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Report

A Causal Link between Visual Spatial Attention and Reading Acquisition

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Summary

Reading is a unique, cognitive human skill crucial to life in modern societies, but, for about 10% of the children, learning to read is extremely difficult. They are affected by a neurodevelopmental disorder called dyslexia [1, 2]. Although impaired auditory and speech sound processing is widely assumed to characterize dyslexic individuals [1–5], emerging evidence suggests that dyslexia could arise from a more basic cross-modal letter-to-speech sound integration deficit [6–9]. Letters have to be precisely selected from irrelevant and cluttering letters [10, 11] by rapid orienting of visual attention before the correct letter-to-speech sound integration applies [12–17]. Here we ask whether prereading visual parietal-attention functioning may explain future reading emergence and development. The present 3 year longitudinal study shows that prereading attentional orienting—assessed by serial search performance and spatial cueing facilitation—captures future reading acquisition skills in grades 1 and 2 after controlling for age, nonverbal IQ, speech-sound processing, and nonalphabetic cross-modal mapping. Our findings provide the first evidence that visual spatial attention in preschoolers specifically predicts future reading acquisition, suggesting new approaches for early identification and efficient prevention of dyslexia.

Results

To test the hypothesis that orienting of visual attention is causally linked to future reading acquisition [13, 16], we examined both serial search performance [17–20] and spatial cueing facilitation [14, 15] in 96 prereader Italian-speaking children in kindergarten (T1). Auditory and speech-sound processing (recognition, segmentation, and blending of syllables) [3–5, 21] and nonalphabetic visual-to-phonological mapping (rapid automatized naming, RAN of colors) [6, 22, 23] were also measured in the same prereading sample. Their emerging reading skills in grade 1 and the development of the reading skills in grade 2 were measured across the next 2 years of compulsory schooling (T2 and T3, respectively). Informed written consent was obtained for each child from their parents and the ethic committee of the "University of Padua" approved the research protocol. The entire investigation process was conducted according to the principles expressed in the Declaration of Helsinki.

The hypothesis that orienting of visual attention is crucial to the emerging reading abilities [13–17, 27] predicts that future first grade poor readers already show both poor serial search and automatic spatial cueing deficit in kindergarten. Independently of any a priori classification of the future reading disorder, if the parietal visual attentional functioning is a neurocognitive causal factor of reading acquisition, prereading visual spatial attention skills in T1 should predict, across the entire sample of children, future reading emergence in grade 1 as well as reading development in grade 2, even if prereaders' chronological age, nonverbal IQ, speech-sound processing [3–5, 21], and nonalphabetic cross-modal mapping [6–8, 22, 23] are controlled for.

Prereading Neurocognitive Deficits in Future Poor Readers: Group Analysis

Based on their standardized score in text reading ability [24], children at the end of grade 1 (T2) were divided into two groups. A child was assigned to the poor readers (PR) group if her/his Z score for averaged fluency and accuracy text reading was below 1.5 SDs. All children who did not meet the criterion for inclusion in the PR group were assigned to the normal readers (NR) group. The two groups thus obtained counted 14 PR and 68 NR with different skills in text reading. In order to control the group-selection reliability, we also analyzed group differences for the other reading and phonological decoding tasks. In grade 1, group differences were found not only in single word and pseudoword reading but also in the fluency of letter naming. Letter naming is a crucial index of letter-to-speech sound integration that has been found to be impaired in both adults and children with dyslexia [6–8]. Although letter naming is considered to be one of the most important predictors of subsequent reading acquisition [1], it should be noted that it is strongly influenced by numerous and partially uncontrolled general factors, such as verbal abilities, teaching methods, and parental input. Letter naming is also closely correlated to phonological awareness [22]. Thus, we investigated letter naming in grade 1 as a basic reading measure rather than a crucial neurocognitive predictor for future reading development.

Interestingly, the two groups differed also in the length effect of the pseudoword, that is an index of a defective serial reading mechanism. The two groups of children, however, were not different for chronological age and nonverbal IQ estimated throughout the block design of the Wechsler preschool and primary scale of intelligence [25](see Table S1 available online).

Prereading Visual Spatial Attention in Future Poor Readers

Errors in the serial visual search task were analyzed by a 2 × 2 mixed analysis of variance (ANOVA) design, in which the within-subject factor was the spacing between symbols (large and small; see Figure 1A, top), and the between-subject factor was group (PR and NR). The main effect of stimulus spacing was significant [$F_{(1,80)} = 5.45$, $p = 0.022$, ή2 = 0.064], showing a crowding effect (the inability to recognize objects in clutter [10, 11, 14]). Importantly, group main effect was also significant [$F_{(1,80)} = 12.24$, $p = 0.001$, ή2 = 0.133]: PR made more errors than NR (see Figure 1A, bottom).

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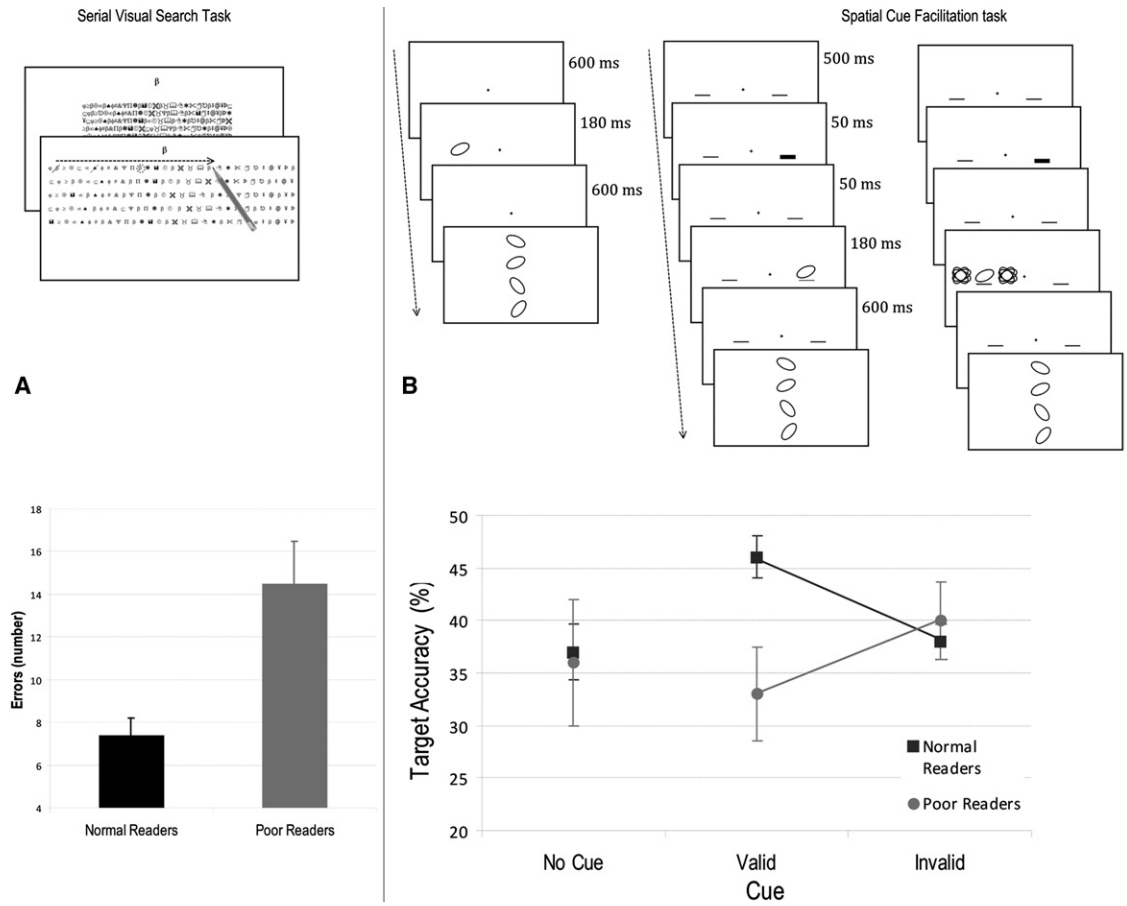

Figure 1. Visual Spatial Attention Tasks and Results

(A) Top panel shows the two types of serial visual search task (large and small spacing between symbols): children have to cancel all the target symbols, proceeding from left to right and line by line. Bottom panel shows that the error number means are represented for NR (n = 14) and PR (n = 68) at the prereading stage.

(B) Top panel shows the stimulus sequence for the peripheral target identification (left) and for the spatial cueing facilitation task (an example of valid cue without masks, and one of invalid cue with masks are depicted) (right). Children have to indicate which of the four ellipses was presented before. Bottom panel shows the mean groups accuracy (%) in peripheral target identification (no cue) and in spatial cue (valid and invalid) condition are depicted for the prereading stage. Error bars represent SE. See also Tables S1 and S2.

Mean accuracy rates (i.e., proportion of targets correctly identified; chance level = 0.25) in the spatial cueing task (see Figure 1B, top) were analyzed by a 2 × 2 × 2 mixed ANOVA design in which the within-subject factors were cue condition (valid and invalid) and target condition (alone and with flanker masks), whereas the between-subject factor was group (NR and PR). Target main effect was significant ($F_{(1,80)}$ = 11.25, p = 0.001, $\eta 2$ = 0.12), showing a crowding effect. Crucially, cue × group interaction was significant ($F_{(1,80)}$ = 9.28, p = 0.003, $\eta 2$ = 0.104; see Figure 1B, bottom). Target identification was more accurate ($F_{(1,67)}$ = 14.44, p = 0.001, $\eta 2$ = 0.177) when the target appeared in the valid (mean = 0.46, SD = 0.18) rather than in the invalid condition only in NR children (mean = 0.38, SD = 0.14) (see Figure 1B). NR and PR performance differed only in valid cue condition ($F_{(1,80)}$ = 6.5, p = 0.013, $\eta 2$ = 0.075) (see Figure 1B and Table S2).

Prereading Speech Sound Processing and Cross-Modal Mapping in Future Poor Readers

Errors in the four auditory and speech sound tasks (syllabic recognition of pseudowords and words, syllabic segmentation, and words blending [26]) were analyzed by a multivariate ANOVA where the group (PR and NR) was the between-subject factor. Only in syllabic recognition of pseudowords ($F_{(1,80)}$ = 2.59, p = 0.056, $\eta 2$ = 0.031) PR children appeared to make more errors (mean = 3.42 and SD = 2.42) than NR children (mean = 2.39 and SD = 2.12; see Table S2). All the other main effects were not significant.

Predicting Future Poor Readers from Prereading Visual Spatial Attention: Individual Data

Although PR children at a prereader stage already showed both inefficient serial visual search and impaired automatic orienting of visual attention at group level, it is important to establish the reliability of this abnormal visual spatial attention functioning at individual level. We therefore assessed the possibility to identify PR children on the basis of the prereading performance in both visual attentional tasks: 8 out of 14 (57%) future PR children were at least 1 SD below the mean of NR in at least one attentional task when they were prereaders. Moreover, to quantify the reliability of these two combined visual attention deficits, we computed the odds ratios between hits and false alarms on the visual attentional index (Z score means between errors in serial visual search task and accuracy in the valid cue condition). The odds ratio is the ratio of the chance of an event occurring in one group to the odds of it occurring in another group. Odds ratio was 8.89 (95% confidence interval from 2.01 to 39.38): i.e., for 1 PR falling below −1 SD for the visual attentional index, only 0.16 of NR children fall below that limit, whereas no PR fell on +1 SD, showing that our visual attentional index was a strong predictor of future poor readers.

Prereading Neurocognitive Skills and Future Reading Abilities: Linear Regression Analysis

After we established that future PR, at the prereading stage, show already visual spatial attentional and speech-sound perception deficits, we further investigated the causal link between individual measures of neurocognitve functioning at T1 (kindergarten), reading emergence (T2 = grade 1), and reading development (T3 = grade 2) across our entire sample of children (n = 82), independently of our a priori group classification of reading disorder.

Predicting Reading Emergence in Grade 1 from Prereading Neurocognitive Skills

After controlling for chronological age and block design by using a series of two-step fixed-entry multiple regression analysis, prereading syllabic blending skill significantly predicted future pseudoword reading (r^2 change = 0.062) and single word reading (r^2 change = 0.076), whereas prereading nonalphabetic RAN predicted future letter naming (r^2 change = 0.067) and single word reading (r^2 change = 0.054). Interestingly, prereading serial search errors significantly predicted not only the future pseudoword (r^2 change = 0.084), single word (r^2 change = 0.133), and text reading skills (r^2 change = 0.131) but also future letter naming (r^2 change = 0.16) and length effect of pseudowords (fluency: r^2 change = 0.085). Consistently, prereading target accuracy in the valid cue condition significantly predicted future pseudoword (r^2 change = 0.103), single word (r^2 change = 0.094), text reading skills (r^2 change = 0.097), and length effect of pseudowords (fluency: r^2 change = 0.093).

To determine the predictive relationships between prereading visual spatial attention functioning and future reading emergence in a more stringent way, we computed five three-step fixed-entry multiple regression analysis in which the dependent variables were as follows: (1) letter naming, (2) pseudoword reading, (3) length effect, (4) single word, and (5) text reading skills. To control for the prereading effects of age and nonverbal IQ, auditory-speech sound, and nonalphabetic cross-modal mapping skills, the predictors entered at the three steps were as follows: (1) age and block design, (2) errors in the syllabic blending and fluency in RAN of colors, and (3) serial search errors and the accuracy of valid cue condition. The prereading measure of speech-sound processing and cross-modal mapping skills, entered second, accounted for a significant quote of variance in letter naming (r^2 change = 0.081), pseudoword (r^2 change = 0.083), and single-word reading (r^2 change = 0.082) (see Table S3). Importantly, prereading visual spatial attention measures, entered last, accounted for a significant quote of unique variance in letter naming (r^2 change = 0.123), pseudoword reading (r^2 change = 0.094), length effect (fluency: r^2 change = 0.101), single word (r^2 change = 0.093), and text reading (r^2 change = 0.152) (see Table S3 and Figure 2). Both visual spatial variables independently predicted a significant quote of unique variance for text reading abilities (visual search r^2 change = 0.075 and valid cue r^2 change = 0.093).

These results demonstrate the specific role played by the visual spatial attention on the future emerging reading abilities in grade 1.

Predicting Reading Development in Grade 2 from Prereading Neurocognitive Skills

After control for chronological age and block design, prereading syllabic blending and nonalphabetic RAN skills significantly predicted future single word (r^2 change = 0.072 and 0.092, respectively) and text reading skills (r^2 change = 0.056 and 0.082, respectively). Interestingly, prereading serial visual search errors and accuracy in valid cue condition significantly predicted both single word (r^2 change = 0.165 and 0.087, respectively) and text reading skills (r^2 change = 0.222 and 0.121, respectively).

To determine more stringently the predictive relationships between prereading visual spatial attention functioning and future reading development, we computed two three-step fixed-entry multiple regression analyses in which the dependent variables were single word and text reading skills measured in grade 2. The measure of prereading speech-sound processing and cross-modal mapping skills, entered second, accounted for a significant quote of variance in single word (r^2 change = 0.125) and text reading (r^2 change = 0.112). The prereading visual spatial attention measures, entered last, accounted for a significant portion of unique variance for single word (r^2 change = 0.121) and text reading (r^2 change = 0.192) (see Table S4). Both visual spatial variables independently predicted a significant quote of unique variance for text reading abilities (visual search r^2 change = 0.12 and valid cue r^2 change = 0.035).

These results demonstrated the specific role played by the visual spatial attention on the future reading development in grade 2 (see Table S5 for correlation between the different neurocognitive measures).

Discussion

The issue of whether visual spatial attention deficits are causally linked to the reading disorders in dyslexic children has been hotly disputed (see [2, 26] versus [13, 16]). In particular, it has been argued that visual attentional deficits could be associated with dyslexia [26] or even be a simple consequence of the reading difficulties. Clear evidence that independently of auditory—and language—related skills, prereading visual spatial attention is really able to predict future reading abilities is, however, still lacking.

In the current longitudinal study, we examined the main, and apparently competitive, neurocognitive predictors of future reading acquisition, such as auditory and speech-sound [1–5] and visual spatial attention processing [13–16] as well as nonalphabetic cross-modal mapping [6–9] skills in young prereader children in kindergarten.

We showed that poor readers in grade 1 already presented a deficit in the serial visual search [17–20] as well as spatial cueing facilitation [13–15] when they were prereaders. In particular, future poor readers showed two times the number of errors in the serial visual search task compared to normal readers at the prereading stage, clearly showing that selective visual spatial attention was impaired before reading acquisition. This result confirms recent longitudinal studies suggesting that visual discrimination and search efficiency as predictors for future reading acquisition play a crucial role. Notably, the fact that the latter studies involved both English and French, in addition to Italian participants, rules

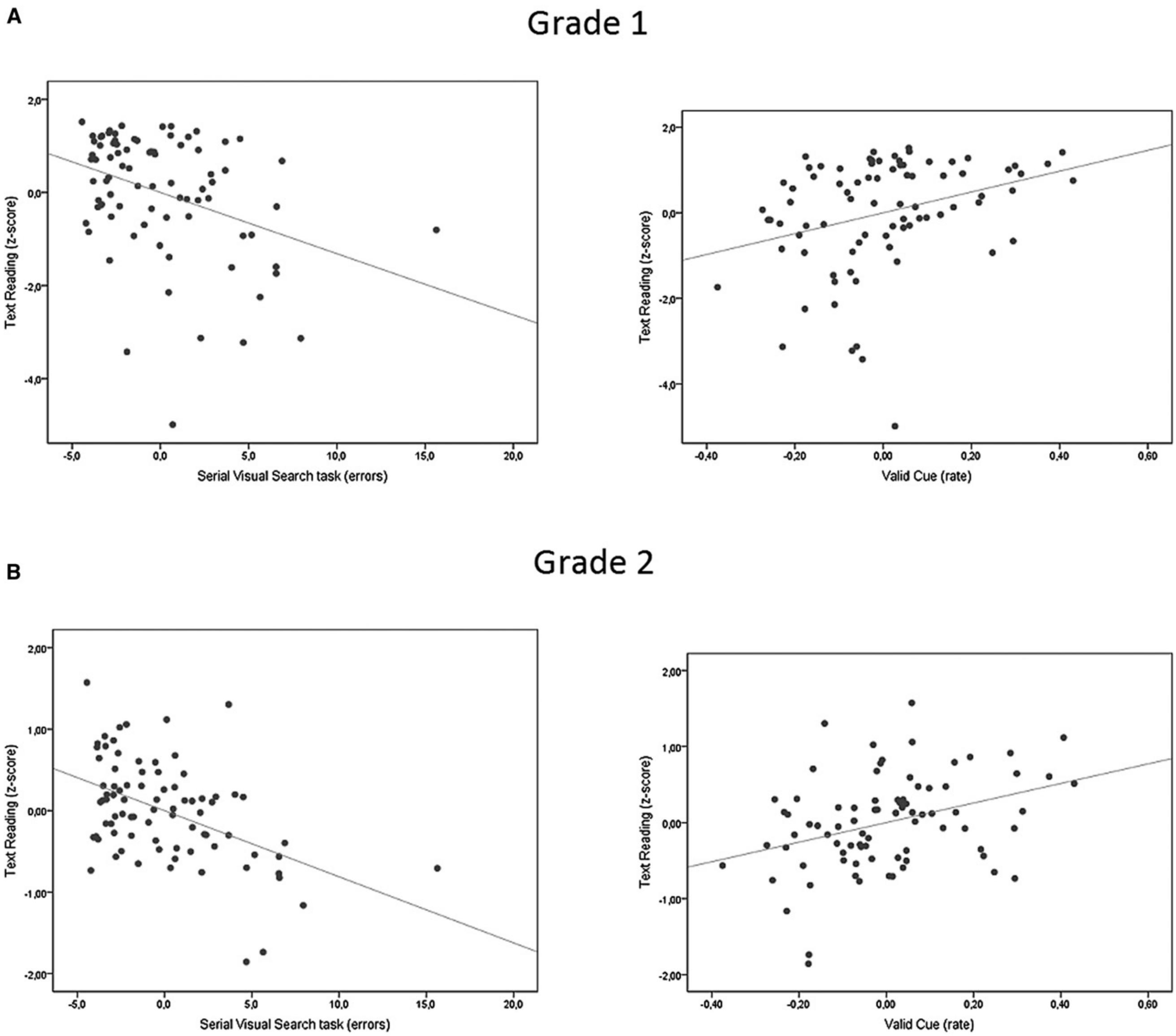

Figure 2. The Relationship between Visual Spatial Attention and Future Reading Skills

(A) Left panel shows the correlation between number of errors in the serial visual search task, measured at the prereading stage and the text reading ability (mean of Z score in speed and accuracy) measured in grade 1. Right panel shows the correlation between the valid cue condition accuracy for the spatial cueing facilitation task, measured at the prereading stage, and the text reading ability (mean of Z score in speed and accuracy) measured in grade 1.
(B) The same correlations of (A) except that the text reading ability is measured in grade 2. See also Tables S3–S5.

out the possibility that our findings are specific to a highly transparent orthography. However, the importance of the visual spatial and the phonological factors could vary across languages based on their transparency degree. Further studies in different languages seem necessary to shed some light on this topic.

Although visual errors in serial search tasks could also measure the possible preschooler reading exposition or training [18–20], the defective prereading automatic orienting of visual attention in future poor readers measured by spatial cueing task rules out this explanation. In the spatial cueing facilitation task, normal readers show a significant cueing effect: i.e., transient and peripheral visual cue improved the accuracy when target and cue were presented at the same location. In contrast, cueing effect was not significant in poor readers. Interestingly, target accuracy in the two groups was different only in valid cue condition, demonstrating that children with reading disorder in grade 1 presented, at the prereading stage, a specific deficit in the enhancement mechanism of visual attention [14, 15]. Moreover, poor reader children showed no deficit in the identification of peripheral targets when no enhancement mechanism of visual attention was involved, such as in invalid cue condition and in no cue target identification task. Finally, at the kindergarten stage, future poor readers did not show different crowding effect compared to future normal readers. These results suggest that reading disorders are not due to a general impairment in the peripheral vision but specifically to a pure deficit in attentional orienting.

The lack of cueing facilitation effect at a short cue-target interval (i.e., 100 ms) observed in future poor readers is predicted by the "sluggish attentional shifting" hypothesis [16] and is consistent with several findings showing that dyslexic individuals present a delayed time-course in spatiotemporal orienting of multisensory attention for different tasks [15, 28, 29]. Because poor readers were less sensitive to the peripheral and dynamic visual cue at their prereading stage, their magnocellular-dorsal stream could be specifically impaired [30–33]. This is consistent with a possible magnocellular-dorsal stream implication in learning to read [13, 16, 17, 29–33]. Several neuroimaging studies in individuals with dyslexia have shown deficient areas surrounding the bilateral temporoparietal junction (TPJ; [34]). Whereas the left TPJ has been linked to auditory and speech-sound processing [1, 2], the right TPJ is a crucial component of the network subserving automatic orienting of spatiotemporal attention [35, 36]. Developmental changes in right TPJ activation have been linked to reading acquisition in normally developing children [37], and some studies observed a right TPJ deficiency in dyslexics (e.g., [38]).

Because attentional orienting improves visual perception by intensifying the signal inside the focus of attention as well as diminishing the effect of noise outside the focus of attention [35, 36], sluggish orienting of automatic attention could be causally linked with higher interference between letters [10, 11, 14]. In turn, this might have a detrimental effect on the basic letter-to-speech sound integration that is specifically impaired in adults and children with dyslexia [6–8]. The involvement of a serial reading mechanism, based on visual attention orienting [39], is assumed by several computational models (e.g., [40, 41]). Before the correct letter-to-speech sound integration is applied, letters have to be, indeed, precisely selected through the rapid serial attentional orienting. Attentional orienting guides cross-modal integration that allows the selective learning of relevant letter-to-speech sound correspondence while suppressing the irrelevant ones [6–8, 42].

One of the most important aims of a longitudinal study on future reading disorders is to increase the ability to identify at-risk children [1]. Our results showed that the abnormality in orienting of visual attention is rather widespread, because about 60% of future poor reader children were at least 1 SD below the controls mean at the prereading stage. This conclusion was supported by our findings that individual differences in the prereading attentional functioning were predictive of future text, word, and pseudoword reading, as well as the basic serial reading mechanisms, such as letter naming and pseudoword length effect, even controlling for age, nonverbal IQ, speech-sound processing, and nonalphabetic cross-modal mapping skills. It is important to stress that the predictive relationship between prereading visual spatial attention functioning and future reading skills held across the entire sample of prereaders, independently of any a priori classification of the future reading disorder. Regardless of whether our poor reader children in grade 1 constitute a future group of children with dyslexia, efficient serial search and rapid orienting of spatial attention play a crucial role in emerging reading abilities. Individual differences in the prereading attentional functioning were predictive of future reading abilities also in grade 2, demonstrating the critical role of visual spatial attention not only in reading emergence but also in the reading skills development.

Because recent studies show that specific prereading programs can improve reading abilities [1], children at risk for dyslexia could be treated with preventive remediation programs of visual spatial attention before they learn to read. It is worth noting that the reading performance of children with dyslexia, or with specific language impairment, has been shown to improve following a specific training for multisensory spatial attention [43, 44]. Interestingly, consistent studies suggest that action video games improve visual attentional abilities [45, 46]. Video gamers better orient their spatiotemporal attention [45], improving the rate at which multisensory information is sampled [46].

Poor readers in grade 1 also showed the expected deficit in auditory-phonological processing (i.e., syllabic discrimination task) when they were prereaders, although in our sample this difference did not reach a significant level. Prereading syllabic blending and nonalphabetic cross-modal mapping in kindergarten predicted future reading skills in grade 1 and 2 even if chronological age and nonverbal IQ were controlled for. These results agree with the typically observed speech-sound processing and nonalphabetic cross-modal mapping disorders shown in prereaders who will develop dyslexia and in children with dyslexia [3–5, 20, 22, 23, 27, 31, 47–50]. Several authors argued that impaired auditory and speech-sound sampling is a core deficit in dyslexia [1–4, 26]. Thus, our findings are consistent with a multifactorial hypothesis of dyslexia [15, 16, 18, 20, 27, 28, 31, 49, 51], which suggests that not only auditory-phonological deficits but also visual spatial attention are causally implicated in dyslexia [52].

Overall, our results demonstrate for the first time that independently of speech-sound perception, as well as nonalphabetic cross-modal mapping skills, visual attentional functioning predicts future reading emergence and development disorders. These findings virtually close not only a long-lasting debate on the causal role of visual spatial attention deficits in dyslexia but also open the way to a new approach for early identification and more efficient prevention of dyslexia.

Supplemental Information

Supplemental Information includes five tables and Supplemental Experimental Procedures and can be found with this article online at doi:10.1016/j.cub.2012.03.013.

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