DYSLEXIA
Published online in Wiley Online Library
(wileyonlinelibrary.com). DOI: 10.1002/dys.1540

Is Reading Impairment Associated with Enhanced Holistic Processing in Comparative Visual Search?

Jiahui Wang[1]*, Matthew H. Schneps[2,3,4], Pavlo D. Antonenko[1], Chen Chen[3] and Marc Pomplun[2]

[1]*School of Teaching and Learning, University of Florida, Gainesville, FL, USA*
[2]*Department of Computer Science, University of Massachusetts at Boston, Boston, MA, USA*
[3]*Harvard Graduate School of Education, Cambridge, MA, USA*
[4]*Massachusetts Institute of Technology, Cambridge, MA, USA*

This study explores a proposition that individuals with dyslexia develop enhanced peripheral vision to process visual–spatial information holistically. Participants included 18 individuals diagnosed with dyslexia and 18 who were not. The experiment used a comparative visual search design consisting of two blocks of 72 trials. Each trial presented two halves of the display each comprising three kinds of shapes in three colours to be compared side-by-side. Participants performed a conjunctive search to ascertain whether the two halves were identical. In the first block, participants were provided no instruction regarding the visual–spatial processing strategy they were to employ. In the second block, participants were instructed to use a holistic processing strategy—to defocus their attention and perform the comparison by examining the whole screen at once. The results did not support the hypothesis associating dyslexia with talents for holistic visual processing. Using holistic processing strategy, both groups scored lower in accuracy and reacted faster, compared to the first block. Impaired readers consistently reacted more slowly and did not exhibit enhanced accuracy. Given the extant evidence of strengths for holistic visual processing in impaired readers, these findings are important because they suggest such strengths may be task dependent.

Keywords: dyslexia; impaired readers; visual–spatial talent; comparative visual search; holistic processing

INTRODUCTION

Five to ten percent of school-aged children are identified with developmental dyslexia (Shaywitz, 1996). It is a consensus that people with dyslexia exhibit subpar reading ability compared to normal readers (Orton, 1925; Geschwind, 1982), which cannot be attributed to a lack of educational opportunities or neurological damage (World Health Organization, 2004). Dyslexia is also characterized by impairments in a range of tasks including word identification, phonological decoding, and spelling.

*Correspondence to: Jiahui Wang, University of Florida, Norman Hall G518, 1221 SW 5th Avenue, Gainesville, FL 32611, USA. E-mail jwang01@ufl.edu

While most dyslexia research has focused on the remediation of deficits associated with dyslexia, some scholars have suggested that individuals with reading difficulties develop compensatory mechanisms that rely on visual–spatial processing brain networks (e.g., Diehl *et al*., 2014). It is important to examine this hypothesis because many fields of human activity depend greatly on visual–spatial processing in general and comparative visual search (CVS) (Pomplun *et al*., 2001) and mental rotation specifically (Uttal & Cohen, 2012). For example, structural geologists employ visual–spatial processing skills to understand the composition of solid earth materials and infer the processes that influenced the formation of current geological features. Radiologists engage in complex visual search to examine two-dimensional and three-dimensional scans and identify anomalies such as cancer nodules (Wolfe, Evans, Drew, Aizenman, & Josephs, 2015). The contribution of visual–spatial processing skills to performance in science, technology, engineering, and mathematics is so significant that it holds even when controlling for other relevant abilities, such as verbal and mathematical reasoning (Wai, Lubinski, Benbow, & Steiger, 2010). Importantly, visual–spatial skills are also malleable—they respond positively to life experiences and learning interventions (e.g., Terlecki, Newcombe, & Little, 2008; Wright, Thompson, Ganis, Newcombe, & Kosslyn, 2008).

CONCEPTUAL FRAMEWORK

Visuospatial Talents Associated with Dyslexia

Despite focus on remediation of deficits associated with dyslexia (Shaywitz, Weiss, Saklofske, & Shaywitz, 2015), some scholars have examined the potential for strengths and improvements in certain aspects of attentional and cognitive processing that individuals with dyslexia may exhibit compared to normal readers (for a review, see Gilger, Allen, & Castillo, 2016). For example, Von Károlyi, Winner, Gray, and Sherman (2003) reviewed existing evidence and claims regarding the existence of the so-called 'visual–spatial talent' in individuals with dyslexia. In their own studies, these authors have found that in certain visual–spatial tasks such as the impossible figures task, individuals with dyslexia were found to possess a talent in processing visual–spatial information holistically rather than locally (Von Károlyi *et al*., 2003; Von Karolyi & Winner, 2004). Geschwind (1982) suggested '…many people with dyslexia have superior talents in certain areas of non-verbal skill, such as art, architecture, engineering, and athletics' (p. 22). Some observers note that visual–spatial talent may be the cause for why many individuals with dyslexia excel in such fields as art (Chakravarty, 2009; Wolff & Lundberg, 2002), architecture (Rosstad, 2002), sciences (Schneps *et al*., 2011), and so on.

The empirical evidence for the viability of dyslexia related visual–spatial talent is controversial, and no current theory explains or predicts the potential processing advantages in individuals with dyslexia (Diehl *et al*., 2014), beyond such theories as 'pathology of superiority' (Geschwind & Galaburda, 1987) that discuss possible compensatory mechanisms but fail to provide compelling empirical evidence to support their claims. Some studies employing non-language visual–spatial tasks have reported that individuals with dyslexia have some superior visuospatial abilities and advantages for image memory (e.g., Hedenius, Ullman, Alm, Jennische, & Persson, 2013; Howard, Howard, Japikse, & Eden, 2006; Schneps, Brockmole, Sonnert, & Pomplun, 2012). Others have found comparable visual–spatial abilities (Bacon, Handley, & McDonald, 2007; Sinatra, 1988). And then there are studies that suggest diminished visual–spatial abilities in those with reading difficulties (Eden, Stein, Wood, & Wood, 1995; Morris *et al*., 1998). As we can see, the findings are mixed, and more empirical research is needed to examine the possible visual–spatial processing differences between individuals who have dyslexia and those who do not.

Dyslexia and enhanced peripheral vision

The possibility of dyslexia related visual–spatial talent can be discussed in the context of research investigating an association between dyslexia and enhanced sensitivity to peripheral visual processing. For example, Schneps, Rose, and Fischer (2007) reviewed the literature on visual learning and implications for dyslexia and suggested that perhaps a subset of individuals with dyslexia exhibit associated advantages for peripheral visual processing. This is contrasted with poor response characteristics in the central visual field. This bias towards the periphery could be advantageous in situations calling for contemporaneous comparative operations but disadvantageous in tasks where sequential visual discrimination is required. In terms of empirical evidence, only a few research studies have examined whether individuals with dyslexia have a better peripheral vision than normal readers. Empirical evidence showed individuals with dyslexia exhibit a visual bias towards the periphery and excel in tasks where peripheral vision needs to be used (e.g., Lorusso *et al*., 2004; Schneps *et al*., 2011). It has been demonstrated in several studies individuals with dyslexia could distribute their visual attention much further to the periphery, compared to normal readers. For example, Geiger and Lettvin (1987) used a mechanical shutter to briefly flash letter pairs, with one in the centre of fixation, and the other in the periphery, varying the peripheral angle. Participants' ability to simultaneously name the letter pairs was measured. Researchers found that individuals with dyslexia outperformed normal readers in identifying the letters that were located in the outer reaches, but were less able to do so near the centre field of vision. Using Geiger's setup, another two studies confirmed that individuals with dyslexia have a broader peripheral vision (Lorusso *et al*., 2004; Perry, Dember, Warm, & Sacks, 1989). Using a different paradigm, a black hole detection task, Schneps *et al*. (2011) found that astrophysicists with dyslexia significantly outperformed their counterparts without dyslexia in detecting radio signatures characteristic of black holes in a laboratory simulation, when the peripheral angles involved in the task were large. Another study compared reaction times for the perceptions of randomly presented 20-ms flashes at 16 cardinal locations and found enhanced peripheral response among individuals with dyslexia (Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000).

Individuals with dyslexia benefit from holistic processing

It was suggested decades ago that individuals with dyslexia tend to process visuospatial information holistically rather than sequentially. Orton (1925) indicated that individuals with dyslexia possess superior abilities in certain visual–spatial domains. Benton (1984) noted that individuals with dyslexia tend to use holistic processing strategy more than normal readers do, and individuals with dyslexia have comparable or even superior holistic processing of visuospatial information. It has been suggested that a bias towards holistic processing in individuals with dyslexia can be attributed to enhanced peripheral vision, particularly during visual search tasks (Schneps *et al.*, 2012). Von Károlyi *et al.* (2003) found individuals with dyslexia excel in visuospatial tasks that require integration of distributed visual–spatial information. Their own studies revealed that individuals with dyslexia were faster than normal readers in determining whether a figure is impossible, without sacrificing the accuracy. Impossible figure is an example of an optical illusion, which represents objects that look three dimensional at first sight, but could not actually exist in real world. The impossible figure is identified as a global visual–spatial task and only by examining the figure holistically does the participant decide the figure is impossible (Von Károlyi, 2001; Von Károlyi *et al.*, 2003).

Dyslexia and enhanced visual memory

Potential advantages in visual–spatial processing in individuals with dyslexia may facilitate visual memory. Hedenius *et al.* (2013) used an object recognition memory task to test declarative memory among individuals with and without dyslexia, and found that individuals with dyslexia showed superior recognition memory. Three other studies also showed that individuals with dyslexia have a better visual memory for spatial layouts in scenes using the contextual cueing paradigm (Chun & Jiang, 1998). In the contextual cueing task, spatial configurations of the target and distractor items occasionally repeat, while others vary. Participants become faster at locating the target in repeated search displays compared to novel ones, which implies that learning of spatial context facilitates efficient visual search for the target. In a visual learning study, Schneps *et al.* (2011) found when images of natural scenes were Gaussian-blurred, individuals with dyslexia significantly outperformed normal readers in learning the spatial contexts. Similarly, Schneps *et al.* (2012) found that participants with dyslexia significantly outperformed normal readers in contextual cueing when contexts were low-pass filtered natural scenes, while no difference was found in contextual-cueing when spatial contexts were letter-like objects, or when contexts were natural scenes. Another study (Howard *et al.*, 2006) showed that, although participants with dyslexia were impaired on the serial response time task, they marginally outperformed normal readers in implicit spatial context learning, using the contextual cueing task. A negative correlation between reading ability and spatial context learning was also found, supporting the suggestion that individuals with dyslexia may excel in spatial context learning.

Neuroscientific evidence regarding dyslexia and visual–spatial talent

So, what factors can account for the possible differences between individuals with dyslexia and normal readers in visual–spatial processing tasks? Neuroanatomical studies suggested that the brains of individuals with dyslexia are atypical in the structure and development (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985). Evidence generated by cognitive neuroscientists is consistent with the possibility that brains of individuals with dyslexia develop dedicated networks assisting with visual–spatial processing that are different from the neural networks developed in normal readers (Riccio & Hynd, 1996). Gilger, Talavage, and Olulade (2013) examined neurophysiology of dynamic 3D spatial problem solving among normal dyslexia, gifted dyslexia, normal non-dyslexia, gifted non-dyslexia, and found gifted individuals with and without dyslexia show very different brain activation patterns during the mental rotation task. Similarly, Diehl *et al.* (2014) showed that behaviourally, the lower reading ability was related to a visual–spatial processing advantage (shorter latencies and equivalent accuracy) on a mental rotation task and an impossible figures task. fMRI data in this study revealed that typically developing readers showed increased right hemisphere responses suggesting that they processed images in a more effortful manner compared to those with reading difficulties. Diehl and associates (Diehl *et al*., 2014) explained that this finding could be attributed to a 'neural tradeoff', a set of compensatory mechanisms, which occurs as a consequence of poor reading.

Development of compensatory mechanisms modifies the way brain networks interact, which means individuals with dyslexia may use certain regions of the brain more often or use the reading-specific regions to perform spatial-related activities (Witelson, 1977). Dehaene and Cohen (2007) proposed the neuronal recycling hypothesis, which represents 'extension of human brain abilities in a radically novel direction, not anticipated by evolution, but made possible by a cultural invention that cleverly exploits cortical circuitry' (p. 393). They found as people learn to read, certain visual–spatial processing abilities are impaired, and as individuals with dyslexia do not use certain parts of the brain for reading just as normal readers do, neurons can be recycled and be utilized for other purposes, such as visual–spatial processing.

Comparative Visual Search

An important visual–spatial processing task is CVS, which is used in such diverse areas as geology, chemistry, palaeontology, topography, radiology, and so on. This is also a task with potential for visual–spatial talent associated with dyslexia specific compensatory mechanisms related to visual–spatial processing. Based on previous findings (e.g., Von Károlyi *et al*., 2003; Von Karolyi & Winner, 2004; Schneps *et al*., 2007), to manifest visuospatial talents associated with dyslexia, the task should rely at least partially on holistic processing of visual stimuli such as an impossible figure task (Von Károlyi *et al*., 2003) or a face recognition task (Tanaka & Farah, 1993). The question of interest to the present study is whether individuals with dyslexia might exhibit visual–spatial advantage within a task that employs either holistic processing strategy where individuals with dyslexia are expected to outperform normal readers or traditional sequential processing strategy that is usually adopted to accomplish a visual search task via local memorization and comparison of displayed items (Pomplun, 1998).

While the task used in Schneps *et al*. (2012) found significant effects of spatial learning in low-pass filtered natural scenes favouring dyslexia, previously, Howard *et al*. (2006) used a contextual cueing task composed of graphical symbols and found similar advantages. This is contrasted with simple visual search where those with dyslexia generally show disadvantages (e.g., Franceschini *et al*., 2012), consistent with deficits in spatial attention. However, the response to CVS task, which combines characteristics of simple search and contextual cueing, here using simple graphical symbols, is unknown, making this of interest.

In the current study, a CVS design (Pomplun *et al*., 2001) was employed in which participants compared two halves of a visual display each comprising three kinds of shapes in three colours, presented side by side. CVS is a variant of the visual search task. In a visual search task, participants would perform feature search if the two parts are compared in a single dimension (e.g., colour), or a conjunctive search if two parts are compared in more than one dimension (e.g., colour and shape; Treisman & Gelade, 1980). CVS requires participants to conduct a conjunctive search between two halves of the display and decide if the two halves are identical for the displayed items. A CVS task should require the participant to switch between two halves of the display several times to hold and compare multiple chunks of items before s/he could decide whether the two halves are identical or different. Human cognitive architecture allows an individual to hold only about 4 items at a time (Cowan, 2001), so holding multiple items (e.g., three sets of different shapes in three different colours) from the left half of the display in working memory all at once while comparing these items to the items in the right half of the display seems impossible. Because CVS requires observers to directly compare portions of the scene widely separated in space, one would expect that use of holistic processing engaging peripheral vision would result in more accurate and efficient search than the less optimal focal processing strategy performed sequentially. Several studies have found that individuals with dyslexia exhibit a significantly wider peripheral vision, enhanced visual memory, and superior holistic processing, so it is reasonable to expect that impaired readers will benefit from holistic processing to examine the entire screen at once in CVS and will outperform normal readers on the measures of accuracy and reaction time.

Based on the conceptual framework, the current study was designed to answer the following research question:

- To what extent does holistic processing influence CVS accuracy and reaction time in impaired readers compared to normal readers?

METHODS

Participants

After obtaining an approved IRB from a large Northeastern university in the United States, a group of undergraduate students was approached about participating in the study and underwent the study screening process. Each participant's literacy profile was assessed using Sight Word Efficiency and Phoneme Decoding Efficiency from Test of Word Reading Efficiency (TOWRE) (Torgesen, Wagner, & Rashotte, 1999), as well as Rapid Letter Naming, Rapid Digit Naming, and Elision from the Comprehensive Test of Phonological Processing (CTOPP) (Wagner, Torgesen, & Rashotte, 1999). For tests that were designed for individuals aged up to 24, we applied the 24-year-old norm to people of all ages. If a participant ranked at the bottom 35 percentile on at least two of the five tests, s/he was categorized as impaired reader. Additionally, the visual attention span task was administered for each participant using a six-letter global report method (Bosse, Tainturier, & Valdois, 2007). Eighteen individuals were diagnosed with dyslexia and invited to participate in the study. The group of impaired readers was matched with a comparison group of 18 normal readers. The final participant pool included 36 undergraduate students (age 18–60, average age 26), 14 of whom were male and 22 were female. Twelve participants wore glasses or contact lenses and 24 did not. All participants had normal or corrected to normal vision. Fifteen participants were nearsighted, and three were farsighted. No participant was colourblind or had any neurological disorders. Using Adult Attention Deficit Hyperactivity Disorder (ADHD) Self-Report Scale (ASRS-V1.1) Symptom Checklist (Kessler *et al.*, 2007), 8 of 18 normal readers and 4 of 18 impaired readers were identified as having comorbid ADHD. Demographics data and the scores for neurocognitive behavioural tests used in the study are provided in Table 1.

Apparatus

CVS stimuli were presented on a 13.3-inch Apple MacBook Pro Retina screen laptop viewed at 50-cm distance, with 2560–1600 resolution at 227 pixels per inch with support for millions of colours (see Figure 1). The luminance was set to a black level of approximately 0.8 cd/m^2 and a white level of 118.7 cd/m^2. A programme written in PsychoPy (Peirce, 2008) was used for stimuli presentation and data acquisition. In order to remain at 50-cm distance from the computer screen, participants used a chinrest (SR-HDR) with a forehead bar to minimize head movement. Ambient room luminosity was between 314.0 lux and 423.0 lux.

Stimulus

The experiment presented two blocks of 72 trials. Each trial consisted of two pictures to be compared side-by-side. Each block included 18 trials different in colour, 18 trials different in shape, and 36 trials identical in both shape and colour, amounting to a total number of 72 presented comparisons per block. A different set of pictures was used for the second block when participants were instructed to employ the holistic processing strategy. The stimuli for the CVS task in the current study were adapted from stimuli used in prior experiments (Pomplun *et al.*, 2001). For each comparison, two side-by-side pictures served as stimuli on a gray

Table 1. Participant characteristics

	Normal readers	Impaired readers
Gender	13 F, 5 M	9 F, 9 M
Age	25.50 (9.54)	26.33 (9.09)
Wear glasses	8 Y, 10 N	4 Y, 14 N
Sight	1 farsighted, 9 nearsighted, 8 normal vision	2 farsighted, 6 nearsighted, 10 normal vision
ADHD	8 identified as ADHD	4 identified as ADHD
Standardized scores		
Elision	9.11 (2.78)	7.89 (2.85)
Rapid digit naming ***	12.44 (2.20)	9.44 (2.28)
Rapid letter naming	16.00 (17.94)	7.56 (1.82)
Phoneme decoding efficiency**	108.00 (9.85)	98.17 (8.32)
Sight word efficiency*	109.56 (5.82)	93.06 (26.87)
Memory for digit	12.00 (1.64)	11.00 (2.52)
VASPAN*	3.85 (0.82)	3.32 (0.47)

*$p < .05$.
**$p < .01$.
***$p < .001$.

Figure 1. Experimental setup for comparative visual search task. (Note: keyboard shown here differs from the Apple wireless keyboard used in the experiment.)

computer screen background (each has a resolution of 1024×768 pixels, separated by a vertical white line; see Figure 2). The brightness of the computer screen display was set to the highest level. The area containing the shapes subtended 5.062° of visual angle horizontally and 8.231° vertically and that each shape subtended 0.953° of visual angle horizontally and 0.953° vertically at the 50-cm viewing distance. Each half of the display contained three types of shapes (triangle, diamond, square), with each shape being displayed in one of the three colours (red, green, blue) for a total of 12 shapes per half of the display. Participants performed a conjunctive search to ascertain whether the two halves were identical in both colour and shape.

Procedures

All 36 participants performed 72 randomized trials in each of the two blocks. Participants were instructed to react as quickly as they could, without sacrificing accuracy. In the first block, participants were provided no instruction regarding

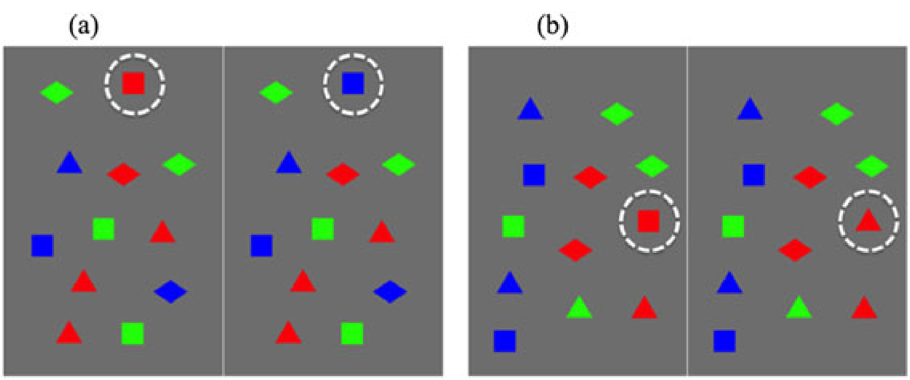

Figure 2. Examples of randomly generated stimulus displays with the difference in colour (a) and shape (b), respectively.

the visual processing strategy they were to employ. It was assumed that the participants employed a sequential processing strategy in this condition (e.g., Pomplun, 1998; Pomplun *et al*., 2001). In the second block, participants were instructed to use a holistic processing strategy—to defocus their attention and perform the comparison by examining the whole screen at once. In both blocks, participants indicated their decision using an Apple wireless keyboard by pressing the 'L' key for 'two halves of the display are different' and pressing the 'S' key for 'two halves are same'. Both keys were identified with stickers in different colour and touch to be more evident to participants. For all experimental trials, feedback about accuracy and reaction time was given to participants after they responded to each comparison on the computer screen. To avoid bias caused by task novelty, participants practiced 19 comparisons before actual data collection. Participants took a short break after the first block of CVS.

Results

Data were analysed using a 2 group (normal typical readers vs. impaired readers) × 2 block (sequential processing vs. holistic processing) × 3 trial type (same vs. differ in colour vs. differ in shape) analysis of variance (ANOVA) design. Group served as the between-subjects measure, and both block and trial type served as repeated measures. In the current study, the data sources included participants' reaction times (in seconds) and accuracy rates (in percent) for each block of CVS. A mixed ANOVA was conducted for accuracy and reaction time to examine potential differences between impaired readers and normal readers and to explore the possibility of dyslexia-specific visual–spatial talent during this task.

Accuracy

The results indicate that the effect of block on accuracy was statistically significant, $F\,(1, 34) = 74.822$, $p < .05$, $\eta^2 = .688$. Block 1 (sequential processing) accuracy was significantly lower than the accuracy within block 2 (holistic processing), controlling for the effect of participant group and trial type. We also found the effect of trial type on accuracy was statistically significant, $F\,(1, 34) = 138.178$, $p < .05$, $\eta^2 = .803$. Table 2 presents the descriptive statistics for accuracy in three trial types for both groups from block 1 to block 2 of the CVS task. Not surprisingly, when the trials presented identical halves, the accuracy score was highest. And when the trials contained differences in shape, the accuracy score was the lowest.

The results also indicated that the block × trial type interaction was statistically significant, $F\,(1, 34) = 6.273$, $p < .05$, $\eta^2 = .156$. Figure 3 illustrates the greatest drop

Table 2. Descriptive statistics for accuracy (%) in three trial types for both groups from block 1 (sequential processing) to block 2 (holistic processing) of the comparative visual search task

	Differ in colour		Same		Differ in shape	
	Block 1	Block 2	Block 1	Block 2	Block 1	Block 2
Impaired readers	0.86 (0.13)	0.72 (0.23)	0.97 (0.04)	0.85 (0.19)	0.65 (0.18)	0.4 (0.17)
Normal readers	0.82 (0.16)	0.60 (0.24)	0.96 (0.05)	0.85 (0.17)	0.66 (0.21)	0.36 (0.14)

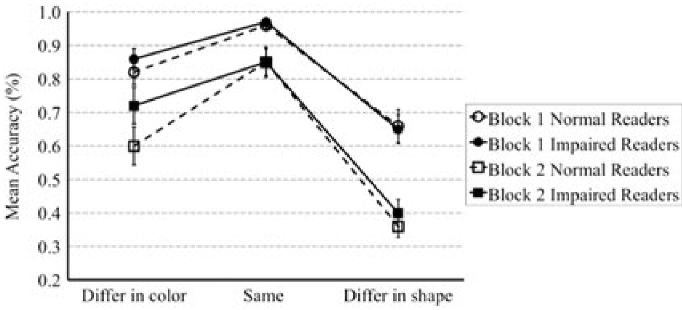

Figure 3. Mean accuracy in three trial types for both groups from block 1 (sequential processing) to block 2 (holistic processing) of the comparative visual search task.

in accuracy from block 1 (sequential processing) to block 2 (holistic processing) took place when the trials contained differences in shape, for both impaired readers and normal readers. The summary of the mixed ANOVA for accuracy is presented in Table 3.

Reaction time

The results indicate that the effect of block on reaction time was statistically significant, controlling for the effect of participant group and trial type, F (1, 34) = 36.720, $p < .05$, η^2 = .519. Participants took significantly less time in block 2 when holistic processing strategy was adopted. The participant group also had a statistically significant effect on reaction time, controlling for block and trial types, and it explained 22% of the between-subject variance of the reaction time, F (1, 34) = 9.648, $p < .05$, η^2 = .221. Impaired readers consistently responded more slowly than normal readers in both blocks, regardless of the trial type. We also found the effect of trial type on reaction time to be statistically significant, F (1, 34) = 103.996, $p < .05$, η^2 = .754. Table 4 presents the descriptive statistics for reaction time in three trial types for both groups from block 1 to block 2 of the CVS task. When the two halves were identical, participants took the longest time to respond. Conversely, colour mismatch took the shortest time to identify.

The results indicate that the group × trial type interaction was statistically significant at F (1, 34) = 5.552, $p < .05$, η^2 = .140. When trials contained two identical halves or a difference in shape, impaired readers revealed a much longer reaction time than normal readers, while the difference in reaction time between the two participant groups was less distinct when trials contained a difference in colour.

Table 3. Mixed ANOVA summary for accuracy

Sources of variations	F-value	Sig.	Partial eta squared
Group	.731	.399	.021
Block	74.822	.000	.688
Trial type	138.178	.000	.803
Group × Block	.722	.401	.021
Group × Trial type	1.426	.247	.040
Block × Trial type	6.273	.003	.156
Group × Block × Trial type	.478	.622	.014

Table 4. Descriptive statistics for reaction time (s) in three trial types for both groups from block 1 (sequential processing) to block 2 (holistic processing) of the comparative visual search task

	Differ in colour		Same		Differ in shape	
	Block 1	Block 2	Block 1	Block 2	Block 1	Block 2
Impaired readers	4.29 (1.48)	4.00 (1.44)	7.80 (2.65)	5.48 (2.15)	7.14 (2.37)	4.64 (1.52)
Normal readers	3.38 (1.04)	2.84 (1.28)	5.86 (1.91)	3.49 (2.04)	5.14 (1.78)	3.22 (1.68)

The results also indicated that the block × trial type interaction was statistically significant, F (1, 34) = 48.558, $p < .05$, η^2 = .588. As Figure 4 demonstrates, the decrease in reaction time from block 1 (sequential processing) to block 2 (holistic processing) was more noticeable when trials contained either a difference in shape or two identical halves, for both impaired readers and normal readers. The summary of the mixed ANOVA is presented in Table 5.

In summary, we found that the accuracy score was lower for block 1 (sequential processing) compared to block 2 (holistic processing) for both groups and reaction time significantly dropped for both groups when holistic processing strategy was adopted. Impaired readers consistently took a longer time to make the comparison than normal readers using either strategy, and they did not achieve a significantly better accuracy score than normal readers in either block. Consequently, we do not see any supportive evidence that impaired readers benefit from holistic processing in CVS.

GENERAL DISCUSSION

This study was designed to explore to what extent impaired readers may benefit from holistic processing in a CVS task compared to normal readers. No significant differences were found in both accuracy and reaction time across two groups in the holistic processing block and sequential processing block of the CVS task in three trial types (halves differ in colours, shapes, and identical). In both blocks, mean accuracy was the highest when the trial contained two identical halves. This finding complied with the previous result from Pomplun *et al.* (2001) study of normal readers. In our study, both groups of participants experienced more difficulty

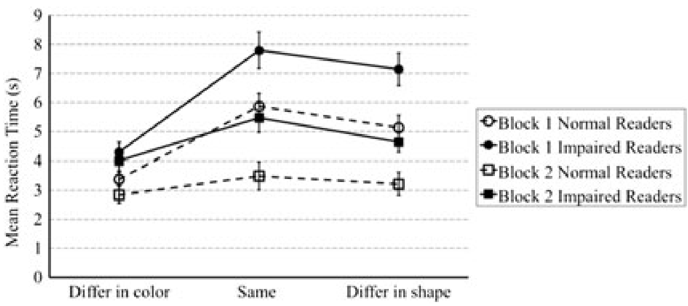

Figure 4. Mean reaction time in three trial types for both groups from block 1 (sequential processing) to block 2 (holistic processing) of the comparative visual search task.

Table 5. Mixed ANOVA summary for reaction time

Sources of variations	F-value	Sig.	Partial eta squared
Group	9.648	.004	.221
Block	36.720	.000	.519
Trial type	103.996	.000	.754
Group × Block	.030	.863	.001
Group × Trial type	5.552	.024	.140
Block × Trial type	48.558	.000	.588
Group × Block × Trial type	1.956	.171	.054

diagnosing differences in colour and differences in shape, the latter resulting in the lowest mean accuracy. This finding is also consistent with the previous result that detecting difference in colour is easier, faster, and requires fewer fixations, compared to identifying shape mismatches in a CVS task. Participants in that study tended to miss the differences in shape more often compared to colour mismatches (Pomplun *et al.*, 2001).

In terms of reaction time, in our study when two halves were identical, it took both groups the longest time to react in both blocks. This is not surprising because determining if two halves are identical requires that participants examine all 12 shapes in each half, leading to longer processing times. Mismatch in shape was a condition resulting in the second-longest reaction time, as participants did not need to examine all the shapes before a mismatch in shape was found. It took the shortest amount of time for both groups to find the difference in colour as the difference in colour is known to more evident compared to the mismatch in shape (Quinlan & Humphreys, 1987).

Holistic processing is regarded to be one of the talents individuals with dyslexia have in visual learning tasks compared to normal readers (Benton, 1984; Schneps *et al.*, 2007; Von Károlyi, 2001; Von Károlyi *et al.*, 2003). Using the holistic processing strategy in this study's CVS task, impaired readers also spent significantly more time making the comparison decisions than normal readers, but they did not achieve a significantly better accuracy score compared to normal readers in each of the three trial types (e.g., when the two halves are identical in both colour and shape, differ in colour, and differ in shape). Therefore, despite the potential promise for holistic processing talent discussed in prior research (Von Károlyi *et al.*, 2003), our findings do not provide any supportive evidence that impaired readers benefit from holistic processing during CVS. Below, we provide two possible explanations as to why impaired readers did not show the expected visual–spatial advantage in the CVS task in this study.

First, it is possible that the holistic processing strategy may be insufficient to complete the CVS task. In previous studies where participants with dyslexia manifested visual–spatial advantages, the success in tasks usually depended on the enhanced peripheral vision, which led to a better global processing of visual–spatial information. For example, Schneps *et al.* (2011) found that astrophysicists with dyslexia significantly excel in detecting radio signatures characteristic of black holes in a laboratory simulation, when the visual periphery was important. While the enhanced peripheral vision would contribute to a larger area of objects being seen by the participants in a CVS task, the goal of comparing two halves may render holistic processing insufficient. This was manifested by the decrease in accuracy in the second block of CVS. The decrease in accuracy can be related to the three-step model of CVS (Pomplun & Ritter, 1999), which proposed that in CVS, participants would need to examine the picture on the left; globally memorize chunks of items and hold them in working memory; and last use eye movements with more focused attention to examine the details of the items. It is not surprising then that both groups took a shorter time to react when a holistic processing strategy was used in CVS, because only two steps of CVS should be undertaken if a holistic processing strategy was adopted. The accuracy rate significantly dropped from the first block to the second block where holistic processing strategy was adopted because visual acuity—that is, step 3 in the Pomplun and Ritter (1999) model—was not utilized to examine the individual features (colour and shape) of the objects. Relatedly, the Feature Integration Theory (Treisman & Gelade, 1980) also suggested that focused attention is needed to store and maintain the conjunctive features of an object (e.g., colour and shape) in parallel in working memory during a visual search task. It is possible that engagement in a holistic processing strategy hindered both normal readers and impaired readers' ability to focus visual attention on the conjunctive features of objects, integrate objects into working memory, and perform comparative organization. Thus, holistic processing led to a higher error rate, but with a shorter reaction time, compared to the first block where sequential processing strategy was presumably utilized. Although many previous studies suggested visual–spatial talent in individuals with dyslexia, bringing hopes for the otherwise impaired population; their visual–spatial ability may not be superior in all types of visual–spatial tasks. It appears that in the CVS task used in this study, holistic processing of visual–spatial information rendered itself inadequate and insufficient for detecting nuanced differences for each displayed item in the task.

A second possible explanation is that it is reasonable to expect that the holistic processing strategy may indeed be beneficial for impaired readers, as they achieved a slightly higher accuracy than normal readers using holistic processing in the current study. Considering the fact that all participants engaged in uninstructed search (i.e., sequential processing strategy) before they were instructed to use holistic processing strategy, it is not feasible to separate learning effects from perceptual difference associated with the use of the holistic processing strategy. Our findings for the second block of the CVS task showed that impaired readers achieved a marginally higher accuracy compared to normal readers ($p = .179$). It is possible that if the order of two CVS blocks had been counterbalanced, we could have possibly detected significant differences between two participant groups when the holistic processing strategy was employed.

Third, the reason as to why impaired readers did not show the distinct visual–spatial advantage could also be that impaired readers in this study had not yet developed the expertise in holistic processing strategy as this could possibly have been the first time they were exposed to this novel processing strategy. When instruction was not specified, participants were expected to engage in the traditional sequential CVS processing, as sequential scanning of all items is likely to 'allow a better adjustment of mergence and hence an improved discriminability of items' (Pomplun, 1998, p. 137). Sequential processing is the strategy individuals tend to adopt as the default strategy (Pomplun *et al*., 2001), and some amount of pretraining in holistic processing would likely be needed before participants are comfortable in using holistic processing. For example, in a relevant study focused on comparing two molecular diagrams, Stieff (2007) instructed participants to use a learned heuristic (feature based analytical approach) to examine symmetrical and asymmetrical psychometric and stereochemistry diagrams. The study found that experts would selectively employ an analytical approach in comparing two molecular diagrams and participants who tended to primarily use mental rotation strategy could be trained to use analytical strategy in this task. It is possible that impaired readers may indeed benefit more from the holistic processing strategy in CVS than normal readers; however, adequate training and practice need to be provided before such visual–spatial advantage can be manifested during a CVS task. Given the malleability of spatial skills, spatial training was shown to be effective (Uttal & Cohen, 2012). As Stieff and Uttal (2015) emphasized, the importance of spatial training is crucial for improving learning and spatial training has the potential to improve students' success. Thus, future studies could explore the effects of visual–spatial training in holistic processing as a beneficial strategy in CVS, particularly for impaired readers.

CONCLUSION

This study explored the proposition that individuals with dyslexia develop enhanced peripheral vision to process visual–spatial information holistically. Our findings revealed that impaired readers did not demonstrate the expected visual spatial advantage in the CVS task used in this study. In other words, the results did not support the hypothesis associating dyslexia with talents for holistic visual processing in the CVS task. The current study is important as the findings suggest that the strength in visual–spatial learning associated with dyslexia may be task-dependent and may require some level of pre-training. These aspects can be explored in future studies.

ACKNOWLEDGEMENTS

This research is based on work supported by Boon Philanthropy (Henry Sinclair Sherrill) and Charles and Ellen LaFollette. We especially thank Anne Crosby and Kevin Kent for their extraordinary support in the dyslexia diagnosis of participants.

REFERENCES

Bacon, A. M., Handley, S. J., & McDonald, E. L. (2007). Reasoning and dyslexia: A spatial strategy may impede reasoning with visually rich information. *British Journal of Psychology (London, England : 1953)*, *98*(1), 79–92.

Benton, A. L. (1984). Dyslexia and spatial thinking. *Annals of Dyslexia*, *34*(1), 69–85.

Bosse, M. L., Tainturier, M. J., & Valdois, S. (2007). Developmental dyslexia: The visual attention span deficit hypothesis. *Cognition*, *104*(2), 198–230.

Chakravarty, A. (2009). Artistic talent in dyslexia—A hypothesis. *Medical Hypotheses*, *73*(4), 569–571.

Chun, M. M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology*, *36*(1), 28–71.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*(1), 87–114.

Dehaene, S., & Cohen, L. (2007). Cultural recycling of cortical maps. *Neuron*, *56*(2), 384–398.

Diehl, J. J., Frost, S. J., Sherman, G., Mencl, W. E., Kurian, A., Molfese, P., … Pugh, K. R. (2014). Neural correlates of language and non-language visuospatial processing in adolescents with reading disability. *NeuroImage*, *101*, 653–666.

Eden, G. F., Stein, J. F., Wood, M. H., & Wood, F. B. (1995). Verbal and visual problems in reading disability. *Journal of Learning Disabilities*, *28*(5), 272–290.

Facoetti, A., Paganoni, P., Turatto, M., Marzola, V., & Mascetti, G. G. (2000). Visual–spatial attention in developmental dyslexia. *Cortex*, *36*(1), 109–123.

Franceschini, S., Gori, S., Ruffino, M., Pedrolli, K., & Facoetti, A. (2012). A causal link between visual spatial attention and reading acquisition. *Current Biology: CB*, *22*(9), 814–819.

Galaburda, A., Sherman, G., Rosen, G., Aboitiz, F., & Geschwind, N. (1985). Developmental dyslexia: Four consecutive cases with cortical anomalies. *Annals of Neurology*, *18*, 222–233.

Geiger, G., & Lettvin, J. Y. (1987). Peripheral vision in persons with dyslexia. *New England Journal of Medicine*, *316*(20), 1238–1243.

Geschwind, N. (1982). Why Orton was right. *Annals of Dyslexia*, *32*(1), 13–30.

Geschwind, N., & Galaburda, A. M. (1987). Cerebral lateralization: Biological mechanisms, associations and pathology. Cambridge, MA: MIT press.

Gilger, J. W., Allen, K., & Castillo, A. (2016). Reading disability and enhanced dynamic spatial reasoning: A review of the literature. *Brain and Cognition*, *105*, 55–65.

Gilger, J. W., Talavage, T. M., & Olulade, O. a. (2013). An fMRI study of nonverbally gifted reading disabled adults: has deficit compensation effected gifted potential? *Frontiers in Human Neuroscience*, 7(August), 507.

Hedenius, M., Ullman, M. T., Alm, P., Jennische, M., & Persson, J. (2013). Enhanced recognition memory after incidental encoding in children with developmental dyslexia. *PLoS ONE*, *8*(5), 1–7.

Howard, J. H., Howard, D. V., Japikse, K. C., & Eden, G. F. (2006). Dyslexics are impaired on implicit higher-order sequence learning, but not on implicit spatial context learning. *Neuropsychologia*, *44*(7), 1131–1144.

Kessler, R. C., Adler, L. A., Gruber, M. J., Sarawate, C. A., Spencer, T., & Van Brunt, D. L. (2007). Validity of the World Health Organization adult adhd self-report scale (ASRS) Screener in a representative sample of health plan members. *International Journal of Methods in Psychiatric Research*, *16* (2), 52–65.

Lorusso, M. L., Facoetti, A., Pesenti, S., Cattaneo, C., Molteni, M., & Geiger, G. (2004). Wider recognition in peripheral vision common to different subtypes of dyslexia. *Vision Research*, *44*(20), 2413–2424.

Morris, R. D., Stuebing, K. K., Fletcher, J. M., Shaywitz, S. E., Lyon, G. R., Shankweiler, D. P., … Shaywitz, B. A. (1998). Subtypes of reading disability: Coherent variability around a phonological core. *Journal of Educational Psychology*, *90*, 1–27.

Orton, S. T. (1925). Word-blindness in school children. *Archives of Neurology & Psychiatry*, *14*(5), 581–615.

Peirce, J. W. (2008). Generating stimuli for neuroscience using PsychoPy. *Frontiers in Neuroinformatics*, 2, 10.

Perry, A. R., Dember, W. N., Warm, J. S., & Sacks, J. G. (1989). Letter identification in normal and dyslexic readers: A verification. *Bulletin of the Psychonomic Society*, *27*(5), 445–448.

Pomplun, M. (1998). Analysis and models of eye movements in comparative visual search. Göttingen, Germany: Cuvillier.

Pomplun, M., & Ritter, H. (1999). A three-level model of comparative visual search. *Proceedings of the Twenty First Annual Conference of the Cognitive Science Society*, 543–548.

Pomplun, M., Sichelschmidt, L., Wagner, K., Clermont, T., Rickheit, G., & Ritter, H. (2001). Comparative visual search: A difference that makes a difference. *Cognitive Science*, *25*(1), 3–36.

Quinlan, P. T., & Humphreys, G. W. (1987). Visual search for targets defined by combinations of color, shape, and size: An examination of the task constraints on feature and conjunction searches. *Perception & Psychophysics*, *41*(5), 455–472.

Riccio, C. A., & Hynd, G. W. (1996). Neuroanatomical and neurophysiological aspects of dyslexia. *Topics in Language Disorders*, *16*(2), 1–13.

Rosstad, A. (2002). Leonardo da Vinci—A dyslectic genius? *Tidsskrift for den Norske Lægeforening*, *122*, 2887–2890.

Schneps, M. H., Brockmole, J. R., Rose, L. T., Pomplun, M., Sonnert, G., & Greenhill, L. J. (2011). Dyslexia linked to visual strengths useful in astronomy. *Bulletin of the American Astronomical Society*, *1*, 21508.

Schneps, M. H., Brockmole, J. R., Sonnert, G., & Pomplun, M. (2012). History of reading struggles linked to enhanced learning in low spatial frequency scenes. *PLoS ONE*, *7*(4), e35724–e35724.

Schneps, M. H., Rose, L. T., & Fischer, K. W. (2007). Visual learning and the brain: Implications for dyslexia. *Mind, Brain, and Education*, *1*(3), 128–139.

Shaywitz, B. A., Weiss, L. G., Saklofske, D. H., & Shaywitz, S. E. (2015). Translating scientific progress in dyslexia into twenty-first century diagnosis and interventions. *WISC-V Assessment and Interpretation: Scientist-Practitioner Perspectives*, 269.

Shaywitz, S. E. (1996). Dyslexia. *Scientific American*, *275*, 98–104.

Sinatra, R. (1988). Styles of thinking and literacy proficiency for males disabled in print acquisition. *Reading Psychology: An International Quarterly*, *9*(1), 33–50.

Stieff, M. (2007). Mental rotation and diagrammatic reasoning in science. *Learning and Instruction*, *17* (2), 219–234.

Stieff, M., & Uttal, D. (2015). How much can spatial training improve STEM achievement? *Educational Psychology Review*, *27*(4), 607–615.

Tanaka, J. W., & Farah, M. J. (1993). Parts and wholes in face recognition. *The Quarterly Journal of Experimental Psychology*, *46*(2), 225–245.

Terlecki, M. S., Newcombe, N. S., & Little, M. (2008). Durable and generalized effects of spatial experience on mental rotation: Gender differences in growth patterns. *Applied Cognitive Psychology*, *22* (7), 996–1013.

Torgesen, J. K., Wagner, R., & Rashotte, C. (1999). TOWRE-2 test of word reading efficiency. Austin, TX: Pro-Ed.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136.

Uttal, D. H., & Cohen, C. A. (2012). Spatial thinking and STEM education: When, why and how. *Psychology of Learning and Motivation*, *57*(2), 147–181.

Von Károlyi, C. (2001). Visual–spatial strength in dyslexia rapid discrimination of impossible figures. *Journal of Learning Disabilities*, *34*(4), 380–391.

Von Károlyi, C., Winner, E., Gray, W., & Sherman, G. F. (2003). Dyslexia linked to talent: Global visual–spatial ability. *Brain and Language*, *85*(3), 427–431.

Von Karolyi, C., & Winner, E. (2004). Dyslexia and visual spatial talents: Are they connected? *Neuropsychology and Cognition*, *25*, 95–118.

Wagner, R., Torgesen, J., & Rashotte, C. (1999). Comprehensive test of phonological processing (CTOPP). Austin, Texas: Pro-Ed.

Wai, J., Lubinski, D., Benbow, C. P., & Steiger, J. H. (2010). Accomplishment in science, technology, engineering, and mathematics (STEM) and its relation to STEM educational dose a 25-year longitudinal study. *Journal of Educational Psychology*, *102*(4), 860–871.

Witelson, S. F. (1977). Developmental dyslexia: Two right hemispheres and none left. *Science*, *195* (4275), 309–311.

Wolfe, J. M., Evans, K. K., Drew, T., Aizenman, A., & Josephs, E. (2015). How do radiologists use the human search engine? *Radiation Protection Dosimetry*, ncv501.

Wolff, U., & Lundberg, I. (2002). The prevalence of dyslexia among art students. *Dyslexia*, *8*(1), 34–42.

World Health Organization (2004). International statistical classification of diseases and related health problems (Vol. 1). Geneva: World Health Organization.

Wright, R., Thompson, W. L., Ganis, G., Newcombe, N. S., & Kosslyn, S. M. (2008). Training generalized spatial skills. *Psychonomic Bulletin & Review*, *15*(4), 763–771.

