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Mirrors are hard to break: A critical review and behavioral evidence on mirror-image processing in developmental dyslexia

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ABSTRACT

The relation between *reversal* errors (e.g., d for b, Я for R) and developmental dyslexia has been elusive. In this study, we investigated the roles of reading level, visual category, and orientation processing in this relation. Children with developmental dyslexia, chronological-age-matched controls, and reading-level-matched controls performed two "same–different" matching tasks on reversible (e.g., b) and nonreversible (e.g., e) letters and on geometric shapes (e.g.,). In the *orientation-based* task, orientation processing was *explicitly* required; in the *shape-based* task, orientation processing would be *automatic* inasmuch as it was task irrelevant and would hinder successful performance. Two orientation contrasts were examined: mirror images (e.g., d–b) and plane rotations (e.g., d–p). For the latter, dyslexics behaved as controls; all were worse on shape-based judgments of plane rotation than on identical (e.g., d–d) pairs and were better able to attend to orientation than to shape. In contrast, for mirror images and across visual categories, dyslexics showed an advantage over typical readers on shape-based judgments. Both control groups had worse performance on shape-based judgments of mirror images than of identical pairs and exhibited similar magnitudes of mirror interference. Dyslexic children were the only group whose shape-based judgments were immune to mirror-image differences because they failed to automatize mirror discrimination during visual object processing. This deficit is not a consequence of reading level, is found across visual categories, and is specific to mirror images.

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Introduction

Reversal errors (henceforth *reversals;* e.g., d for b, Я for R) are common in beginning readers and seem to linger in those who struggle with reading (Fischer, Liberman, & Shankweiler, 1978; Liberman, Shankweiler, Orlando, Harris, & Berti, 1971; Terepocki, Kruk, & Willows, 2002; Wolff & Melngailis, 1996). Orton (1928) even suggested that reversals were a core symptom of *developmental dyslexia,* that is, a persistent neurobiological reading disorder despite motivation to learn and no general learning problem (e.g., Peterson & Pennington, 2015). However, after a century of research (Mach & Williams, 1897; Smith, 1928), the association between reversals and dyslexia remains elusive.

Reversals occur in visual recognition (e.g., Nelson & Peoples, 1975; Staller & Sekuler, 1975) and in writing (e.g., Cornell, 1985; Frith, 1971) for *reversible* letters (which differ solely by orientation contrast; e.g., d and b, n and u) and *nonreversible* letters (for which orientation is not a diagnostic feature; e.g., Я is not a letter of the Latin alphabet). Many factors have been ambiguous in this literature, precluding the understanding of the cognitive underpinnings of reversals. Although Orton (1928) distinguished reversals from *serial-order* errors (e.g., saw–was), and latter studies demonstrated their independence (e.g., Liberman et al., 1971; Lyle, 1969), they have occasionally been confused (e.g., Hildreth, 1934; Vellutino, Smith, Steger, & Kaman, 1975). Here, the term reversal is adopted only when referring to *mirror-image* errors (i.e., 180° reflection) of isolated stimuli. We present a critical review and an empirical study on the role of three factors in the association between reversals and dyslexia: orientation processing, reading level, and visual category.

During the first years of schooling, children with dyslexia present more reversals than typical readers of the same age (Liberman et al., 1971; Lyle & Goyen, 1968; Wechsler & Hagin, 1964; Wolff & Melngailis, 1996). These errors have been suggested to reflect a general difficulty in visual orientation processing by dyslexic readers and, hence, would occur for any orientation contrast (Graveson & Standing, 1986; Kaltner & Jansen, 2014; Terepocki et al., 2002). However, the tendency to confuse mirror images reflects an intrinsic property of visual object recognition called mirror-image generalization (Bornstein, Gross, & Wolf, 1978; Logothetis, Pauls, & Poggio, 1995; Rollenhagen & Olson, 2000), symmetry generalization (Lachmann, 2002; Lachmann & van Leeuwen, 2014), or *mirror invariance* (Dehaene, 2009; Dehaene, Cohen, Morais, & Kolinsky, 2015) that does not generalize to other orientation contrasts like rotations in the picture plane (henceforth *plane rotations;* e.g., 180° clockwise: u and n, d and p). Neurophysiological studies showed that the inferior temporal cortex, homologue of the human *ventral occipitotemporal* (vOT) region, part of the ventral visual stream dedicated to object recognition (Goodale & Milner, 1992), treats mirror images as the same percept but discriminates plane rotations (Logothetis et al., 1995; Rollenhagen & Olson, 2000).

These properties of the vOT do not merely reflect differences in visual similarity between mirror images and plane rotations. In terms of physical similarity to which the primary occipital cortex responds (Haushofer, Livingstone, & Kanwisher, 2008), the degree of overlap between mirror images and 180° plane rotations is the same and both have the same global shape. Stronger sensitivity to differences across the horizontal axis cannot explain it, given that mirror invariance also occurs across the horizontal axis (e.g., d–q) but does not generalize to plane rotations, both in humans (i.e., infants, children, and adults; e.g., Bornstein et al., 1978; Gregory, Landau, & McCloskey, 2011) and in other animals (Rollenhagen & Olson, 2000). Neuropsychological cases with the double dissociation pattern—that is, impairment in discrimination of mirror images and spared discrimination of plane rotations (mirror agnosia; e.g., Patient FIM in Davidoff & Warrington, 2001; Patient GR in Priftis, Rusconi, Umilta, & Zorzi, 2003) versus spared mirror discrimination and impaired plane-rotation discrimination (orientation agnosia; e.g., Patient SC in Turnbull, Beschin, & DellaSala, 1997)—demonstrate that discrimination of these orientation contrasts is (at least partially) supported by independent neural mechanisms. Thus, it seems that "when b is read as d the visual phenomena involved is quite different from that taking place when n is read as u" (Wechsler & Pignatelli, 1937, p. 217).

Most studies on dyslexia underestimated the difference between mirror-image and plane-rotation errors (e.g., Frith, 1971; Gibson, Pick, Osser, & Gibson, 1962; Graveson & Standing, 1986; Liberman et al., 1971), and these cannot be disentangled for symmetric stimuli (e.g., for the letter C, the mirror