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Research report

Blind readers break mirror invariance as sighted do

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ABSTRACT

Mirror invariance refers to a predisposition of humans, including infants and animals, which urge them to consider mirrored images as corresponding to the same object. Yet in order to learn to read a written system that incorporates mirrored letters (e.g., <b> vs. <d> in the Latin alphabet), humans learn to break this perceptual bias. Here we examined the role visual experience and input modality play in the emergence of this bias. To this end, we tested congenital blind (CB) participants in two same-different tactile comparison tasks including pairs of mirrored and non-mirrored Braille letters as well as embossed unfamiliar geometric shapes and Latin letters, and compared their results to those of age-matched sighted participants involved in similar but visually-presented tasks. Sighted participants showed a classical pattern of results for their material of expertise, Latin letters. CB's results signed for their expertise with the Braille script compared to the other two materials that they processed according to an internal frame of reference. They also evidenced that they automatically break mirror invariance for different materials explored through the tactile modality, including Braille letters. Altogether, these results demonstrate that learning to read Braille through the tactile modality allows breaking mirror invariance in a comparable way to what is observed in sighted individuals for the mirrored letters of the Latin alphabet.

1. Introduction

Reading is a cultural activity that requires considerable training and which is known to profoundly reorganize the brain and several cognitive functions (for a review, see Dehaene, Cohen, Morais, & Kolinsky, 2015), among which is *mirror invariance*. Also referred to as *mirror generalization*, mirror invariance typically refers to humans' (including 3-month-old infants, Bornstein, Gross, & Wolf, 1978) and other animals' (monkeys, pigeons and even octopuses) tendency to

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consider mirrored images – produced thanks to the reflection across a given axis – as corresponding to the same object even if they induce different retinal projections (for a review, see e.g., Corballis & Beale, 1976). Mirror invariance is an efficient property of the ventral visual system for the processing of various visual stimuli such as faces, animals and objects because it facilitates view-invariant object recognition (Baylis & Driver, 2001; Dehaene et al., 2010; Freiwald & Tsao, 2010; Logothetis, Pauls, & Poggio, 1995; Pegado, Nakamura, Cohen, & Dehaene, 2011; Rollenhagen & Olson, 2000). It needs however to be overcome during reading acquisition, or at least to be inhibited during letter recognition (e.g., Ahr, Houdé, & Borst, 2016; Borst, Ahr, Roell, & Houdé, 2015; Duñabeitia, Molinaro, & Carreiras, 2011; Perea, Moret-Tatay, & Panadero, 2011), in order for beginner readers of the Latin alphabet to differentiate mirrored letters such as and <d>, for example, and consequently master the script they are exposed to. Consistently, proficient readers of the Latin alphabet are able to discriminate between mirrored patterns, and are consequently unable to ignore mirrored contrasts even when this hinders performance (Fernandes, Leite, & Kolinsky, 2016; Kolinsky & Fernandes, 2014; Pegado, Nakamura et al., 2014), which attests that their visual system automatically encodes mirrored stimuli as being different. This is not the case of preliterate children who are known to make mirror errors when they start reading and writing (e.g., Fernandes et al., 2016) and of adults who either remained illiterate for socio-economic reasons (Kolinsky et al., 2011; Pegado, Comerlato et al., 2014) or who acquired a script that does not include mirrored characters (Danziger & Pederson, 1998; Pederson, 2003). In addition, it has been shown that, once triggered by literacy, the capacity to break mirror invariance generalizes to non-linguistic visual stimuli (e.g., Fernandes & Kolinsky, 2013; Kolinsky et al., 2011) and that this generalization is stronger for materials that resemble letters such as false-fonts or geometric shapes compared to pictures of familiar objects (Fernandes et al., 2016; Hannagan, Amedi, Cohen, Dehaene-Lambertz, & Dehaene, 2015; Kolinsky & Fernandes, 2014; Kolinsky et al., 2011; Pegado, Comerlato et al., 2014; Pegado, Nakamura et al., 2014).

Among the brain regions associated to reading is a region of the left ventral occipito-temporal cortex, commonly called the *visual word form area* (VWFA, Cohen et al., 2002). It is associated with literacy acquisition across different scripts (e.g., Baker et al., 2007; Bolger, Perfetti, & Schneider, 2005; Nakamura et al., 2012; Wu, Ho, & Chen, 2012) and is robustly activated when written strings of a known script are presented to sighted literates (for a review, see e.g., Dehaene & Cohen, 2011). It has been suggested that this region, part of the ventral occipito-temporal stream, is coopted for reading (Dehaene & Cohen, 2007) because it presents appropriate connectivity with the spoken language network (as indicated by functional/structural connectivity and co-lateralization studies, e.g., Bouhali et al., 2014; Cai, Lavidor, Brysbaert, Paulignan, & Nazir, 2008) and because it offers useful properties for written strings recognition such as some degree of abstraction, namely the ability to process letter strings identities irrespective of case, font, size or location in the visual field (e.g., Cohen et al., 2002; Dehaene et al., 2001, 2004; Qiao et al., 2010; but see; Rauschecker, Bowen, Parvizi, & Wandell, 2012). This brain region has also been described as underlying the ability to perform mirror discrimination of words (Dehaene et al., 2010) and of single letters (Pegado et al., 2011).

In short, acquiring a script that includes mirrored characters pushes sighted individuals to break mirror invariance for the characters they learn to read, and this effect generalizes to visual materials sharing visual similarity with the original script. Is this process limited to the visual modality, or can it generalize to any sensory input used to read, which would then reflect a more general perceptual computation not specifically tight to vision?

In line with this research question, the goal of this study was to test whether the developmental process of breaking mirror invariance depends, or not, on visual experience and visual inputs. The study of congenitally blind individuals provides a unique opportunity to test this hypothesis since most of them learn to read Braille, a written system relying on tactile exploration of embossed dot patterns that, in the same way as some of the Latin letters, are symmetric to each other. It is known that congenitally blind subjects efficiently detect (Cattaneo, 2017) and process the symmetry of tactile patterns (Cattaneo et al., 2010) among which Braille-like displays (Bauer et al., 2015), but their ability to break mirror invariance when they are exposed to a linguistic or a non-linguistic material had never been tested so far. We therefore developed a behavioral protocol specifically dedicated to the tactile exploration of mirrored and non-mirrored pairs of Braille letters and of embossed geometric shapes and Latin letters, and tested a large group of congenital blind (CB) Braille readers. More specifically, CB participants were tested in two same-different judgment tasks of simultaneously presented stimuli. One task assessed their expertise at processing different materials through the measure of their performance on mirrored items whose general orientation had to be taken into account and associated to a "different" response for successful performance (*orientation-based* task). The other task evaluated their ability to automatically break mirror invariance through mirrored items whose general orientation had to be ignored and associated to a "same" response for successful performance (*shape-based* task, cf. Fernandes et al., 2016; Kolinsky & Fernandes, 2014). Their results were compared to those of an age-matched group of sighted individuals tested on the same materials but presented visually. Given that these subjects were experts at processing Latin letters, we expected them to show a classical pattern of results for this material, namely a relative ease at considering mirrored items as "different" in the *orientation-based* task and a relative difficulty at considering mirrored items as "same" in the *shape-based* task. We also predicted that CB participants would be particularly good at the orientation-based task given their reported tactile acuteness with both Braille and other (including non-meaningful) tactile stimuli (Bauer et al., 2015; Goldreich & Kanics, 2003). Regarding the shape-based task, we foresaw that even though they acquired literacy through the tactile modality and in the absence of vision, CB participants would automatically break mirror invariance for all materials and especially for Braille letters, the material they had the most expertise with.