacy development is indeed likely to involve such unlearning process, because visual sensitivity to left-right orientation has been shown to increase with literacy acquisition (Kolinsky et al., 2011; Dunabeitia et al., 2013). At the neural level, the mirror-image discrimination during reading has been associated with a subpart of the L-OTC termed the VWFA (Dehaene et al., 2010a,b; Pegado et al., 2011).

In the present study, we examined whether or not the VWFA system previously associated with mirror-image discrimination comprises a local inhibitory mechanism for suppressing neural activations induced by mirror-reversed letter-strings. We observed that magnetic stimulation of the L-OTC interfered with mirror-image recognition more greatly for words than for other objects. In contrast, the transient disruption of the R-OTC did not produce such category-specific impact on mirror-image processing. Rather, additional analyses of control experiments showed that the main effects of category and orientation during R-OTC stimulation did not differ in effect-size from those obtained from the Vx and no-TMS sessions, suggesting that TMS of the R-OTC did not interfere with mirror-image recognition. These findings therefore suggest that the observed increase in mirror processing cost for words is a regional specific effect of L-OTC stimulation, which is distinct from the effects observed for other control sites, including R-OTC and Vx.

The present results further suggest that the L-OTC in itself does not exert inhibitory influence over mirror-image representations of letter-strings, because the visual processing of mirror words should be facilitated when such local inhibitory circuit is disrupted by the magnetic stimulation of the L-OTC. Rather, our results revealed that TMS of this region produced a significant delay in mirror-image recognition only for words and not for objects. Since the same-different judgment of visual stimuli and their mirror reversals relies on their shared, orientation-invariant representations, this finding concurs with the notion that the same part of the ventral visual system stores such higher-order, invariant identity of letter-strings (Dehaene et al., 2005). It is therefore likely that mirror-image discrimination during skilled reading does not occur inside the VWFA but rather involve other orientation-sensitive cortical regions, such as LOC (Eger et al., 2004; Vuilleumier et al., 2005) and PPC (Poldrack and Gabrieli, 2001).

Indeed, the left and right LOCs are thought to constitute a "posterior letter recognition system" involved in the visual analysis of letter shapes (Tarkiainen et al., 2002; Ellis et al., 2009). It seems rather plausible that literacy training develops a feed-forward mechanism favoring normally oriented words over their mirror images, since visual face recognition, i.e., another well-known example of expert visual recognition, is thought to rely on a strong structural and functional coupling between these extrastriate regions and OTCs that is at least partially enhanced by visual experience (Fairhall and Ishai, 2007; Gschwind et al., 2012). If this is the case, mirror-image discrimination may be achieved in the VWFA by collecting strong bottom-up activations of orientation-sensitive LOC neurons produced by normally oriented letters and filtering out weaker activations produced by mirror-reversed letters. Indeed, recent neurobiological data show that stimulus selectivity, at least for early visual cortex, is mediated by such feed-forward mechanism incorporating non-linear properties of cortical neurons (e.g., spike threshold, contrast saturation), rather than by classical lateral inhibition circuits (Priebe and Ferster, 2008). Thus, if the higher-order ventral visual area also relies on the similar feed-forward connections, the strong selectivity of the VWFA to normal oriented letters/words as observed in previous fMRI studies (Dehaene et al., 2010a; Pegado et al., 2011) may arise from a bottom-up activation of abstract orthographic codes driven by excitatory signals from the earlier, orientation-sensitive LOC regions.

On the other hand, mirror-image discrimination for letters may also partially rely on the dorsal visual pathway, including the PPC, which is generally known to be sensitive to the orientation of visual stimuli (Culham and Valyear, 2006) and modulate the activation level of the object-sensitive extrastriate areas in the control of spatial attention (Serences et al., 2004; Shomstein and Behrmann, 2006). Recent brain imaging data indeed suggest that the left and right PPCs participate in a tightly interconnected network for reading across different writing systems (Cohen et al., 2008; Nakamura et al., 2012a). Importantly, however, neuropsychological data suggest that damage to the PPC causes left-right disorientation for non-linguistic objects but not for letters (Davidoff and Warrington, 2001; Priftis et al., 2003; Vinckier et al., 2006). It is therefore possible that efficient mirror-image discrimination during reading is mediated by the ventral visual area independently of the parieto-occipital region (see Pegado et al., 2011 for further discussion). Even if this is the case, however, it is still open whether and to what extent mirror-image discrimination of letters can occur automatically without focused attention. Rather, it might rely on top-down allocation of spatial attention, since, for instance, mirror-image letters (e.g., "b" and "d") are more easily confused in peripheral vision than in central vision (Chung, 2010). Moreover, even mirror-image generalization, i.e., a more innate and intrinsic property of the ventral visual system and probably less attention-dependent process, seems to depend on spatial attention and does not occur automatically for unattended or unconsciously perceived visual stimuli (Bar and Biederman, 1998; Eger et al., 2004). Clearly, further behavioral and brain imaging data should be collected to determine the relative contribution of the dorsal attention-control system in mirror-image discrimination during expert visual word recognition.

To summarize, we found that mirror processing cost increased for written words and not for other objects when TMS was applied to the L-OTC. This finding suggests that this region *per se* does not comprise a local inhibitory circuit for suppressing mirror-image representations of letter-strings and better fits with a hierarchical model whereby the VWFA represents abstract identity of letter-strings by collecting feed-forward signals from earlier orientation-sensitive extrastriate regions (Dehaene et al., 2005). In addition, at the methodological side, an important advantage of TMS over other brain imaging techniques (e.g., fMRI, magnetoencephalography) is that it allows causal inferences about brain structure and function (Pascual-Leone et al., 1999). The present results hence provide new causal evidence showing that the L-OTC is specifically involved in mirror-image discrimination during fluent reading. Such visual expertise for letters would rely on a fine tuning of the ventral visual system through literacy development and thus represent a detectable behavioral-level signature of the literate brain.

ACKNOWLEDGMENT

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How does literacy break mirror invariance in the visual system?

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A growing literature has been showing a profound impact of alphabetization at several levels of the visual system, including the primary visual cortex (Szwed et al., 2014) and higher-order ventral and dorsal visual areas (Carreiras et al., 2009; Dehaene et al., 2010). Importantly, in typical alphabetization courses, learning to read is not isolated but instead combined with both learning to write and learning to segment the spoken language, relating all these different representations to each other. Indeed, learning to write and to pronounce the elementary sounds of language promotes additional mapping between the visual and motor systems by linking visual representations of letters and motor plans for handwriting and speech production. Thus, besides the already recognized influence of the phonological system, the potential influence from other neural systems in the functioning of the visual system seems to be relatively neglected. In this opinion paper we highlight the importance of multi-systems interplay during literacy acquisition, focusing on the question of how literacy breaks mirror invariance in the visual system. Specifically, we argue for a large contribution of top-down inputs from phonological, handwriting and articulatory representations toward the ventral visual cortex during the development of the visual word form system, which then plays a pivotal role in mirror discrimination of letters in literate individuals.

HOW PHONOLOGY AFFECTS VISUAL REPRESENTATIONS FOR READING

A key aspect of alphabetization is to set in place the audio-visual mapping known as "phoneme-grapheme correspondence," whereby elementary sounds of language (i.e., phonemes) are linked to visual representations of them (i.e., graphemes) (Frith, 1986). This correspondence is progressively acquired and becomes automatized typically after 3–4 years of training (Nicolson et al., 2001; Van Atteveldt et al., 2004; Lachmann and van Leeuwen, 2008; Dehaene et al., 2010; Lachmann et al., in this special issue). Illiterates, who do not learn this audio-visual correspondence, are unable to show "phonological awareness" (i.e., the ability to consciously manipulate language sounds) at the phonemic level (Morais et al., 1979; Morais and Kolinsky, 1994), presenting different visual analytical characteristics (Lachmann et al., 2012; Fernandes et al., 2014). Accordingly, activations in phonological areas increases in proportion to the literacy level of participants, e.g., *planum temporale* responses to auditory sentences and left superior temporal sulcus responses to visual presentations of written sentences (Dehaene et al., 2010). These results therefore suggest an important link between the visual and auditory systems created by literacy training. Indeed, the reciprocal interregional coupling between visual and auditory cortical areas may constitute a crucial component for fluent reading, since dyslexic children, who present slow reading, show reduced activations to speech sounds in the perisylvian language areas and ventral visual cortex including the Visual Word Form Area (VWFA) (Monzalvo et al., 2012).

HOW WRITING AFFECTS VISUAL REPRESENTATIONS FOR READING

In parallel, children (and adults) under alphabetization also learn to draw letters of the alphabet. Indeed, writing requires fine motor coordination of hand gestures, a process guided by online feedback from somatosensory and visual systems (Margolin, 1984). In particular, gestures of handwriting are thought to be represented in the dorsal part of the premotor cortex, rostral to the primary motor cortex responsible for hand movements, i.e., a region first coarsely described by Exner as the "graphic motor image center" (see Roux et al., 2010 for a review). Exner's area is known to be activated when participants write letters but not when they copy pseudoletters (Longcamp et al., 2003). Moreover, direct brain stimulation of the same region produces a specific inability to write (Roux et al., 2009). Importantly, this region is activated simply by visual presentations of handwritten stimuli (Longcamp et al., 2003, 2008), even when they are presented unconsciously (Nakamura et al., 2012). Additionally these activations take place in the premotor cortex contra-lateral to the dominant hand for writing (Longcamp et al., 2005). These results suggest that literacy training establishes a tight functional link between the visual and motor systems for reading and writing. In fact, it has been proposed that reading and writing rely on distributed and overlapping brain regions, each showing slightly different levels of activation depending on the nature of orthography (Nakamura et al., 2012). As for the reciprocal link between the visual and motor components of this reading network, brain-damaged patients and fMRI data from normal subjects consistently suggest that top-down activation of the posterior inferior temporal region constitutes a key component for both handwriting (Nakamura et al., 2002; Rapcsak and Beeson, 2004) and reading (Bitan et al., 2005; Nakamura et al., 2007).

HOW SPEECH PRODUCTION AFFECTS VISUAL REPRESENTATIONS FOR READING

While the impact of auditory phonological inputs for literacy acquisition has been well demonstrated (e.g., phonological awareness studies), relatively less explored has been the connection between the speech production system and other systems during alphabetization. Indeed, although all alphabetizing children already speak fluently, an unusual segmentation and refinement of motor plans for speech production should be learned to pronounce isolated phonemes, allowing a multisensory association (explicitly or implicitly) of these new fine-grained phonatory representations with visual and auditory representations. One study has shown activation in a cortical region involved in speech production (Broca's area) in relation to handwriting learning and letter identification (Longcamp et al., 2008). In fluent readers, the inferior frontal area involved in speech production in one hand and the VWFA in another hand show fast and strong inter-regional coupling (Bitan et al., 2005), which operates even for unconsciously perceived words (Nakamura et al., 2007). This distant visual and articulatory link mediating print-to-sound mapping is probably established during the earliest phase of reading acquisition and serves as a crucial foundation for the development of a dedicated reading network (Brem et al., 2010).

LITERACY ACQUISITION AS A MULTI-SYSTEM LEARNING PROCESS: THE EXAMPLE OF MIRROR DISCRIMINATION LEARNING

Taken together, these studies converge to the idea that far fromiinfar from a unimodal training on visual recognition, literacy acquisition is an irreducibly multi-system learning process. This lead us to predict that as one becomes literate, the expertise acquired through a given modality is not restricted to it, but can have an impact on other neural systems.

Perhaps the most spectacular case in point, and the one we choose to focus on in this article, is the spontaneous link between the motor and visual systems during literacy acquisition. This link is revealed in the beginning of the alphabetization process by the classic emergence of spontaneous mirror writing, i.e., writing letters in both orientations indistinctly (Cornell, 1985). Indeed our primate visual system presents a mirror invariant representation of visual stimuli, which enables us to immediately recognize one image independently of left or right viewpoints (Rollenhagen and Olson, 2000; Vuilleumier et al., 2005; Biederman and Cooper, 2009). This generates a special difficulty to distinguish the left-right orientation of letters (e.g., b vs. d) (Orton, 1937; Corballis and Beale, 1976; Lachmann, 2002; Lachmann et al. in this special issue). One account for the emergence of mirror writing is that writing gestures can be "incorrectly" guided by mirror invariant visual representations of letters, a framework referred to as "perceptual confusion" (see Schott, 2007 for a review on this topic).

In complement, recent studies demonstrate that *after* literacy acquisition, mirror invariance is lost for letter strings (Kolinsky et al., 2011; Pegado et al., 2011, 2014) and that the VWFA shows mirror discrimination for letters (Pegado et al., 2011); see figure upper part. Interestingly, in this special issue, Nakamura and colleagues provide evidence for the causal role of the left occipito-temporal cortex (encompassing the VWFA) in mirror discrimination by using transcranial magnetic stimulation. However, it is still an open question whether this region becomes completely independent to discriminate the correct orientation of letters or if it still depends on inputs from phonological, gestural, and/or vocal representations.

A MULTI-SYSTEM MODEL OF MIRROR DISCRIMINATION LEARNING

How is mirror discrimination acquired *during* the process of literacy acquisition? Here we sketch a model that takes into account not only the multisensory nature of alphabetization but also the multi-systems interplay, i.e., how representations in one system could influence the functioning of another system (e.g., mirror invariance in the visual system). In **Figure 1**, we present the hypothetical "multi-system input model" for mirror-letters discrimination learning during literacy acquisition. In order to correctly and rapidly identify letters for a fluent reading, the VWFA (in red) should visually distinguish between mirror representations of letters (see figure upper part). Top-down inputs from phonological, handwriting and speech production representations can provide discriminative information to the VWFA, helping this area that presents intrinsic mirror invariance, to accomplish its task of letter identification. This process probably requires focused attention (not represented in the figure) during the learning process and is likely to become progressively automatized. These top-down inputs toward the VWFA possibly influence this region to select relevant bottom-up inputs from lower-level visual areas (represented in pink in the figure) carrying information about the orientation of stimuli. For simplicity inter-hemispheric interactions are not represented here, but it should be acknowledged that during this learning process, local computations in the VWFA can include inhibition of mirror-inversed inputs from the other hemisphere.

Note that although we illustrate it by using mirror-letters (b-d or p-q), our model can eventually be extended to non-mirror letters, such as "e" or "r" for instance, given that each letter has a specific representation at the phonological, gestural (handwriting) and phonatory system. It cannot be excluded however that for these non-mirror letters, the simple

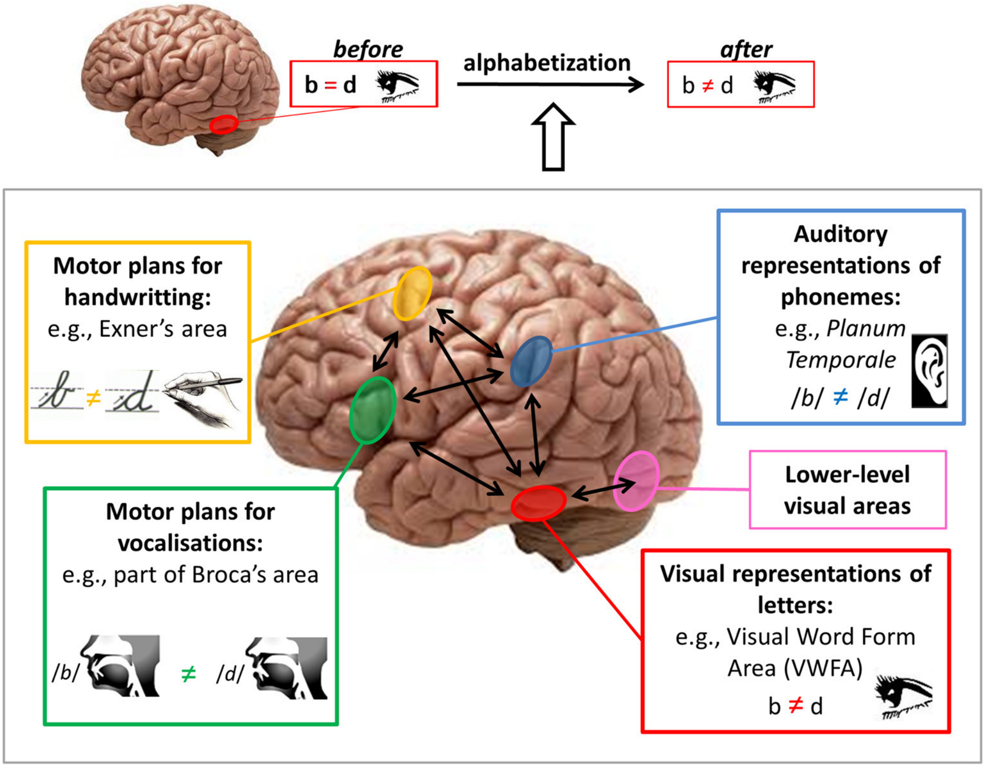

FIGURE 1 | Brain pathways for mirror discrimination learning during literacy acquisition. Upper: The Visual Word Form Area [VWFA] (in red) presents mirror invariance before alphabetization and mirror discrimination for letters after alphabetization. Lower: During alphabetization, the VWFA can receive top-down inputs with discriminative information from phonological, gestural (handwriting) and speech production areas and bottom-up inputs from lower level visual areas. All these inputs can help the VWFA to discriminate between mirror representations, thus correctly identifying letters to enable a fluent reading.

extensive visual exposure to their fixed orientation could, in principle, be sufficient to induce visual orientation learning for them. In contrast, this simple passive learning mechanism is unlikely to explain orientation learning for mirror letters given that both mirror representations are regularly present (e.g., b and d). Thus at least for mirror letters, the discrimination mechanism is more likely to involve cross-modal inputs, as represented in our figure. Accordingly, it is known that learning a new set of letters by handwriting produces a better discrimination of its mirror images than when learning by typewriting (Longcamp et al., 2006, 2008). Moreover, despite low performances in pure perceptual visual tasks in mirror discrimination, illiterates are as sensitive as literates in mirror discrimination on vision-for-action tasks (Fernandes and Kolinsky, 2013). Thus, inputs of gestural representations of letters influencing the VWFA perception could have a special weight in the processes of learning mirror discrimination.

It can also be expected that the existence of mirror letters forces the visual system to discriminate them, because it is necessary to correctly read words comprising mirror letters, such as in "bad" (vs. "dad") for instance. Moreover, evidence suggest that such mirror discrimination sensitivity in literates can be partially generalized to other visual stimuli such as false-fonts (Pegado et al., 2014) and geometric figures (Kolinsky et al., 2011). Thus, it is plausible that during literacy acquisition mirror letters could "drive" the learning process of letter orientation discrimination, eventually extending it for non-mirror letters. Accordingly, in writing systems that do not have mirror letters in their alphabet (e.g., tamil script), even after learning to read and write, literates still present difficulties in mirror discrimination (Danziger and Pederson, 1998). In addition, a superior mirror priming effect for inverted non-mirror letters (e.g., "r") relative to mirror letters (e.g., "b") has been reported (Perea et al., 2011), suggesting thus a more intensive automatic discrimination for mirror-letters in comparison to non-mirror letters.

Although it is not known how mirror discriminations of letters and words could be achieved in the complete absence of feedback from phonological, gestural or speech representations, recent empirical and computational modeling work on baboons, who can be trained to acquire orthographic representations in a purely visual manner (Grainger et al., 2012; Hannagan et al., 2014) paves the way to answer this question.

Acknowledging this multi-system interplay during literacy acquisition can have potential implications for educational methods. Interestingly, experiments have suggested that multisensory reinforcement can present an advantage for literacy acquisition: arbitrary print-sound correspondences could be facilitated by adding an haptic component (tactile recognition of letters) during the learning process (Fredembach et al., 2009; Bara and Gentaz, 2011). Large scale studies are now needed to test if promoting multi-system learning is able to provide a clear advantage in real life alphabetization.

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Let's face it: reading acquisition, face and word processing

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A TIGHT LINK BETWEEN READING ACQUISITION AND CHANGES IN FACE PROCESSING

The invention of writing is one of the most important cultural changes of mankind. Notably, because reading was invented only 5000 years ago, there was not sufficient time to evolve a brain system devoted to visual word recognition. Nevertheless, learning to read leads to the development of a strong response to written materials in the left fusiform gyrus, in the "visual word form area" (VWFA, e.g., Dehaene, 2009). Consequently, reading must rely on pre-existing neural systems for vision and language, which may be partially "recycled" for the specific problems posed by reading (Dehaene, 2005; Dehaene and Cohen, 2007). This consistent localization is related to prior properties of the corresponding tissue, which make it particularly suitable to the specific problems posed by the invariant visual recognition of written words (Dehaene, 2009): bias for foveal stimuli (Hasson et al., 2002), posterior-to-anterior increase in perceptual invariance (Grill-Spector et al., 1998; Lerner et al., 2001), and more direct projection fibers to language areas (Cohen et al., 2000; Epelbaum et al., 2008).

The neuronal recycling model predicts that, as cortical territories dedicated to evolutionarily older functions are invaded by novel cultural objects, their prior organization should slightly shift away from the original function (though the original function is never entirely erased). As a result, reading acquisition should displace whichever evolutionary older function is implemented in the site of the VWFA. In a recent fMRI study (Dehaene et al., 2010) comparing illiterate to literate adults, we showed that learning to read competes with the cortical representation of other visual objects, especially faces. With increasing literacy, cortical responses to faces decrease slightly in the left fusiform region, while increasing strongly in the right fusiform area (FFA). Thus, right-hemispheric lateralization for faces is increased in literates compared to illiterates. Consistent evidence was also reported when comparing 9-year-old normal readers and dyslexic children. Not only did responses to written words showed a greater left lateralization in normal readers, but responses to faces were also more strongly right lateralized (Monzalvo et al., 2012; cf. also Monzalvo, 2011).

Further developmental studies also reveal a tight link between reading acquisition and changes in face processing. Cantlon et al. (2011) demonstrated that 4-year-old-children show decreasing responses to faces in the left fusiform gyrus with increasing knowledge of letter and number symbols. Li et al. (2013) found for Chinese preschooler's a facilitative effect of early exposure to reading in neural responses to visual words. Such a facilitative effect had a temporary cost in neural response to faces, which did not show the mature pattern seen in adults. Dundas et al. (2012) studied the development of hemispheric specialization for written words and faces in children, adolescents and adults, and found that the left-hemispheric specialization for words develops prior to the right-hemispheric specialization for faces, with face lateralization related to reading comprehension ability (cf. also Pinel et al., 2014).

The competition between different categories seems to rely on enhanced neuronal specificity, namely on decreased responses to non-preferred stimuli as opposed to an increased response to the preferred category. Indeed, Cantlon et al. (2011) found a decrease for non-preferred stimuli in VWFA and FFA during child development. Joseph et al. (2011) reported both *progressive changes*, i.e., increasing face-specialization in a brain region with age, and *regressive changes*, i.e., decreasing face-specialization with age. Indeed, many brain regions recruited in children for face processing showed reduced specialization for faces by adulthood. Such regressive changes support the idea that some areas of the face network may lose out, at a cellular and a functional level, to promote specialization. Consistent with this scenario, in Pinel et al. (2014)'s study stronger leftward asymmetry for the VWFA and rightward asymmetry for the FFA were characterized by reduced activation in homolog areas of the contralateral hemisphere.

All these observations support the existence of competition for cortical space between the VWFA and the pre-existing neural coding of faces (Dehaene, 2005; Dehaene and Cohen, 2007; Plaut and Behrmann, 2011), with some displacement of fusiform face-sensitive areas toward the right hemisphere. A similar theoretical perspective (Nestor et al., 2012; Behrmann and Plaut, 2013) espouses a competitive interaction between distributed circuits for faces and word recognition for foveally-biased cortex, constrained by the need to integrate reading with the language system primarily left-lateralized.

Recently, we investigated the behavioral consequences of this brain reorganization (Ventura et al., 2013). Using the face composite task, we found that literates are consistently less holistic than illiterate individuals without any reading experience. The effect is not even specific to faces, but extends to houses. It thus seems that literacy induces a shift in the ability to deploy analytic visual strategies, over and above any specific effect that it may have on face processing, at least in tasks requiring selective attention to part of an object: it reduces automatic reliance on holistic processing when it is detrimental to the task by enabling the use of a more analytic and flexible processing strategy (Ventura et al., 2013). These findings are in apparent contradiction with Lachmann et al's (2012) study of congruence effects for letters vs. geometric shapes. Illiterates displayed negative CEs for both letters and shapes a finding which was interpreted as indicative of a generic and primary analytic perceptual processing strategy that is not reading specific, on par with the holistic strategy. In a previous study (Ventura et al., 2008) using the Framed-Line-test, we showed that both illiterates and ex-illiterates use context dependent/holistic processing. These apparently contradictory results most probably result from a host of factors including characteristics of the different stimuli, different task demands, and different meanings of analytic and holistic in these different studies.

In sum, the studies reviewed show that the acquisition of reading has an extensive impact on the developing brain and reveal a tight link between reading acquisition and changes in face processing. In the following section I evaluate whether reading acquisition leads to words becoming an object of visual expertise with some processing characteristics similar to faces and other objects of expertise.

WORDS AS AN OBJECT OF VISUAL EXPERTISE

Faces are made from common features (eyes, nose, mouth, etc.) arranged in the same general configuration. Thus, beyond the presence of specific features or the location of these features, subtle differences in facial features and their spatial relations are particularly useful for successful recognition of a given face (e.g., Maurer et al., 2002). To facilitate extraction of configural information people process faces holistically—as a whole—rather than as a collection of individual face features.

The many thousands encounters with visual words lead to a visual expert processing of these stimuli. Like in face processing, recognition of written words relies on both their features (e.g., letters) and the configuration between them. Recent work by Wong and colleagues adopting the sequential matching paradigm commonly used with faces showed HP to be a marker of expertise for perception of English words (Wong et al., 2011). Wong and colleagues also showed that HP of words was sensitive to amount of experience with the stimuli, with larger holistic processing for native English readers than Chinese readers who learned English as their second language. Holistic processing of Chinese characters also seems to develop as one acquires expertise (Wong et al., 2012). Indeed, expert Chinese readers displayed a larger holistic processing for characters than non-characters.

The larger holistic processing of words with reading experience seems in apparent contradiction with our evidence of smaller holistic processing of faces and houses (Ventura et al., 2013). This discrepancy may stem from differences in the processes that lead to the development of holistic processing in the face/object domain vs. word domain: fine subordinate-level discrimination among highly similar objects vs. the development with reading expertise of orthographic representations comprising multiple components that can be processed in parallel (Wong et al., 2012), enabling direct access to the lexicon. In this vein, it would be interesting to evaluate more directly the development of holistic processing of words as children develop reading proficiency. The beginning reader uses a letter-by-letter reading strategy. It is during this relatively slow process of phonological recoding that exposure to printed words enables the setting up of a specialized system for parallel letter processing (cf. Share, 1995; Grainger et al., 2012). One might predict a relationship between the development of this parallel orthographic processing and HP of words.

Although the same composite paradigm has been used to reveal HP for faces and words, this does not mean that the same mechanisms underlie the effects for the two domains (Chen et al., 2013). However, Chen et al. (2013) showed that HP of words has an early perceptual locus similar to that for faces. Nevertheless, the correlate of HP for characters was P1 (reflecting perceptual processing in extrastriate visual cortex) different from the N170 commonly found for face HP.

Reading is undoubtedly an expert visual function and these experiments show that word perception can be affected by holistic processes. However, there are fundamental distinctions between words and faces. The mature reading network comprises not only a visual shape analysis (VWFA system), but also components involved in print-to-sound translation and access to word meaning.

Considering print-to-sound translation, classic studies (e.g., Ziegler et al., 2000) have shown that upon seeing a written word both an orthographic and a phonological code are rapidly activated, although this last code lags slightly beyond the orthographic code. It is clear that the experiments of Wong and colleagues show HP for words: matching target parts of a word was interfered by the irrelevant parts, and such interference was reduced when the parts were misaligned. But this reduction with misalignment might result not (only) from disruption of visual configural processes, but (also) from a disruption of the phonological code. This question is the subject of ongoing research. One avenue is to compare computer vs. handwritten print. Letters in handwritten words are noisy, variable, and ambiguous and their physical forms are affected by neighboring letters and thus configural processes may assume a more prominent role in handwritten words (Barnhart and Goldinger, 2013). If the effects found in the word composite task are indeed due to configural visual processes, HP should be greater for handwritten words. If, however, the effects are, at least in part, due to disruption of phonological codes, there should be small differences between both types of words. Another avenue is to use words with letters that have different pronunciations (e.g., "rena," dear, and "remo," rowing, in which the "e" grapheme has different phonological values). If the effects reported above are purely visual, these different pronunciations should not influence the HP of words.

Another interesting point concerns the definition of the left and right parts of the (alphabetic) words used in the holistic paradigm. Written words have several linguistic units: syllables, onsets, and rimes, graphemes, and letters. In the experiments of Wong et al. (2011), for some stimuli the left-right division respects a division between two psycholinguistic units—onset and rime (e.g., cr|ew)—while for others the division straddles psycholinguistic units: onset and nucleus vs. coda (e.g., ki|ck). It would be interesting to compare systematically the holistic/configural effects for sets of words in which the left|right division respects a division between two psycholinguistic units vs. a left|right division that do no respect such a division. If the effects reported are indeed due to configural/holistic processes, they should occur even when the left|right division straddles psycholinguistic units.

In sum, words are psycholinguistics units comprising both perceptual and linguistic factors. The many thousands encounters with words by the typical literate person give rise to a perceptual expertise with effects similar to what has been observed for faces and other objects of expertise. However, further clarification of the origin of HP effects for words is needed.

In conclusion, reading acquisition leads to changes in face processing and extensive reading experience can result in expertise effects for words similar to what has been found for faces and other objects of face-like expertise.

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