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Dyslexia and dyscalculia are characterized by common visual perception deficits

Dazhi Cheng[a,b,c,d*], Qing Xiao[e*], Qian Chen[c], Jiaxin Cui[a,b,d], and Xinlin Zhou[a,b,d]

[a]State Key Laboratory of Cognitive Neuroscience and Learning, School of Brain and Cognitive Sciences, Beijing Normal University, Beijing, China; [b]Advanced Innovation Center for Future Education, Beijing Normal University, Beijing, China; [c]Department of Pediatric Neurology, Capital Institute of Pediatrics, Beijing, China; [d]Siegler Center for Innovative Learning, Beijing Normal University, Beijing, China; [e]Department of specialty, Beijing Chinese Language and Culture College, Beijing, China

ABSTRACT

A number of studies have investigated the cognitive deficits underlying dyslexia and dyscalculia. Yet, it remains unclear as to whether dyslexia and dyscalculia are associated with the common visual perception deficits. The current investigation analyzed cognitive performance in children with dyslexia, dyscalculia, comorbidity, and typically developing subjects. The results showed that children with dyslexia, dyscalculia and comorbidity exhibited common deficits in numerosity processing and visual perception. Furthermore, visual perception deficits accounted for deficits in numerosity processing in all three groups. The results suggest that visual perception deficits are a common cognitive deficit underlying both developmental dyslexia and dyscalculia.

Introduction

Learning disabilities including reading disabilities (e.g., dyslexia) and mathematical learning disabilities (e.g., dyscalculia) are estimated to affect up to 10% of children (Butterworth & Kovas, 2013). Dyslexia refers to a specific deficit in learning to read (especially word recognition and decoding) (Layes, Lalonde, Mecheri, & Reba, 2015; Vellutino, Fletcher, Snowling, & Scanlon, 2004), whereas dyscalculia describes a specific deficit in the acquisition of arithmetic skills (especially number fact knowledge and computation) (Geary, 2011; Rousselle & Noël, 2007; Schleifer & Landerl, 2011). Numerous studies have investigated whether dyslexia and dyscalculia share common cognitive mechanisms. Two major hypotheses have been proposed regarding the cognitive mechanisms of dyslexia and dyscalculia. The first hypothesis postulates that dyslexia and dyscalculia exhibit distinct cognitive profiles, namely, a phonological deficit in dyslexia and a deficit in numerosity processing in dyscalculia (Butterworth & Kovas, 2013; Landerl, Fussenegger, Moll, & Willburger, 2009; Moll, Göbel, & Snowling, 2015). The second hypothesis proposes that both dyslexia and dyscalculia share a more fundamental cognitive deficit, such as a reduction in working memory (Moll, Göbel, Gooch, Landerl, & Snowling, 2014; Schuchardt, Maehler, & Hasselhorn, 2008). Moreover, recent studies have indicated that visual perception deficits may play an important role in either dyslexia or dyscalculia. Some studies have reported visual perception deficits as important components of dyslexia (Goswami et al., 2010; Stefanics et al., 2011; Vidyasagar & Pammer, 2010; Zhao, Qian, Bi, & Coltheart, 2014). In contrast, other researchers have identified visual perception deficits associated

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CONTACT Xinlin Zhou ✉ zhou_xinlin@bnu.edu.cn State Laboratory of Cognitive Neuroscience and Learning, Institute of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing 100875, China

*These authors contributed equally to this work.

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with dyscalculia (Sigmundsson, Anholt, & Talcott, 2010; Zhou & Cheng, 2015a). Deficits in the approximate number system (ANS) are potentially associated with visual perception deficits (Butterworth, Varma, & Laurillard, 2011; Mazzocco, Feigenson, & Halberda, 2011; Zhou & Cheng, 2015a). However, it remains unclear whether dyslexia and dyscalculia share a common visual perception deficit. To address this research question, the present study used a geometric figure-matching task (Basso et al., 1985; Strien, Licht, Bouma, & Bakker, 1989; Zhou & Cheng, 2015a; Zhou, Wei, Zhang, Cui, & Chen, 2015b) and an accompanying battery of cognitive tests to explore the role of visual perception in dyslexia and dyscalculia.

The role of visual perception in dyslexia

Abnormal visual perception is thought to be a fundamental mechanism of dyslexia (Eden et al., 1996; Saksida et al., 2016; Stefanics et al., 2011; Valdois et al., 2011; Vidyasagar & Pammer, 2010; Zhao et al., 2014). Although it might be assumed that phonological deficits account for developmental dyslexia, phonological deficits can stem from more fundamental deficits in visual perceptual processing (Stefanics et al., 2011; Stein & Walsh, 1997; Vidyasagar & Pammer, 2010). Emerging evidence indicates that phonological problems and reading impairments arise from poor visual perception processing (e.g., detection of letter-strings, speed discrimination) (Goswami et al., 2010; Valdois et al., 2011; Zhao et al., 2014). In one study, researchers employed a task that required participants to detect coherently moving dots on a screen and found that individuals with dyslexia exhibited abnormal visual motion processing (Eden et al., 1996). In contrast, individuals with dyslexia did not have deficits in processing the static presentation of the same dots. It has been reported that training visual texture discrimination improves reading speed in patients affected by dyslexia (Wang et al., 2014).

The visual magnocellular dorsal pathway is a possible neural substrate of visual perception in reading. The magnocellular dorsal stream is sensitive to visual stimuli with low spatial frequency, low contrast, and high temporal frequency (Stein & Walsh, 1997). These visual features are common in fast-changing or moving stimuli, and individuals with dyslexia show poor performance and abnormal patterns of neural activity in response to these visual features (Conlon, Sanders, & Wright, 2009; Demb, Boynton, & Heeger, 1998; Eden et al., 1996).

ANS deficits and visual perception in dyscalculia

Children with dyscalculia exhibit severe impairments in the ANS (Butterworth, 2010; Iuculano, Tang, Hall, & Butterworth, 2008; Mazzocco et al., 2011; Mejias, Grégoire, & Noël, 2012; Piazza et al., 2010; Skagerlund & Träff, 2014; Wilson et al., 2014). The ANS is typically assessed using numerosity comparison tasks wherein the participants is asked to select an item (e.g., a dot) array that has a higher or lower number of items compared to two other item arrays (Butterworth & Kovas, 2013; Piazza et al., 2010). Piazza et al. (2010) used this paradigm to empirically demonstrate that children with dyscalculia demonstrate ANS deficits. A cohort of 10-year-old children with dyscalculia showed poor number acuity in a numerosity comparison task that was consistent with the performance of a 5-year-old normally developing child. Children with dyscalculia showed difficulties across all magnitude dimensions (i.e., space, time, and number) and showed impaired ANS acuity compared to the control group (Skagerlund & Träff, 2014).

Previous research has examined the perceptual properties of numerosity processing (Burr & Ross, 2008; Tibber, Greenwood, & Dakin, 2012). For example, Burr and Ross (2008) found that apparent numerosity was decreased by adaptation to large numbers of dots and increased by adaptation to small numbers of dots, similar to adaption mechanisms for other primary visual properties of a scene such as color, contrast, size, and movement speed. To this end, recent studies have suggested that ANS deficits are associated with visual perception deficits. First, Zhou and colleagues (2015b) showed that tight coupling between the ANS and math fluency was fully explained by general visual perception measured with a geometric figure matching task (Demb et al., 1998; Valdois et al., 2011). Second, Zhou and Cheng (2015a) showed that ANS deficits in dyscalculia were likely due to visual perception deficits; variations in visual perception were found to account for variations in numerosity processing in children with dyscalculia.

Current investigation

As mentioned above, visual perception is thought to play an important role in both dyslexia and dyscalculia. Yet, it remains unclear as to whether dyslexia and dyscalculia share common visual perception deficits. Therefore, the goal of the current study was to examine visual perception deficits in individuals with dyslexia and dyscalculia using a geometric figure matching task. Four groups of children were included: a dyslexia group, a dyscalculia group, a comorbidity (dyslexia and dyscalculia) group, and a typically developing (TD) group. With regard to the visual perceptional properties of numerosity processing, we expected that children with dyslexia, dyscalculia, and comorbid dyslexia with dyscalculia would exhibit deficits in visual perception and ANS and that visual perception deficits would account for ANS deficits.

To study the role of visual perception in both dyslexia and dyscalculia, we controlled for potential confounding factors related to cognitive processing. We included five other cognitive tasks associated with mathematical and linguistic cognition (Cirino, 2011; Halberda, Mazzocco, & Feigenson, 2008). A basic reaction time task was used to control for the effect of manual response and mental processing speed (Butterworth, 2003). We included a task to assess visual-tracing ability because poor oculomotor coordination has been linked to reading disability (Groffman, 1994) and mathematical deficits (Eden et al., 1996; Groffman, 2009). Raven's Progressive Matrices measures basic "intelligence," and scores on this test have been correlated with mathematical performance (Kyttälä & Lehto, 2008; Rohde & Thompson, 2007). Mental rotation tasks were used to control for the effect of spatial processing (Berg, 2008). A numerosity comparison task measured the extent to which processing plays a role in mathematical cognition (Butterworth et al., 2011).

Methods

Participants

Participants were retrospectively enrolled from a dataset collected by the State Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal University. The dataset included 1,142 third grade to fifth grade children (580 boys and 562 girls; age range, 8–11 year) from 57 classes at 5 primary schools in Beijing, China. The classes were randomly selected from the schools. All students in each selected class participated in the study. Each class included approximately 20–40 children. All participants were native Chinese speakers and had normal or corrected-to-normal vision. The current investigation was approved by the State Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal University and the principals of the schools. The parents or legal guardians of participating children provided written informed consent.

Dyslexia was defined in terms of standard scores on reading fluency. The criteria for dyslexia were (1) a score within less than the 7th percentile (−1.50 standard deviations from the mean) for reading measured with a sentence completion task; (2) a score above the 25th percentile (−.67 standard deviations from the mean) for nonverbal intelligence measured with a nonverbal matrices reasoning task; and (3) a score within −1.50 standard deviations from the mean for math fluency measured with subtraction tasks. Meanwhile, the participants with comorbid dyslexia and dyscalculia were excluded. A total of 39 children from the dataset met the criteria for dyslexia.

Dyscalculia was defined in terms of standard scores on math fluency. The criteria for dyscalculia were (1) a score below the 7th percentile (−1.50 standard deviations from the mean) for math fluency; (2) a score above the 25th percentile (−.67 standard deviations from the mean) for nonverbal intelligence; and (3) a score above the 7th percentile (−1.50 standard deviations from the mean) for reading. Meanwhile, the participants in comorbidity group were excluded. A total of 48 children from the dataset met the criteria for dyscalculia.

Comorbid dyslexia and dyscalculia was defined in terms of standard scores on both reading and math fluency. The criteria for comorbid dyslexia and dyscalculia were as follows: (1) scores below the 7th percentile (−1.50 standard deviations from the mean) for both reading and math fluency and (2) a score above the 25th percentile (−.67 standard deviations from the mean) for nonverbal intelligence. Meanwhile, the participants with only dyslexia or dyscalculia were excluded. A total of 18 children from the dataset met the criteria for comorbid dyslexia and dyscalculia.

Forty-eight TD children were included as a control group. These children were randomly sampled from the remaining 1,037 children in the dataset with the following constraints: (1) TD children were individually matched to children in the dyscalculia group in terms of age, gender, and grade; (2) scores above the 7th percentile (−1.50 standard deviations from the mean) for math fluency and reading; and (3) a score above the 25th percentile (−.67 standard deviations from the mean) for nonverbal intelligence. The demographic characteristics of included participants are shown in Table 1.

Procedure

The task battery was administered across two 45-min sessions. Testing was conducted in groups (one class at a time) in computer classrooms. Each class was monitored by six to seven experimenters (five to six children per experimenter) and one of the class teachers. Tasks were administered in the same order for all students. For each task, an instruction was given and a practice session was completed prior to formal testing. The practice session for each task consisted of four to six trials that were similar to those used in the formal testing. During practice trials, the computer provided children with feedback on the screen; the feedback for correct responses was “Correct! Can you go faster?” and the feedback for incorrect responses was “It is wrong. Try again.” Children were allowed to ask the experimenters questions during practice sessions. After all children in a class had finished the practice session and had no more questions for the experimenters, the main experimenter said, “Start,” and the children pressed any key to begin the formal testing.

For all but one task, children responded by pressing one of two keys (“P” or “Q”) on a computer keyboard. For the visual tracing task, the children used a cursor to mark the correct end point after tracing a particular line. Student responses were automatically recorded and conveyed over the Internet to a server located in the Key Laboratory for storage. All data were collected between December 2013 and June 2014.

Tasks

Sentence completion

The sentence completion task used in this study was similar to a previously described task (Mummery, Patterson, Hodges, & Price, 1998; So & Siegel, 1997). Materials in the task were adapted from textbooks used in primary schools from first grade to ninth grade. For each trial, a sentence was presented in the middle of the computer screen with a word missing. Participants were instructed to complete the sentence by selecting one of two candidate words presented beneath

Table 1. Demographic characteristics of participants.

Variable	Dyslexia	Dyscalculia	Comorbidity	Controls
N	39	48	18	48
Age (mean years [SD])	9.7 (.8)	9.5 (.7)	9.5 (.8)	9.5 (.7)
Gender (male/female)	24/15	28/20	10/8	28/20

Note: There was no age effect among the four groups, $F(3, 149) = .77$, $p = .51$, $\eta_p^2 = .015$. The ratio of gender among the four groups also does not reach significant level, $\chi^2 = .21$, $p = .98$.

the sentence by pressing a left key ("P") or a right key ("Q"). The stimulus remained on the screen until the participants responded. There were 120 questions. This was a time-limited (5-min) task.

Subtraction

The subtraction task included simple and complex subtraction problems for which participants were not allowed to use paper and pencil. For all 92 problems in the simple subtraction task, the minuends were 18 or smaller, and differences were single-digit numbers. Two candidate answers were presented beneath each problem. Participants were instructed to select the correct answer by pressing the "Q" key to choose the answer on the left and the "P" key to choose the answer on the right. Each incorrect candidate answer was within ±3 values of the correct answer. This was a time-limited (2-min) task.

All 96 problems in the complex subtraction task involved two-digit operands. Most problems required borrowing. Two candidate answers were presented beneath each problem and again participants were instructed to select the correct. Each incorrect candidate answer was within ±10 values of the correct answer. Other aspects of the procedure (stimulus presentation, response method) were identical to those in the simple subtraction task. This was a time-limited (2-min) task.

The numbers of correct trials in each of the two tasks were averaged to yield a general score for math fluency.

Choice reaction time

In each trial of the choice reaction time task, a white dot was presented on a black screen either to the left or to the right of a fixation cross. The position of the dot was within a 15° visual angle of the fixation cross. Participants were asked to press the "Q" key if the dot appeared on the left and the "P" key if the dot appeared on the right. The task included a total of 30 trials (15 trials with the dot on the left and 15 trials with the dot on the right). The size of the screen on which the dot appeared varied randomly across trials. The interstimulus interval as randomly varied between 1,500 and 3,000 ms.

Mental rotation

The mental rotation task used in this study was adapted from a previously described task (Vandenberg & Kuse, 1978). In each trial, a three-dimensional image was presented on the upper part of the screen and two more images were presented on the lower part of the screen. Participants were asked to choose the image from the lower part of the screen that matched the image on the upper part of the screen; the matching image could only be identified by mental rotation. The nonmatching image was a rotated mirror image of the target. The rotation angles of the matching images ranged from 15° to 345° (intervals of 15°). Participants pressed the "Q" key to choose the image on the left and the "P" key to choose the image on the right. Stimuli remained on the screen until participant responded by pressing the "P" key or the "Q" key. This task consisted of 180 trials and was a time-limited (3-min) test.

Nonverbal matrix reasoning

A simplified version of the Raven's Progressive Matrices test (Raven, 1998) was used to assess general intelligence. In this task, participants were asked to identify a missing segment that would complete a figure's pattern. Two candidate answers were presented beneath each problem and participants were instructed to press "Q" if the missing segment was on the left and "P" if it was on the right. The test consisted of 80 trials and was a time-limited (3-min) test.

Visual tracing

The visual tracing task used in this study was adapted from Groffman's visual-tracing test (Groffman, 1966). Several curved lines were interwoven within a square, starting from the left side of the square and ending on the right side. Participants were asked to track a particular line from the beginning to the end using only their vision (i.e., they were not allowed to use a finger or the cursor to trace the line path) and then to mark the correct end point. This task became more difficult as the total number of lines increased. There were 12 pictures used in 3 trials. This was a time-limited (4-min) task.

Numerosity comparison

We used a numerosity comparison task to measure ANS function and magnitude processing (Ginsburg & Baroody, 1990; Zhou et al., 2015b). Two dots arrays of varying size were presented simultaneously on a screen and participants were asked to judge which dot array contained more dots while ignoring the sizes of individual dots (Figure 1). Participants pressed “Q” to indicate the array on the left and “P” to indicate the array on the right. The number of dots in each set varied from 5 to 32. The ratios of the numbers of dots in the two arrays ranged from 1.2 to 2.0. Dot arrays in each trial were presented for 200 ms. After the participants responded, a blank screen was shown 1 s before the next trial. For half of the trials, the total combined area of all dots in each set was controlled to be the same. For the other half of the trials, the average area of all dots in each set was controlled to be the same. The test consisted of 120 trials across 3 sessions, with 40 trials in each session. Children were asked to complete all trials.

Figure matching

The figure-matching task was adapted from an identical picture test in the Manual for Kit of Factor-Referenced Cognitive Tests (Ekstrom, French, Harman, & Dermen, 1976). There were 120 trials. In each trial, a target picture was displayed on the left side and three candidate pictures were displayed on the right side of a screen (Figure 1). The pictures were made from 150 abstract line figures. In each trial, four pictures were presented simultaneously for 400 ms. Participants were asked to judge whether the picture on the left side also appeared on the right side by pressing the button “Q” to indicate yes and the “P” button to indicate no. Children completed three 40-trial sessions and were asked to complete all trials.

Data analysis

For all but one task (i.e., the choice reaction time), corrected scores were calculated by subtracting the number of incorrect responses from the number of correct responses; this was done to control

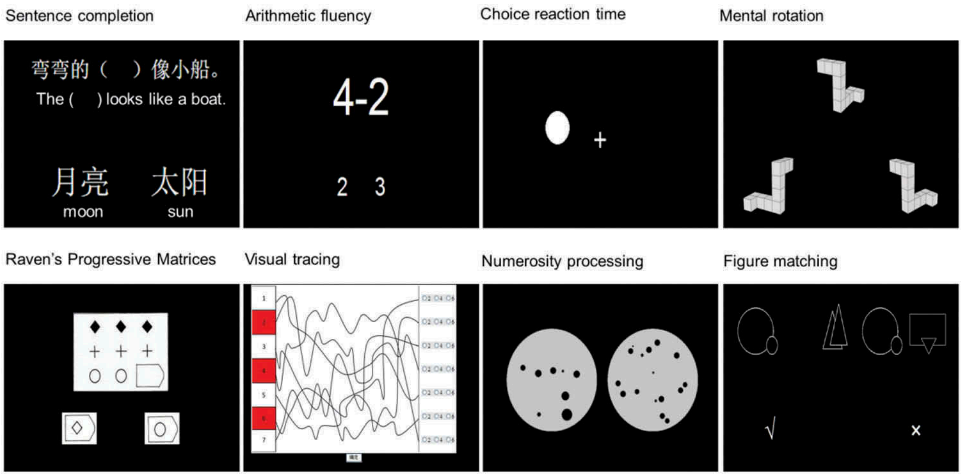

Figure 1. Examples of stimuli used for cognitive tasks.

for the effect of guessing (Cirino, 2011; Hedden & Yoon, 2006; Salthouse & Meinz, 1995). For the math fluency and sentence completion tasks, we calculate standard *Z* scores for each participant based on the corrected scores. For the choice reaction time task, only the median reaction time for each participant was analyzed. The mean error rate was low (4.4%) and thus was not further analyzed.

Correlation analyses were performed to identify relationships between the cognitive tests for all participates. Then, for each task, a between-subject analysis of variance using group as the between-subject factor was calculated to compare performance among the four groups, with *posthoc* pair-wise analysis using Bonferroni correction. Finally, an analysis of covariance was conducted to examine numerosity processing deficits among the four groups using visual perception as well as other cognitive measures (i.e., choice reaction time, mental rotation, and visual tracing) as covariates. The data analysis was performed in the IBM SPSS 21 software.

Results

Table 2 shows the mean score and standard error for each task. A significant group effect was identified for the sentence completion task, $F(3, 149) = 173.74$, $p < .001$, $\eta_p^2 = .76$. Simple contrasts indicated that the control group had higher scores in the sentence completion task compared to the other groups ($p < .05$ for all comparisons) and that the dyscalculia group performed better than the dyslexia and comorbidity groups. There was no significant difference between the dyslexia and comorbidity groups.

A significant group effect was identified for the subtraction task, $F(3, 149) = 153.57$, $p < .001$, $\eta_p^2 = .76$. Simple contrasts indicated that the control group had higher scores in the subtraction task compared to the other groups, and that the dyscalculia group performed more poorly than the dyslexia group. Scores in the comorbidity group were lower than those in the dyslexia group but did not differ from those in the dyscalculia group.

There was no significant effects of group for the choice reaction time task, $F(3, 149) = 2.37$, $p = .07$, $\eta_p^2 = .05$, the mental rotation task, $F(3, 149) = 1.81$, $p = .15$, $\eta_p^2 = .04$, the nonverbal matrix reasoning task, $F(3, 149) = .73$, $p = .54$, $\eta_p^2 = .01$, or the visual tracing task, $F(3, 149) = 1.33$, $p = .27$, $\eta_p^2 = .13$.

A significant group effect was identified for the numerosity comparison task, $F(3, 149) = 7.26$, $p < .001$, $\eta_p^2 = .13$. Simple contrasts indicated that the control group had higher scores in the numerosity comparison task compared to the other groups. There were no significant differences among the other groups. Similarly, a significant group effect was identified for the figure matching task, $F(3, 149) = 8.45$, $p < .001$, $\eta_p^2 = .15$, and simple contrasts indicated that the control group had higher scores compared to the other groups, but there were no significant differences among the other groups.

Table 2. Means (standard deviations) of scores and *F*-test values for children with dyslexia, dyscalculia, comorbidity, and controls on all tasks.

Task	Dyscalculia	Dyslexia	Comorbidity	Controls	*F*
Sentence completion	−.14 (.62)	−2.20 (.60)	−2.22 (.51)	.33 (.63)	173.74***
Subtraction	−2.00 (.50)	−0.53 (.68)	−2.37 (.76)	.28 (.5642)	153.57***
Choice reaction time	485.08 (167.56)	508.46 (194.10)	575.83 (236.99)	457.00 (97.19)	2.37
Mental rotation	15.38 (10.98)	16.59 (10.98)	17.22 (10.89)	20.25 (9.86)	1.81
Nonverbal matrix reasoning	19.10 (4.45)	19.18 (5.29)	20.61 (3.84)	20.19 (5.45)	.73
Visual tracing	13.67 (5.24)	13.85 (5.94)	11.78 (4.91)	14.73 (5.25)	1.33
Numerosity comparison	42.00 (29.14)	37.69 (27.02)	38.22 (30.44)	61.54 (23.83)	7.26***
Figure matching	26.04 (23.09)	24.00 (19.24)	14.33 (15.77)	42.96 (30.03)	8.45***

Note: ***$p < .001$.

Table 3. Correlations among task scores for all participants.

Tests	1	2	3	4	5	6	7
Sentence completion	–						
Subtraction	.23**	–					
Choice reaction time	−.02	.17*	–				
Mental rotation	.08	.20*	.12	–			
Nonverbal matrix reasoning	.02	.00	.11	.08	–		
Visual tracing	.13	.17*	.07	.30**	.05	–	
Numerosity comparison	.36**	.22**	.09	.09	.07	.13	–
Figure matching	.35**	.31**	.10	.16	.04	.27**	.50**

Note: $*p < .05$; $**p < .01$.

After controlling for the scores for the three cognitive tasks (i.e., the choice reaction time task, mental rotation task, and visual tracing task), between-group differences for the numerosity processing task remained significant, $F(3, 145) = 6.32$, $p < .001$, $\eta_p^2 = .115$. However, group differences disappeared after additionally controlling for scores in the figure matching task, $F(3, 144) = 2.53$, $p = .06$.

The correlations among task scores are shown in Table 3. Sentence completion scores were significantly correlated with numerosity comparison and figure matching scores. Subtraction scores were also significantly correlated with scores in both numerosity comparison and figure matching tasks as well as with choice reaction, mental rotation, and visual tracing. Numerosity comparison scores were significantly correlated with figure matching scores.

Discussion

The present study examined whether cognitive visual perception deficits were common to both dyslexia and dyscalculia. The results showed that dyslexia, dyscalculia, and comorbid dyslexia with dyscalculia were all characterized by deficits in numerosity processing and visual perception. Furthermore, visual processing deficits measured by the figure matching task were able to account for numerosity processing deficits in all three disorder groups. These results suggest that visual perception is a common cognitive deficit underlying developmental dyslexia and dyscalculia.

Visual perception deficits in developmental dyslexia and dyscalculia

This study controlled for general processing speed (measured with a choice reaction time task), spatial processing (measured with a mental rotation task), and visual attention (measured with a visual tracing task) in its analysis. Although these tasks involved visual perception, visual perception involvement was not likely to be as extensive in these tasks as in the figure matching task, which can explain the absence of performance differences between the TD and disorder groups for these tasks. This is consistent in a previous study that found that dynamic visual perception but not static visual discrimination was associated with dyslexia (Eden et al., 1996).

Visual perception deficits may be a fundamental mechanism underlying dyslexia and dyscalculia. The immaturity of the dorsal visual system seems to characterize a number of developmental disorders including dyslexia, Williams syndrome, and dyscalculia (Atkinson et al., 1997). Accordingly, studies suggest that dyslexia and dyscalculia share the visual magnocellular dorsal pathway as a common neural substrate. For example, individuals with dyslexia showed poor performance and abnormal activation in the magnocellular dorsal stream during a visual moving stimulus task (Conlon et al., 2009; Demb et al., 1998; Eden et al., 1996). In an electroencephalography study, young adults with dyscalculia showed abnormal visually evoked N60 and P100 components in numerosity processing (Jastrzebski, Crewther, & Crewther, 2015). It provided direct evidence of abnormality in the occipital processing of magnocellular information in those with mathematical impairment.

Numerosity processing deficits in developmental dyslexia and dyscalculia

Consistent with previous studies (Butterworth, 2010; Iuculano et al., 2008; Mazzocco et al., 2011; Mejias et al., 2012; Piazza et al., 2010; Skagerlund & Träff, 2014; Wilson et al., 2014), we identified numerosity processing deficits in children with developmental dyscalculia, representing ANS acuity impairment. As a novel finding, we identified similar numerosity processing deficits in children with developmental dyslexia. The results indicated that dyslexia and dyscalculia share common visual perception deficits and that visual perception performance could explain numerosity processing deficits in the disorder groups. A previous study also reported that numerosity processing is primarily a visual task (Burr & Ross, 2008; Zhou et al., 2015b). Consistent with the findings of the previous study, children with developmental dyslexia also showed deficits in the numerosity comparison task.

In conclusion, visual perception deficits appear to arise from a common cognitive mechanism underlying dyslexia, dyscalculia, and comorbid dyslexia with dyscalculia. Our results provide an alternative explanation for the comorbid presentation of dyslexia and dyscalculia. We showed that deficits in visual perception contributed to the ANS deficits observed in children with learning disabilities; however, knowledge regarding the causes of these disorders remains incomplete. Further studies must be conducted to determine whether visual perception training could help to improve associated cognitive functions in children with learning disabilities.

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References

Atkinson, J., King, J., Braddick, O., Nokes, L., Anker, S., & Braddick, F. (1997). A specific deficit of dorsal stream function in Williams' syndrome. *Neuroreport*, *8*, 1919–1922. doi:10.1097/00001756-199705260-00025

Basso, A., Capitani, E., Luzzatti, C., Spinnler, H., & Zanobio, M. E. (1985). Different basic components in the performance of Broca's and Wernicke's aphasics on the colour-figure matching test. *Neuropsychologia*, *23*, 51–59. doi:10.1016/0028-3932(85)90043-0

Berg, D. H. (2008). Working memory and arithmetic calculation in children: The contributory roles of processing speed, short-term memory, and reading. *Journal of Experimental Child Psychology*, *99*, 288–308. doi:10.1016/j.jecp.2007.12.002

Burr, D., & Ross, J. (2008). A visual sense of number. *Current Biology*, *18*, 425–428. doi:10.1016/j.cub.2008.02.052

Butterworth, B. (2010). Foundational numerical capacities and the origins of dyscalculia. *Trends in Cognitive Sciences*, *14*, 534–541. doi:10.1016/j.tics.2010.09.007

Butterworth, B., & Kovas, Y. (2013). Understanding neurocognitive developmental disorders can improve education for all. *Science*, *340*, 300–305. doi:10.1126/science.1231022

Butterworth, B., Varma, S., & Laurillard, D. (2011). Dyscalculia: From brain to education. *Science*, *332*, 1049–1053. doi:10.1126/science.1201536

Butterworth., B. (2003). *Dyscalculia screener*. London: nferNelson Pub.

Cirino, P. T. (2011). The interrelationships of mathematical precursors in kindergarten. *Journal of Experimental Child Psychology*, *108*, 713–733. doi:10.1016/j.jecp.2010.11.004

Conlon, E. G., Sanders, M. A., & Wright, C. M. (2009). Relationships between global motion and global form processing, practice, cognitive and visual processing in adults with dyslexia or visual discomfort. *Neuropsychologia*, *47*, 907–915. doi:10.1016/j.neuropsychologia.2008.12.037

Demb, J. B., Boynton, G. M., & Heeger, D. J. (1998). Functional magnetic resonance imaging of early visual pathways in dyslexia. *Journal of Neuroscience*, *18*, 6939–6951. doi:10.1523/JNEUROSCI.18-17-06939.1998

Eden, G. F., Vanmeter, J. W., Rumsey, J. M., Maisog, J. M., Woods, R. P., & Zeffiro, T. A. (1996). Abnormal processing of visual motion in dyslexia revealed by functional brain imaging. *Nature*, *382*, 66–69. doi:10.1038/382066a0

Ekstrom, R. B., French, J. W., Harman, H. H., & Dermen, D. (1976). *Manual for kit of factor-referenced cognitive tests.* Princeton, NJ: Educational testing service.

Geary, D. C. (2011). Consequences, characteristics, and causes of mathematical learning disabilities and persistent low achievement in mathematics. *Journal of Developmental & Behavioral Pediatrics*, *32*, 250–263. doi:10.1097/DBP.0b013e318209edef

Ginsburg, H. P., & Baroody, A. J. (1990). *Examiners manual of the test of early mathematics ability* Austin, TX: Pro-Ed.

Goswami, U., Wang, H. L. S., Cruz, A., Fosker, T., Mead, N., & Huss, M. (2010). Language-universal sensory deficits in developmental dyslexia: English, Spanish, and Chinese. *Journal of Cognitive Neuroscience*, *23*, 325–337. doi:10.1162/jocn.2010.21453

Groffman, S. (1966). Visual tracing. *Journal of American Optometric Association*, *37*, 139–141.

Groffman, S. (1994). The relationship between visual perception and learning. In: Scheiman, MM., Rouse, MW. eds. *Optometric management of learning-related vision problems*. St. Louis: Mosby-Year Book.

Groffman, S. (2009). Subitizing: Vision therapy for math deficits. *Optometry and Vision Development*, *40*, 229.

Halberda, J., Mazzocco, M. M., & Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature*, *455*, 665–668. doi:10.1038/nature07246

Hedden, T., & Yoon, C. (2006). Individual differences in executive processing predict susceptibility to interference in verbal working memory. *Neuropsychology*, *20*, 511. doi:10.1037/0894-4105.20.5.511

Iuculano, T., Tang, J., Hall, C. W. B., & Butterworth, B. (2008). Core information processing deficits in developmental dyscalculia and low numeracy. *Developmental Science*, *11*, 669–680. doi:10.1111/j.1467-7687.2008.00716.x

Jastrzebski, N. R., Crewther, S. G., & Crewther, D. P. (2015). Mathematical impairment associated with high-contrast abnormalities in change detection and magnocellular visual evoked response. *Experimental Brain Research*, *233*, 3039–3046. doi:10.1007/s00221-015-4373-y

Kyttälä, M., & Lehto, J. E. (2008). Some factors underlying mathematical performance: The role of visuospatial working memory and non-verbal intelligence. *European Journal of Psychology of Education*, *23*, 77–94. doi:10.1007/BF03173141

Landerl, K., Fussenegger, B., Moll, K., & Willburger, E. (2009). Dyslexia and dyscalculia: Two learning disorders with different cognitive profiles. *Journal of Experimental Child Psychology*, *103*, 309–324. doi:10.1016/j.jecp.2009.03.006

Layes, S., Lalonde, R., Mecheri, S., & Reba, M. (2015). Phonological and cognitive reading related skills as predictors of word reading and reading comprehension among Arabic dyslexic children. *Psychology*, *06*, 20–38. doi:10.4236/psych.2015.61003

Mazzocco, M. M. M., Feigenson, L., & Halberda, J. (2011). Impaired acuity of the approximate number system underlies mathematical learning disability (Dyscalculia). *Child Development*, *82*, 1224–1237. doi:10.1111/j.1467-8624.2011.01608.x

Mejias, S., Grégoire, J., & Noël, M. P. (2012). Numerical estimation in adults with and without developmental dyscalculia. *Learning & Individual Differences*, *22*, 164–170. doi:10.1016/j.lindif.2011.09.013

Moll, K., Göbel, S. M., Gooch, D., Landerl, K., & Snowling, M. J. (2014). Cognitive risk factors for specific learning disorder processing speed, temporal processing, and working memory. *Journal of Learning Disabilities*, *49*(3), 272–281. doi:10.1177/0022219414547221

Moll, K., Göbel, S. M., & Snowling, M. J. (2015). Basic number processing in children with specific learning disorders: Comorbidity of reading and mathematics disorders. *Child Neuropsychology*, *21*, 399–417. doi:10.1080/09297049.2014.899570

Mummery, C. J., Patterson, K., Hodges, J. R., & Price, C. J. (1998). Functional neuroanatomy of the semantic system: Divisible by what? *Journal of Cognitive Neuroscience*, *10*, 766–777. doi:10.1162/089892998563059

Piazza, M., Facoetti, A., Trussardi, A. N., Berteletti, I., Conte, S., Lucangeli, D., Dehaenea, S., Zorzi, M. (2010). Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. *Cognition*, *116*, 33–41. doi:10.1016/j.cognition.2010.03.012

Raven, J. (1998). *Manual for Raven's progressive matrices and vocabulary scales: Section 1.* Oxford, UK: Oxford Psychologists Press.

Rohde, T. E., & Thompson, L. A. (2007). Predicting academic achievement with cognitive ability. *Intelligence*, *35*, 83–92. doi:10.1016/j.intell.2006.05.004

Rousselle, L., & Noël, M. P. (2007). Basic numerical skills in children with mathematics learning disabilities: A comparison of symbolic vs non-symbolic number magnitude processing. *Cognition*, *102*, 361–395. doi:10.1016/j.cognition.2006.01.005

Saksida, A., Iannuzzi, S., Bogliotti, C., Chaix, Y., Demonet, J. F., Bricout, L., Billard, C., Nguyen-Morel, M., Le Heuzey, M., Soares-Boucaud, I., George, F., Ziegler, J., Ramus, F. (2016). Phonological skills, visual attention span, and visual stress in developmental dyslexia. *Developmental Psychology*, *52*, 1503–1516. doi:10.1037/dev0000184

Salthouse, T. A., & Meinz, E. J. (1995). Aging, inhibition, working memory, and speed. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *50*, P297–P306. doi:10.1093/geronb/50B.6.P297

Schleifer, P., & Landerl, K. (2011). Subitizing and counting in typical and atypical development. *Developmental Science*, *14*(212), 280–291. doi:10.1111/j.1467-7687.2010.00976.x

Schuchardt, K., Maehler, C., & Hasselhorn, M. (2008). Working memory deficits in children with specific learning disorders. *Journal Learning Disability*, *41*, 514–523. doi:10.1177/0022219408317856

Sigmundsson, H., Anholt, S. K., & Talcott, J. B. (2010). Are poor mathematics skills associated with visual deficits in temporal processing? *Neuroscience Letters*, *469*, 248–250. doi:10.1016/j.neulet.2009.12.005

Skagerlund, K., & Träff, U. (2014). Number processing and heterogeneity of developmental dyscalculia: Subtypes with different cognitive profiles and deficits. *Journal of Learning Disabilities*, *49*(1), 36. doi:10.1177/0022219414522707

So, D., & Siegel, L. S. (1997). Learning to read Chinese: Semantic, syntactic, phonological and working memory skills in normally achieving and poor Chinese readers. *Reading & Writing*, *9*, 1–21. doi:10.1023/A:1007963513853

Stefanics, G., Fosker, T., Huss, M., Mead, N., Szucs, D., & Goswami, U. (2011). Auditory sensory deficits in developmental dyslexia: A longitudinal ERP study. *Neuroimage*, *57*, 723–732. doi:10.1016/j.neuroimage.2011.04.005

Stein, J., & Walsh, V. (1997). To see but not to read; the magnocellular theory of dyslexia. *Trends in Neurosciences*, *20*, 147–152. doi:10.1016/S0166-2236(96)01005-3

Strien, J. W. V., Licht, R., Bouma, A., & Bakker, D. J. (1989). Event-related potentials during word-reading and figure-matching in left-handed and right-handed males and females. *Brain & Language*, *37*, 525–547. doi:10.1016/0093-934X(89)90110-7

Tibber, M. S., Greenwood, J. A., & Dakin, S. C. (2012). Number and density discrimination rely on a common metric: Similar psychophysical effects of size, contrast, and divided attention. *Journal of Vision*, *12*, 8. doi:10.1167/12.6.8

Valdois, S., Bidet-Ildei, C., Lassus-Sangosse, D., Reilhac, C., N'guyen-Morel, M., Guinet, E., Orliagueta, J. (2011). A visual processing but no phonological disorder in a child with mixed dyslexia. *Cortex*, *47*, 1197–1218. doi:10.1016/j.cortex.2011.05.011

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills*, *47*, 599–604. doi:10.2466/pms.1978.47.2.599

Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): What have we learned in the past four decades? *Journal of Child Psychology & Psychiatry*, *45*, 2–40. doi:10.1046/j.0021-9630.2003.00305.x

Vidyasagar, T. R., & Pammer, K. (2010). Dyslexia: A deficit in visuo-spatial attention, not in phonological processing. *Trends in Cognitive Sciences*, *14*, 57–63. doi:10.1016/j.tics.2009.12.003

Wang, Z., Cheng-Lai, A., Yan, S., Cutting, L., Jiang, Y., Lin, O., Meng, X., Zhou, X. (2014). A perceptual learning deficit in chinese developmental dyslexia as revealed by visual texture discrimination training. *Dyslexia*, *20*, 280–296. doi:10.1002/dys.1475

Wilson, A. J., Andrewes, S. G., Struthers, H., Rowe, V. M., Bogdanovic, R., & Waldie, K. E. (2014). Dyscalculia and dyslexia in adults: Cognitive bases of comorbidity. *Learning & Individual Differences*, *37*, 118–132. doi:10.1016/j.lindif.2014.11.017

Zhao, J., Qian, Y., Bi, H. Y., & Coltheart, M. (2014). The visual magnocellular-dorsal dysfunction in Chinese children with developmental dyslexia impedes Chinese character recognition. *Scientific Reports*, *4*, 7068. doi:10.1038/srep07068

Zhou, X., & Cheng, D. (2015a). When and why numerosity processing is associated with developmental dyscalculia. In Chinn, S. *The routledge international handbook of dyscalculia and mathematical* (pp. 78–89). Swales & Willis Ltd, Exeter, Devon, UK: Routledge.

Zhou, X., Wei, W., Zhang, Y., Cui, J., & Chen, C. (2015b). Visual perception can account for the close relation between numerosity processing and computational fluency. *Frontiers in Psychology*, *6*, 1364. doi:10.3389/fpsyg.2015.01364