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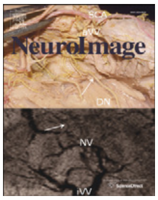

Visual print tuning deficits in dyslexic adolescents under minimized phonological demands

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ABSTRACT

The left ventral occipitotemporal cortex is reliably activated by visual orthographic stimulation and has repeatedly been found underactivated in developmental dyslexia. However, previous studies have made little effort to specifically probe orthographic processing while minimizing the need for higher-order reading related operations, especially phonological processing. Phonological deficits are well documented in dyslexia but may limit interpretations of ventral occipitotemporal underactivation as a primarily orthographic coding deficit, considering that different processing modes occur highly parallel. We therefore used a task that restricts higher-order processing to better isolate orthographic deficits. Thirteen dyslexic adolescents and twenty-two matched typical readers performed a low-level target detection task combined with rapidly presented stimuli of increasing similarity to real words during functional magnetic resonance imaging. The clear deviance found in impaired readers' left ventral occipitotemporal organization suggested deficits in print sensitivity at bottom-up processing stages that are largely independent of phonological operations. This finding elucidates print processing during a critical developmental transition from child- to adulthood and extends current accounts on left ventral occipitotemporal functionality.

Introduction

Developmental dyslexia (DD) is a learning disability of neurobiological origin with substantial familial and genetic risk (Pennington and Olson, 2008; Schulte-Körne et al., 2006). It is characterized by specific impairments in the acquisition of efficient reading, often accompanied by spelling difficulties. Impairments emerge despite conventional instruction, adequate intelligence and motivation (Lyon et al., 2003). DD is one of the most widespread disorders, affecting around 5% of school-aged children (Schulte-Körne, 2010; Schulte-Körne and Remschmidt, 2003). Converging evidence from neuroimaging studies in DD points to both structural and functional deficits in brain regions involved in reading, including inferior frontal, temporal, as well as parieto- and occipitotemporal regions of mainly the left hemisphere (Jobard et al., 2003; Richlan et al., 2009, 2011; Temple, 2002; Vigneau et al., 2006). The left ventral occipitotemporal (vOT) cortex has received increasing attention in dyslexia research (e.g., Richlan et al., 2011) given its robust response to orthographic stimulation in typical readers (e.g., Baker et al., 2007; Ben-Shachar et al., 2011; Cohen et al., 2002; Dehaene et al., 2002; Kronbichler et al., 2004; Vinckier et al., 2007; for a review, see Wandell, 2011) and given that lesions at this site may lead to alexia (Cohen et al., 2003; Dejerine, 1891; Starrfelt et al., 2009). Thus, this region is functionally associated with orthographic processing and coding, which in the present context refer to the visual (bottom-up) aspect of print processing, in contrast to phonological or semantic processing, which involve the access to the sound structure or the conceptual knowledge needed for understanding of words, respectively. The present conceptualization of orthographic coding comprises both coarse and fine print tuning based on our previous developmental work (e.g., Brem et al., 2009; Maurer et al., 2005, 2006). Coarse neural tuning of left vOT regions has been found for single letters or letter strings when contrasted with pseudofont or symbol strings (Baker et al., 2007; Brem et al., 2006; Brem et al., 2009; Maurer et al., 2005, 2006; Xue and Poldrack, 2007), while fine-tuning refers to the sublexical and whole word levels (Binder et al., 2006; Dehaene

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Abbreviations: DD, developmental dyslexia; FB, frequent bigram condition; FF, false font condition; IPL, inferior parietal lobule; M, mean; MTGp, posterior middle temporal gyrus; RB, rare bigram condition; ROI, region of interest; SD, standard deviation; SEM, standard error of the mean; SOA, stimulus onset asynchrony; STGp, posterior superior temporal gyrus; vOT, ventral occipitotemporal; W, word condition.

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et al., 2005; Glezer et al., 2009; Kronbichler et al., 2004; Vinckier et al., 2007) as for example reflected by orthographic measures of regularity like bigram (letter-pair) frequency. To further elucidate the level of vOT functionality and dysfunction in dyslexia is one main aim of the present study, as described below.

Importantly, left vOT regions have repeatedly been shown underactivated in dyslexic children (Maurer et al., 2007; Schulz et al., 2009; Shaywitz et al., 2002; van der Mark et al., 2009), adolescents and adults (Brambati et al., 2006; Brunswick et al., 1999; Helenius et al., 1999; Hoeft et al., 2007; McCrory et al., 2005; Paulesu et al., 2001; Richlan et al., 2010; Salmelin et al., 1996; Wimmer et al., 2010), with more extended underactivation in adults compared to children (for a meta-analysis, see Richlan et al., 2011).

However, with only one exception (Helenius et al., 1999) all of these studies explicitly or implicitly left ample opportunity to process presented letter strings in a phonological manner in addition to orthographic processing. Even if the functional role of left vOT regions are highly associated with orthographic processing, modulatory or re-entrant effects of, for instance, phonological processing are likely (Price and Devlin, 2011; Richardson et al., 2011; Twomey et al., 2011). Thus, findings of dyslexic vOT underactivation might at least in part be caused by phonological deficits, given that impaired learning of spelling–sound associations represents one of the core deficits in DD (Goswami, 2000; Ramus et al., 2003; Shaywitz and Shaywitz, 2005; Snowling, 2000; Vellutino et al., 2004). Hence, if task-related phonological processing is not reduced to a minimum, the complex interrelations of different processing stages in print processing may indeed limit interpretations of left vOT underactivation in DD as primarily an orthographic coding deficit.

In the present study, we adopted a task design intended to “restrict as much as possible top-down effects which can modulate or even reverse activation patterns in the visual cortex” (Vinckier et al., 2007), and building on evidence that vOT regions may particularly be probed by rapidly presented stimuli (Mechelli et al., 2000; Price et al., 1996). The present task therefore combines short stimulus duration (yet clearly above perception threshold) at high presentation rate with a low-level detection task as in Vinckier et al. (2007). While such a framework will reduce task-related and deliberate higher-order processes, task-unrelated automatic phonological and semantic access as advocated by current models of reading (Price and Devlin, 2011) will hardly be entirely suppressed. For instance, even subconsciously presented priming stimuli that share phonological and/or conceptual aspects with a subsequent target stimulus suffice to modify BOLD responses to those targets in left vOT regions (Kherif et al., 2011). On the other hand, there are also priming studies that emphasize the importance of task context even for subconscious phonological and semantic processes (Nakamura et al., 2007; Norris and Kinoshita, 2008). For instance, Nakamura et al. (2007) found the task set to influence which brain region showed response modulation by subconsciously perceived primes, suggesting that voluntary task control can affect involuntary, automatic processing. Hence, the present non-linguistic task might contribute to a reduction of automatic higher-order processes, although this cannot be determined with certainty. Taken together, we believe that this task provides an interesting framework for reliably probing vOT print sensitivity while reducing deliberate and possibly also automatic higher-order processes.

Four types of stimuli with increasing similarity to real words are used: (1) false font strings, (2) strings containing rare bigrams (i.e. pairs of letters that rarely adjoin), (3) strings containing frequent bigrams, and (4) real words. Vinckier et al. (2007) observed a left vOT posterior to anterior gradient of increasing orthographic specialization indicating that visual processing of real words activates more anterior vOT portions than, for example, rare bigrams or symbol strings. They concluded that the left vOT cortex becomes attuned to orthographic regularities during reading skill acquisition. Hence, it was hypothesized that in our adolescent sample (a) nonimpaired readers exhibit such a posterior to anterior gradient of increasing print sensitivity; and (b) that impaired readers lack such gradual specializations in this brain region (van der Mark et al., 2009). If true, we provide evidence that vOT dysfunctions in DD are relatively independent of the well-established phonological core deficit. Insights about vOT characteristics in adolescents are particularly valuable given that previous evidence is sparse and that they may contribute in clarifying the largely unresolved transitions from child- to adulthood in these regions (Richlan et al., 2011).

Methods

Participants

A total of 45 adolescents was recruited by the end of 9th grade, the last grade of compulsory schooling in Switzerland (Table 1). All were part of a longitudinal panel either tracked since kindergarten (~75% of participants) or since 5th grade (Maurer et al., 2003, 2007, 2011; Schulz et al., 2008, 2009). According to current and 5th grade reading scores, 22 adolescents were assigned to a nonimpaired reading group and 13 were categorized as reading-impaired (see below). The 8 participants falling in between these groups were only included in correlation analyses. One participant was excluded due to technical problems during recording, another one due to ADHD comorbidity (see below). Participants reported normal or corrected-to-normal vision. All were native speakers of (Swiss-) German. Nonverbal IQ fell in the range of ± 1 SD, except in one control subject (nonverbal IQ = 75; all critical statistical analyses were repeated firstly with nonverbal IQ as covariate and secondly after exclusion of this participant, leading to the same results). Adolescents and their parents gave informed written consent upon participation. The study was approved by the local ethics committee.

Screening for neurological diseases or psychiatric disorders indicated attention deficits/hyperactivity in one dyslexic female according to parents (Child Behavior Checklist, Achenbach, 1991) and self rating (Strengths and Difficulties Questionnaire, Klasen et al., 2003). This participant was excluded from all analyses (although core results remained significant if included). In order to assess reading level, subjects were tested for current word and pseudoword reading fluency (Salzburger Lesetest II, SLRT II, Moll and Landerl, 2010), sentence processing speed (Salzburger Lesescreening, SLS, Auer et al., 2005), and spelling ability (Rechtschreibungstest, Kersting and Althoff, 2004). In 5th grade, 15 participants had scored below 10% in word or pseudoword reading. Given that at present only 7 of them still had reading difficulties to this extent,

Table 1
Demographic characteristics of control and dyslexic participants (number or M ± SD) and group differences (*t*-tests or Fisher's exact test).

	Control	Dyslexic	*P*-value
n	22	13	–
Age (years)	15.9 ± 0.5	16.1 ± 0.7	n.s.
Sex (male:female)	10:12	8:5	n.s.
Handedness (right:left:ambidextrous)	18:4:0	10:2:1	n.s.
Handedness continuous	57.6 ± 68.0	48.8 ± 61.4	n.s.
Estimated verbal IQ	112 ± 10	108 ± 17	n.s.
Estimated nonverbal IQ	110 ± 14	107 ± 11	n.s.
Estimated working memory	101 ± 13	85 ± 11	$P<0.001$
Correctly read words/min			
Currently (9th grade)	115.8 ± 11.2	82.9 ± 13.1	$P<0.001$
5th grade	95.2 ± 13.7 (n = 21)	49.1 ± 8.6 (n = 12)	$P<0.001$
Correctly read pseudowords/min			
Currently (9th grade)	76.3 ± 13.4	44.9 ± 7.5	$P<0.001$
5th grade	56.3 ± 9.7 (n = 21)	30.3 ± 3.7 (n = 12)	$P<0.001$
Sentence processing speed	38.0 ± 7.6	25.8 ± 6.0	$P<0.001$
Spelling errors	14.4 ± 9.7	38.4 ± 7.2	$P<0.001$

M = mean and SD = standard deviation.