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Is excessive visual crowding causally linked to developmental dyslexia?

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ABSTRACT

For about 10% of children reading acquisition is extremely difficult because they are affected by a heritable neurobiological disorder called developmental dyslexia (DD), mainly associated to an auditory-phonological disorder. Visual crowding is a universal phenomenon that impairs the recognition of stimuli in clutter, such as a letter in a word or a word in a text. Several studies have shown an excessive crowding in individuals with DD, but the causal link between excessive crowding and DD is not yet clearly established. An excessive crowding might be, indeed, a simple effect of DD due to reduced reading experience. The results of five experiments in 181 children reveal that: (i) an excessive crowding only at unattended locations characterizes an unselected group of children with DD (Experiment 1); (ii) an extra-large spaced text increases reading accuracy by reducing crowding in an unselected group of children with DD (Experiment 2); (iii) efficient attentional action video game trainings reduce crowding and accelerate reading speed in two unselected groups of children with DD (Experiment 3 and 4), and; (iv) pre-reading crowding longitudinally predicts future poor readers (Experiment 5). Our results show multiple causal links between visual crowding and learning to read. These findings provide new insights for a more efficient remediation and prevention for DD.

1. Introduction

Reading is a unique cognitive human skill crucial to life in modern societies, but for about 10% of children, learning to read is extremely difficult. These children are affected by developmental dyslexia (DD) and they have difficulties with accurate or fluent word recognition and spelling despite adequate instruction, intelligence and sensory abilities. DD is defined by difficulties with phonological decoding, whereas comprehension is more intact (American Psychiatric Association, 2013; Gabrieli, 2009; Peterson and Pennington, 2012). Several longitudinal studies have shown that auditory-phonological processing is already impaired at the pre-reading stage in children who eventually develop DD (e.g., Carroll et al., 2016; Franceschini et al., 2012; Black et al., 2017). Although the most common explanation of DD suggests a specific disorder in auditory and phonological processing (Hornickel and Kraus, 2013; Peterson and Pennington, 2015), several studies show that also difficulties in visual crowding and spatial attention could be core deficits in DD (Bosse et al., 2007; Zorzi et al., 2012; Facoetti et al., 2010a,b; Franceschini et al., 2012, 2013; Stein, in press in this issue), impairing orthographic development (Vidyasagar and Pammer, 2010; Stein, 2014; Grainger et al., 2016a,b).

Crowding is a universal phenomenon that limits our ability to identify individual stimuli when multiple objects are displayed in their vicinity (see Pelli, 2008; Pelli and Tillman, 2008; Whitney and Levi, 2011; Gori and Facoetti, 2015; Rosenholtz, 2016, for reviews). Crowding selectively impairs the discrimination and the ability to recognize stimuli in clutter (Whitney and Levi, 2011). Some neuroimage studies have shown that the strongest effects of crowding occur in the earliest stages of cortical processing in V1 (Chen et al., 2014; Millin et al., 2014), whereas other studies showed that it could arise at later stages in the visual processing hierarchy (Chicherov et al., 2014; Ronconi et al., 2016a,b; Ronconi and Bellacosa Marotti, 2017). Crowding depends on the critical spacing between target and flankers, which is defined as the minimal distance between the target and the flankers that is necessary to accurately recognize the target comparable to when the flankers are absent (Yashar et al., 2015). Bouma's law states that critical spacing is proportional to target eccentricity: the higher the target eccentricity

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the larger the critical spacing for correctly discriminating the target (Bouma, 1970; Whitney and Levi, 2011). Crowding can occur with simple objects such as oriented gratings (e.g., Greenwood et al., 2012), and with complex objects such as faces and letters (Pelli and Tillman, 2008; Freeman et al., 2012; Whitney and Levi, 2011). In the periphery of the visual field, many letters printed at fixed spacing and embedded within a word are unrecognizable because of crowding (Bouma, 1970; Martelli et al., 2009).

Letter identification is a fundamental stage in visual word recognition and reading (McClelland and Rumelhart, 1981; Pelli et al., 2003; Perry et al., 2007). During reading acquisition the analysis of the graphemes that compose the letters string is a fundamental component of phonological decoding, i.e. the translation of the orthographic code into its phonological counterpart (Perry et al., 2007; Goswami, 2003; Ziegler and Goswami, 2005). Phonological decoding is also fundamental for a fast access to semantics from print during reading acquisition (Share, 1995). Recently, Grainger et al. (2016) described a specialized system for parallel letter processing that assigns letter identities to different locations along the horizontal meridian within the limits mainly imposed by crowding, in which spatial attention is used to set up this system during reading development. In particular, efficient development of reading skills involves the use of visuo-spatial attention to implement parallel letter processing. Developing a mechanism of spatial attention to process letter identities, their location and their position within a word, is one of the keys to becoming a skilled reader (Grainger et al., 2016a,b).

Although some studies showed no or small effects of spatial attention on crowding (Nazir, 1992; Wilkinson et al., 1997, Joo et al., 2018), other studies suggest that crowding could be the result of a limit in the resolution of spatial attention (He et al., 1996; Intriligator and Cavanagh, 2001; Strasburger, 2005; Yeshurun and Rashal, 2010; Grubb et al., 2013). Indeed, a spatial cue that orients attention on the target position before the array of stimuli (target and flankers) reduces crowding (Huckauf and Heller, 2002; Scolari et al., 2007; Franceschini et al., 2012), decreasing the critical spacing (Yeshurun and Rashal, 2010).

People with DD appear to suffer from an excessive crowding as compared to typical readers (e.g., Geiger and Lettvin, 1987; Moores et al., 2011; Callens et al., 2013; Moll and Jones, 2013; see Gori and Facoetti, 2015 for a review; but Doron et al., 2015; Sacchi et al., 2018). An excessive crowding in individuals with DD could be due to sluggish orienting of their spatial attention (Facoetti et al., 2000, 2001, 2008, 2010, 2010; Lallier et al., 2009, 2010; Ding et al., 2016; see Hari and Renvall, 2001; Gori and Facoetti, 2014; Krause, 2015; Grainger et al., 2016a,b for reviews).

However, the causal link between an excessive crowding and DD is not yet clearly established because group differences between individuals with and without DD in crowding might be a simple effect of the reduced reading experience associated to DD (Goswami, 2003, 2015). Some studies showed that extra-large interletter spacing enhances their reading efficiency on the fly, suggesting a possible causal link (e.g., Spinelli et al., 2002; Zorzi et al., 2012; but Schneps et al., 2013). Here, we employ a comprehensive approach incorporating all causal experimental designs to test the relationship between an excessive crowding and DD.

In particular, after testing the efficacy of our task to capture an excessive crowding in children with DD, we measured the crowding to show the possible causal link in: (i) a study in which we manipulated directly the interletter and interline spacing; (ii) two interventions studies; and (iii) a longitudinal study. The intervention and longitudinal studies are the main experimental design to demonstrate whether an excessive crowding has a pivotal role in a more specific-domain skill (i.e., reading).

In Experiment 1, we measured crowding in two age-matched groups of children with and without DD manipulating spatial attention. Results show an excessive crowding in children with DD only for unattended location. In Experiment 2, we experimentally decreased crowding through an extra-large spaced text, showing that reading accuracy was increased in children with DD. In addition, two intervention studies (Experiment 3 and 4) and a longitudinal study (Experiment 5) were conducted to directly establish a causal link between crowding and reading skills development. In the intervention studies, children with DD were trained with action video games (AVG), which have repeatedly shown to reduce crowding (Green and Bavelier, 2007; Franceschini et al., 2013, 2017b) and improve spatial attention (see Green and Bavelier, 2012 for a review and Bediou et al., 2018 for a recent meta-analysis). AVG were also found to improve reading efficiency in individuals with DD (Franceschini et al., 2013, 2017a, 2017b; Gori et al., 2016; Łuniewska et al., 2018; see Franceschini et al., 2015 for a review) and other visual disorders (Vedamurthy et al., 2015; Gambacorta et al., 2018), possibly through the amelioration of the dorsal fronto-parietal pathway efficiency (Bavelier et al., 2012; Gori et al., 2016; Föcker et al., 2018a, 2018b). Thus, in Experiment 3 and 4 we used AVG training to reduce crowding and to improve reading efficiency in two groups of unselected children with DD. For unselected group we mean children with diagnosed DD that are not selected by subtype of DD or for different neurocognitive deficits. Finally, in Experiment 5, we used a longitudinal approach where crowding was measured in pre-readers and its predictability for future reading development is prospectively investigated.

2. Experiment 1: crowding in attended and unattended location

2.1. Material and methods

2.1.1. Participants

Thirteen children (5 female) with DD, and twenty-two children (11 female) who were typical readers (TR) took part in the experiment. Children received the diagnosis of DD by the Italian National Health Service, based on standard exclusion and inclusion criteria (APA, 2013). The reading performance of each child with DD was at least −1 SDs below the age-standardized norm in the average score of the 4 clinical measures (Sartori et al., 2007). Other inclusion criteria for this study were normal IQ (≥85), normal or corrected-to-normal vision, absence of neurological deficit and ADHD diagnosis (APA, 2013). The two groups (DD and TR) were not different ($t_{(33)} = -1.298$, $p > 0.203$) for chronological age (TR mean = 9.25, SD = 0.78 and DD mean = 8.91, SD = 1.49), whereas they were different ($t_{(33)} = 5.623$, $p = 0.0001$) both in words reading time (TR: mean = 90.09 s, SD = 31.17 s; DD: mean = 298.08 s, SD = 170.42 s) and errors ($t_{(33)} = 10.29$, $p = 0.0001$; TR: mean = 1.23, SD = 1.38; DD: mean = 12.85, SD = 5.03), as well as in pseudowords reading time ($t_{(33)} = 10.44$, $p = 0.0001$; TR: mean = 67.14 s, SD = 15.11 s; DD: mean = 174.46 s, SD = 44.43 s) and errors ($t_{(33)} = 10.39$, $p = 0.0001$; TR: mean = 2.32, SD = 2.36; DD: mean = 14.38, SD = 4.54).

The entire investigation process was conducted according to the principles expressed in the Declaration of Helsinki. Written informed consent was obtained by parents of children, and all procedures were jointly approved by the Ethics Committee of the University of Padua.

2.1.2. Crowding task

Participants were seated 50 cm away from the screen. Children were asked to recognize the orientation of the target. The stimuli (target = letter T; flankers = letters H) were shown on a computer screen at 11° from the fixation point (a small cross). The small cross (0.1° and 0.6 cd/m2) appeared at the centre of the screen for 1000 msec. After, a cue (composed by four red dots each one of 0.17°) was shown for

100 msec. The cue was presented in the same peripheral location of the target (attended condition) to capture visual attention at the target location (Yeshurun and Rashal, 2010) or at the centre of the screen (unattended condition) in order to induce visual attention to remain at the fixation location. Then, the target and the flankers appeared for 75 msec. The target could have four different orientations: upward, downward, rightward or leftward (chance level = 25%). The target-to-flanker spacing (T-F S) was measured as the centre-to-centre distance - and was equal to 2.2°, 2.5° or 2.8°. The four possible target orientations were shown at the end of the trial until the child response was entered by the experimenter through the keyboard. A total amount of 96 trials were presented (see Fig. 1 A and B).

2.2. Results

The target accuracy was analysed by two separate mixed analysis of variance (ANOVA), one for the unattended and one for the attended condition, with a 3 × 2 design. The within-subject factor was the T-F S (2.2°, 2.5° and 2.8°), while the between-subject factor was the group (children with DD and TR).

The ANOVA in the unattended condition showed a T-F S main effect ($F_{(2,66)} = 5.864$, $p = 0.005$, $\eta^2 = 0.151$) and a group main effect ($F_{(1,33)} = 5.050$, $p = 0.031$, $\eta^2 = 0.133$; see Fig. 1C). Although the T-F S and group interaction was not significant ($F_{(2,66)} = 1.314$, $p = 0.276$), in order to exclude a general impairment for peripheral letter recognition in children with DD, three between-subjects planned comparisons at the different T-F S were conducted. We used for multiple comparison t-tests. The two groups differed at the 2.2° ($t_{(33)} = -2.397$, $p = 0.011$; TR mean = 0.65, SD = 0.19 and DD mean = 0.48, SD = 0.22) and at the 2.5° ($t_{(33)} = -1.853$, $p = 0.037$; TR mean = 0.67, SD = 0.18 and DD mean = 0.56, SD = 0.18), but not at the 2.8° ($t_{(33)} = -0.746$, $p > 0.461$; TR mean = 0.72, SD = 0.17 and DD mean = 0.67, SD = 0.21; see Fig. 1D).

In the second ANOVA conducted in the attended condition, no significant effect was present.

3. Experiment 2: reading extra-large spacing word text

3.1. Material and methods

3.1.1. Participants

Eighteen children (14 female) with DD, and thirty-two TRs (11 female) took part in this experiment. The same DD diagnostic criteria of Experiment 1 were used. The two groups (DD and TR) did not differ ($t_{(48)} = -0.439$, $p > 0.662$) for chronological age (TR mean = 11.6, SD = 20 and DD mean = 11.8, SD = 23) and IQ (Wechsler, 2003; all ps > .38), whereas they differed ($t_{(48)} = 2.93$, $p = 0.005$) both in words reading time (TR: mean = 105 s, SD = 40; DD: mean = 146 s, SD = 56) and errors ($t_{(48)} = 4.55$, $p = 0.0001$; TR: mean = 2.8, SD = 2.13; DD: mean = 7, SD = 4.57), as well as in pseudowords reading time ($t_{(48)} = 2.75$, $p = 0.01$; TR: mean = 80 s, SD = 26; DD: mean = 107 s, SD = 42) and errors ($t_{(48)} = 5.78$, $p = 0.0001$; TR: mean = 3.7, SD = 2.77; DD: mean = 9, SD = 3.64).

The entire investigation process was conducted according to the principles expressed in the Declaration of Helsinki. Written informed consent was obtained by parents of children, and all procedures were jointly approved by the Ethics Committee of the University of Padua.

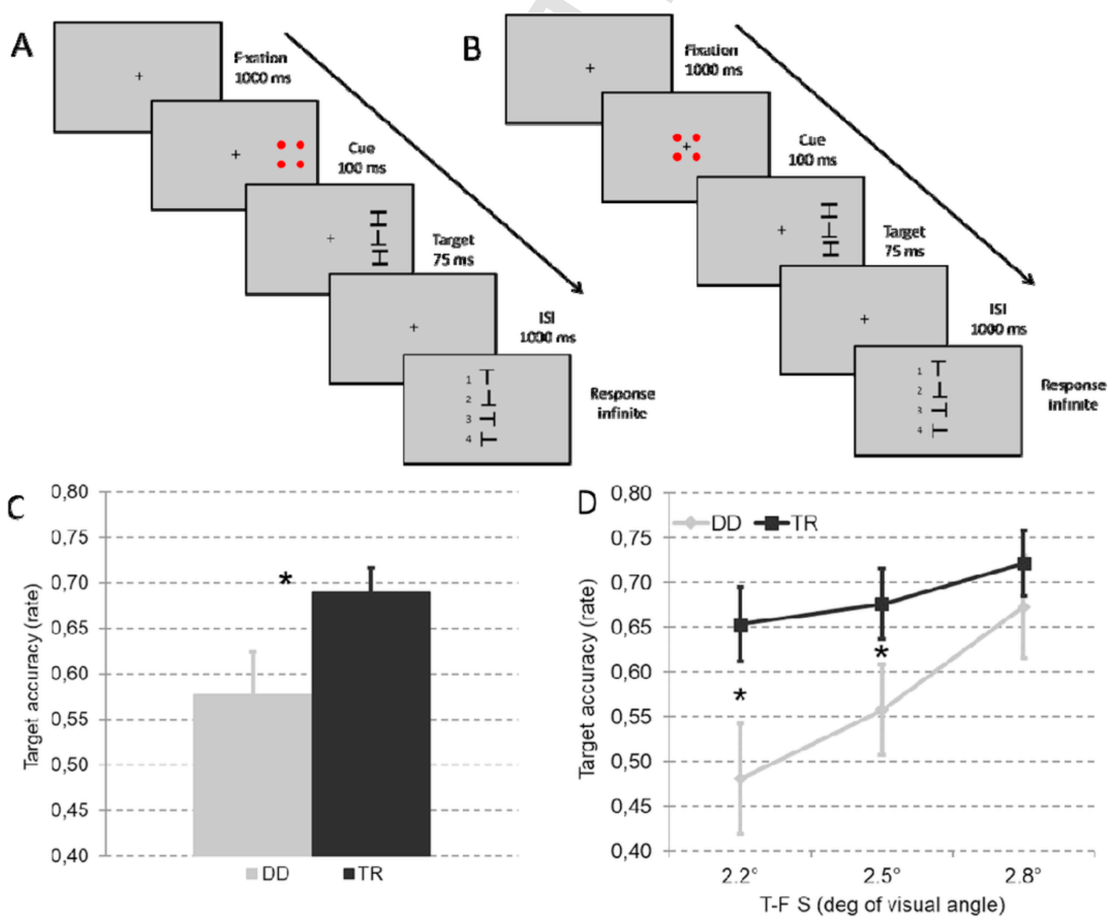

Fig. 1. Crowding task in attended (A) and unattended (B) conditions. C: Target accuracy (in rate) in typical readers (TR) and children with developmental dyslexia (DD) groups. D: Target accuracy (in rate) in DD and TR groups at different target to flanker spacing (T-F S). Bars represent standard errors.

3.1.2. Extra-small and extra-large reading tasks

Two different word texts (based on "Marcovaldo", Calvino, 1966) were presented to the children in two different evaluation sessions. A text was presented in extra-small spaced condition and the other in extra-large spaced condition. Children were randomly divided in four groups in which the extra-small and extra-large spacing conditions and two word texts were counterbalanced between children.

The texts were printed in black on a white A4 paper sheet using Times-Roman font and print size of 14 point (pt; 1 pt = 0.353 mm in typesetting standards). The extra-small text is characterized by an interletter and interline spacing reduction than normal text. In contrast, the extra-large text is characterized by an interletter and interline spacing enlargement than normal text. In particular, the interletter spacing was 1 pt and 2.5 pt in the extra-small and extra-large text, respectively. The interline spacing was 1 pt and 2 pt in the extra-small and extra-large text, respectively. In order to control the size of noising letters per line (Schneps et al., 2013), the number of syllables per line was the same in the extra-small and in the extra-large texts (see Fig. 2 A and B).

3.2. Results

The reading performance (errors and reading time) was analysed by two separate ANOVAs.

The within-subject factor was the spacing condition (extra-small and extra-large), while the between-subject factor was group (children with DD and TR).

The ANOVA on errors showed a spacing condition main effect ($F_{(1,48)} = 16.132$, $p = 0.0001$, $\eta^2 = 0.252$), a group main effect ($F_{(1,48)} = 22.919$, $p = 0.0001$, $\eta^2 = 0.323$), and a significant spacing condition X group interaction ($F_{(1,48)} = 4.488$, $p = 0.039$ $\eta^2 = 0.086$; see Fig. 2C). The within-subjects planned comparisons showed that only in the DD group there was a difference in the number of errors between the two spacing conditions ($t_{(17)} = 4.322$, $p = 0.0001$). Two between-subjects planned comparisons at two spacing conditions showed that the two groups differed both in extra-small ($t_{(48)} = -4.735$, $p = 0.0001$; TR mean = 5.34, SD = 3.97 and DD mean = 10.78, SD = 3.75) and in extra-large reading tasks ($t_{(48)} = -3.350$, $p = 0.002$; TR mean = 4.31, SD = 2.91 and DD mean = 7.44, SD = 3.60).

The ANOVA on reading time (syll/sec) showed a significant group main effect ($F_{(1,48)} = 8.231$, $p = 0.006$, $\eta^2 = 0.146$), but neither main effect of spacing condition or spacing condition × group interaction were significant (all ps > .107).

4. Experiment 3: AVG training reduces crowding and increase reading speed

4.1. Material and methods

4.1.1. Participants

The participants were fourteen children (6 female; mean age = 10.1 years, SD = 1.6) with DD that agreed to participate in an experimental video game training. The same DD diagnostic criteria of Experiment 1 and 2 were used. Information about video game experience were collected in interviews with parents during pre-informative briefing about the experimental training. Children with DD did not know the aim of the training and they declared that in the previous six months they did not play AVG more than 1 h per month. Seven children with DD were randomly assigned to AVG and 7 to the non-AVG (NAVG) training. Participants were tested 3–5 days before the start of interventions and re-tested between 1 and 3 days after the end of interventions. Crowding task and reading skills were measured before (T1) and after (T2) the two different video game trainings.

The entire investigation process was conducted according to the principles expressed in the Declaration of Helsinki. Written informed consent was obtained by parents of children, and all procedures were jointly approved by the Ethics Committee of the University of Padua.

4.1.2. Reading skills

Phonological decoding ability was measured using: (i) two texts, each of 46 pseudowords, composed of 1–3 syllables (same syllables in different order for both texts) for a total amount of 100 syllables for each text (Franceschini et al., 2016), and; (ii) 2 lists of 15 pseudowords composed of 2–4 syllables (the same syllables in different order for both lists) (Franceschini et al., 2016). Pseudowords texts and lists administration order was counterbalanced between children in T1 and T2. Reading speed and accuracy were measured in terms of syllables per second (syll/sec) and the number of errors, respectively.

4.1.3. Crowding task

Participants were individually tested in a dimly lit and quiet room. Crowding was measured with a similar task used in Experiment 1, but we used two larger T-F Ss (3.6° and 4.8°), to obtain more efficient baseline condition in which the performance of children with DD should not be impaired.

4.1.4. Training procedure

Each child was individually trained by playing a commercial Wii™ video game for a total of 12 h. Video games were played at 200 cm from a 27-in TV screen. A commercial Wii™ video game from Ubisoft™ (deemed suitable for children age 7 and older by the Pan European Game Information) called "Rayman Raving Rabbids" was used. Single mini-games were selected from the overall game and categorized

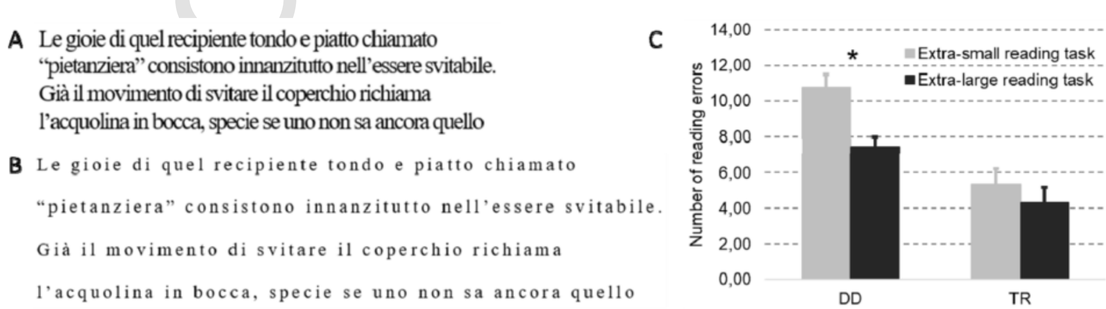

Fig. 2. Extra-small (A) and extra-large (B) word text reading tasks. C: Number of reading errors in extra-small and extra-large spacing tasks in children with developmental dyslexia (DD) and typical readers (TR).

as AVG or NAVG. In order to classify the mini-games, the checklist developed by Bediou et al. (2018), was followed: all AVGs share a set of qualitative features, including (1) extraordinary speed both in terms of very transient events and in terms of the velocity of moving objects; (2) a high degree of perceptual, cognitive, and motor load in the service of an accurate motor plan; (3) unpredictability both temporal and spatial; (4) an emphasis on peripheral processing. We labeled AVGs only the mini-games that presented all the four characteristics listed above, whereas NAVGs presented not more than one of them. The NAVG participants did not see the mini games used by the AVG players and vice versa. We trained children for 9 sessions of 80 min per day distributed in a period of two weeks (see for details Franceschini et al., 2013; Gori et al., 2016; Franceschini et al., 2017a, 2017b).

4.2. Results

In T1 the phonological decoding performance (speed and accuracy) and the accuracy in crowding task were similar in the two groups (all ps > .2 and all p > 0.09, respectively).

4.2.1. Training effect on reading skills

Reading speed improvement (syll/sec) was evaluated by a mixed ANOVA with a 2 × 2 x 2 design. The within-subject factors were the time (T1 and T2) and the reading tasks (pseudoword texts and lists); while the between-subjects factor was the group (AVG and NAVG training). Results show a significant main effect of time ($F_{(1,12)} = 9.012$, $p = 0.011$ $\eta 2 = 0.429$), and a significant time × group interaction ($F_{(1,12)} = 5.889$, $p = 0.032$ $\eta 2 = 0.329$; see Fig. 3A). In T2 the reading speed was significantly different in the two groups ($t_{(12)} = 2.120$, $p = 0.028$). Within-subject planned comparisons showed that only the DD children trained with AVG significantly improved their reading speed ($t_{(6)} = -5.013$, $p = 0.002$; T1 mean = 1.27 syll/sec, SD = 0.23; T2 mean = 1.47 syll/sec, SD = 0.29). The clinical relevance of this result can be fully appreciated by noting that the pseudoword decoding improvements (mean 0.2 syll/sec) obtained after 12 h of AVG training were higher than the mean improvements expected in a child with DD (0.15 syll/sec) after 1 year (8760 h) of spontaneous reading development.

The same ANOVA, considering as dependent variable the number of errors, did not showed any significant effect.

4.2.2. Training effect on crowding task

In Experiment 1 the difference between DD and TR performance was found only in the smaller T-F Ss (i.e., 2.2° and 2.5°). Thus, in Experiment 3 the crowding analysis were carried out on the average of accuracy at the 2.2° and 2.5° (i.e., small spacing condition) and on the average of accuracy at the 3.6° and 4.8° (i.e., large spacing condition).

The results showed that after the AVG training, the DD children improved their target perception in the small spacing ($t_{(6)} = -2.150$, $p = 0.038$), but not in the large spacing condition ($t_{(6)} = -1.104$, $p = 0.156$), whereas DD children of the NAVG group did not improve their performance in any conditions (all $ps > 0.1$). In T2 the target accuracy was significantly different in the two groups only in the small spacing condition ($t_{(12)} = 2.421$, $p = 0.032$; see Fig. 3B).

5. Experiment 4: AVG training reduces crowding and increase reading speed only in high learning DD players

5.1. Material and methods

5.1.1. Participants

The participants were eighteen children (8 female; mean age = 9.79 years, SD = 1.33) with DD that agree to participate to a clinical AVG training. The same DD diagnostic criteria of Experiment 1, 2 and 3 were used. As in Experiment 3, information about video game experience were collected in interviews with parents during pre-informative briefing about the clinical training. Children with DD did not know the aim of the training and they declared that in the previous six months they did not play AVG more than 1 h for month. Reading skills and crowding task (Fig. 1) were measured before (T1) and after (T2) the AVG training. Participants were individually tested and trained in a dimly lit and quiet room. The participants of this Experiment are reported in published study (Franceschini and Bertoni, in press in this issue).

The entire investigation process was conducted according to the principles expressed in the Declaration of Helsinki. Written informed consent was obtained by parents of children, and all procedures were jointly approved by the Ethics Committee of the University of Padua.

5.1.2. Reading skills

The reading skills were measured with the same tasks used in Experiment 3.

5.1.3. Crowding task

The crowding performance was measured with the same tasks used in Experiment 1 and 3.

5.1.4. Training procedure

The training procedure was the same of Experiment 3, but the children were trained for 12 sessions of 60 min per day distributed in a period of two weeks and the AVGs were different. We used two commercial video games similar for action features: "Plants vs. Zombies: Garden Warfare" (PopCap Games©, 2014; suitable for children age 7 and older) for Play Station 3©; and "Nanostray 2" (Blizzard©, 2006; suitable

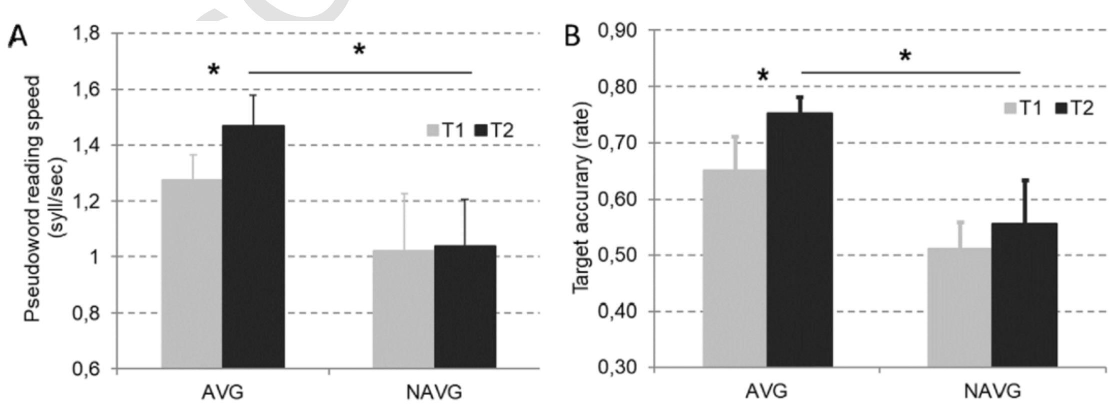

Fig. 3. A: Reading speed (syll/sec) in pseudoword tasks before (T1) and after (T2) action video game (AVG) or non-action video game (NAVG) training. B: Target accuracy (in rate) in crowding task before (T1) and after (T2) AVG or NAVG training in the small spacing condition.

for children age 3 and older) for Nintendo DS©. Nine children were trained with the first AVG and the other 9 with the second AVG.

For each child we calculated the difference between the first game score greater than zero recorded from the beginning of the training, and the game score obtained at the end of the training (i.e., the game score improvement). Initial game scores equal to zero were not used because they indicated that the children were not sufficiently able to use the device and to interact with the events of the games.

The median game score improvement was calculated. We divided the total group of players with DD in those who showed a game score improvement greater to the median score (high learning players, HL) and those who showed an improvement lower or equal than the median score (low learning players, LL). The two groups did not differ in age and reading performance (time and errors), as well as in their initial game score neither in the “Plants vs zombies” game group (HL score mean = 403, SD = 181; LL mean = 394 SD = 95, $t_{(7)} = 0.099$, $p = 0.924$), nor in the “Nanostray 2” group (HL score mean = 10212, SD = 13809; LL mean = 12875 SD = 11903, $t_{(7)} = 0.307$, $p = 0.769$) before the clinical AVG training. Based on our a priori classification, the game score improvement in HL and LL group was significantly different both in “Plants vs zombies” (HL mean = 428 SD = 215; LL mean = 9 SD = 76; $t_{(7)} = 4.103$, $p = 0.005$) and “Nanostray 2” (HL mean = 97600 SD = 21842; LL mean = 38218 SD = 20582; $t_{(7)} = 4.189$, $p = 0.004$; see Franceschini and Bertoni, in press in this issue for details).

5.2. Results

5.2.1. Training effect on reading skills

Reading speed improvement (syll/sec), as in the Experiment 3, was evaluated by a mixed ANOVA with a 2 × 2 x 2 design. The within-subject factors were the time (T1 and T2) and the reading tasks (pseudoword texts and lists), whereas the between-subject factor was group (LL and HL). Results showed a significant main effect of time ($F_{(1,16)} = 4.850$, $p = 0.043$ $\eta^2 = 0.233$), and a significant time × group interaction ($F_{(1,16)} = 5.494$, $p = 0.032$ $\eta^2 = 0.256$; see Fig. 4 panel A). Within-subjects planned comparisons showed that only the DD children of the HL group significantly improved their reading speed ($t_{(7)} = -3.115$, $p = 0.017$; T1 mean = 1.14 syll/sec, SD = 0.43; T2 mean = 1.25 syll/sec, SD = 0.41).

The same ANOVA considering as dependent variable the number of errors, showed no significant main effect or interactions.

5.2.2. Training effect on crowding task

As in Experiment 3, the analysis were carried out in the small spacing (mean between 2.2° and 2.5° T-F S) and in the large spacing condition (mean between 3.6° and 4.8° T-F S). The results showed that only the DD children of the HL group improved their performance in the small spacing ($t_{(7)} = -1.901$, $p = 0.049$; see Fig. 4B), but not in the large spacing condition ($t_{(7)} = -1.173$, $p = 0.140$), while the children of the LL group did not improve their performance in both spacing conditions (all ps > 0.1).

6. Experiment 5: longitudinally testing the causal hypothesis between excessive crowding and DD

6.1. Material and methods

6.1.1. Participants

In Experiment 5, we longitudinally investigated the causal link between crowding and learning to read. Sixty-four (33 female), 5-year-old pre-reading children attending the last year of kindergarten in Northern Italy, were selected by a larger sample and took part in our longitudinal study. In the Italian school system, formal reading instruction starts in grade 1. Consequently, Italian pre-schoolers are also pre-readers. We excluded the few children that were able to read at the kindergarten stage. All children were native Italian speakers without any documented history of brain damage, ADHD diagnosis, and hearing or visual (uncorrected) deficits. Participants were individually tested in a dimly lit and quiet room.

The entire investigation process was conducted according to the principles expressed in the Declaration of Helsinki. Written informed consent was obtained by parents of children, and all procedures were jointly approved by the Ethics Committee of the University of Padua.

6.1.2. Procedure: tasks, stimuli and procedures in kindergarten (T1)

6.1.2.1. Crowding task Crowding was evaluated in a more ecological setting using a paper and pencil serial visual search task (Franceschini et al., 2012). They had to find and cancel with a pencil a specific target symbol (always visible on the top of the sheet), by searching sequentially from left to right and line-by-line. The visual search task was composed by 2 sheets, both with 5 lines of 31 symbols (5 target and 26 distractors; 5 × 5 mm). There were two task conditions that were administered in counterbalance order between participants: (i) Large spacing (i.e., visuo-spatial index), and (ii) Small spacing (i.e., crowding index). The difference between the two conditions was the inter-stimuli spacing (8 and 4 mm, respectively; see Fig. 5 A and B). Time (in sec) and errors were measured.

6.1.2.2. Intelligent quotient (IQ) Verbal IQ level was estimated through the administration of the “Vocabulary” subtest of the Wechsler Preschool and Primary Scale of Intelligence (Wechsler, 2002).

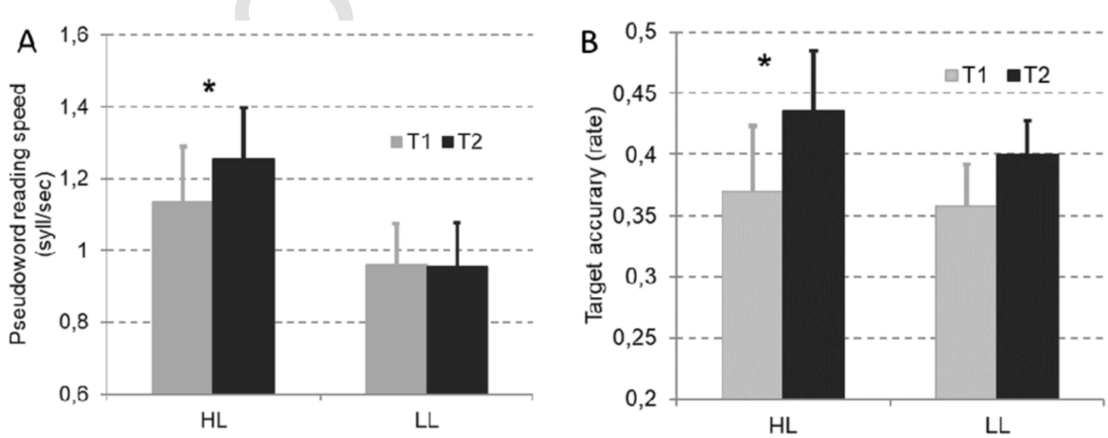

Fig. 4. A: Pseudoword reading speed (syll/sec) before (T1) and after (T2) clinical action video game (AVG) training in high learners (HL) and low learners (LL) groups. B: Target accuracy (in rate) in crowding task before (T1) and after (T2) AVG training in HL and LL groups in the small spacing condition.

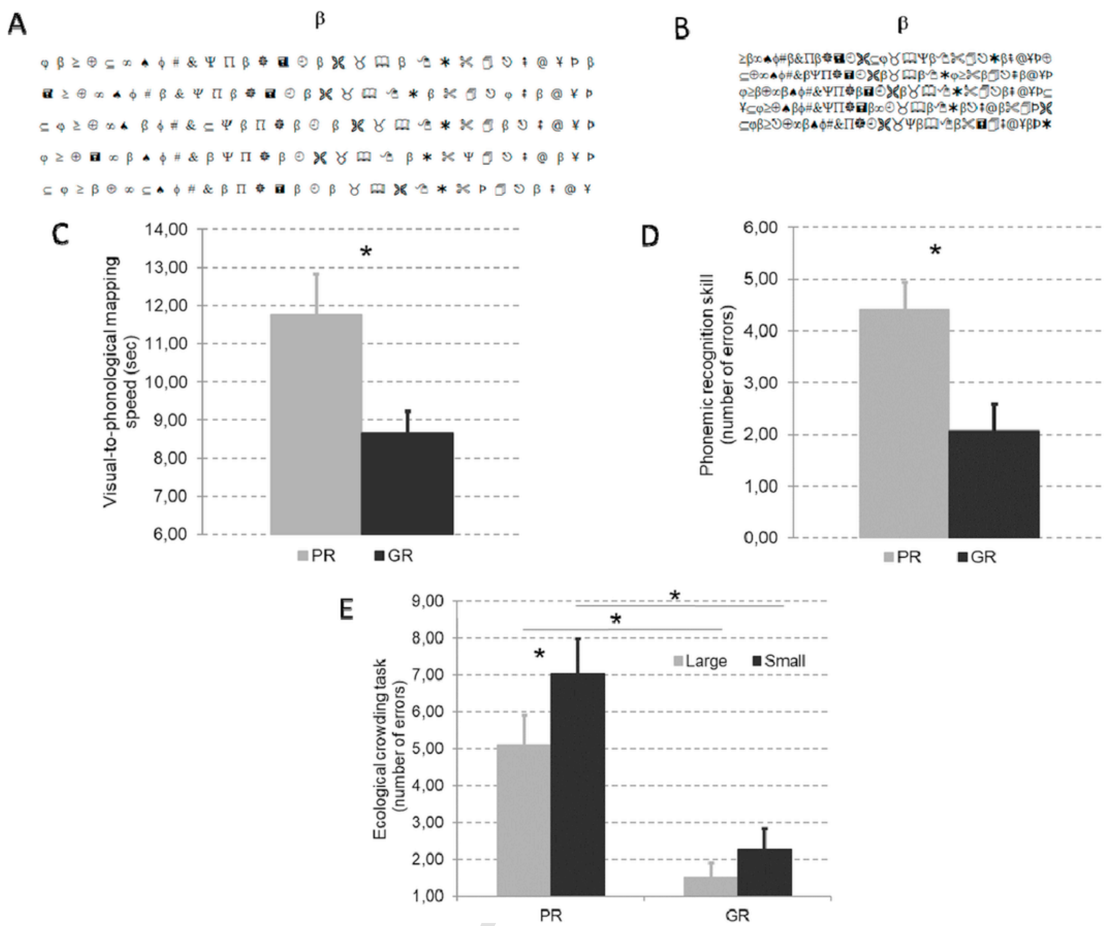

Fig. 5. Serial visual search task to measure crowding in an ecological setting in Experiment 5: the large spacing (A) and the small spacing (B) conditions. C: Visual-to-phonological mapping speed (sec.) in kindergarten (T1) in future poor readers (PR) and good readers (GR). D. Number of errors in phonemic recognition task in T1 in future PR and GR. E: Number of errors in ecological crowding task in kindergarten (T1) in large and small spacing condition in future PR and GR.

6.1.2.3. Phonemic recognition task This task measured the ability to identify if two similar pseudo-words were composed by the same or different phonemes (15 pseudo-words pairs e.g., "paca" and "baca"; Marotta et al., 2004).

6.1.2.4. Visual-to-Phonological Mapping Task Cross-modal mapping from visual stimuli to the correspondent spoken words (i.e., phonological lexicon access from the visual input) was measured by using a non-alphabetic rapid automatized naming task, in which the visual items were 16 filled colored circles (Franceschini et al., 2012). The participants' task was to name as fast as possible the familiar colors filling the circles. The total time (in sec) for naming all the visual items was measured.

6.1.3. Procedure: tasks, stimuli and procedures in grade 1 (T2)

Reading fluency (in syll/sec) and accuracy of a standardized word text was employed to measure ecological-context reading (Cornoldi and Colpo, 2004). Fluency and accuracy z-scores were averaged to control reading speed-accuracy trade-off effect.

6.1.3.1. Crowding task The same task used in kindergarten (T1) was administered in T2.

6.2. Results

We selected our pre-reading sample of future poor readers (PR, n = 37) and good readers (GR, n = 27) on the basis of their reading performance at the end of Grade 1 (T2; Cornoldi and Colpo, 2004). A child was assigned to the PR group if her/his z score for average fluency and accuracy standardized word text reading performance was below −1.5 SDs. In contrast, a child was assigned to the GR group if her/his z score for average fluency and accuracy reading was above +0.5 SDs.

The two groups were not different for chronological age (PR mean = 5.87 years SD = 0.34; GR mean = 5.84 years SD = 0.27) and verbal IQ (PR mean = 11 standard point SD = 3.18; GR mean = 13 standard point SD = 2.71; all ps > .08).

In contrast, the performance of the two groups in T1 differed in the visual-to-phonological mapping speed ($t_{(62)} = 2.29$, $p = 0.026$; PR mean = 11.75 s. SD = 6.54; GR mean = 8.67 s. SD = 2.89; Fig. 5C), and in the number of errors in the phonemic recognition task ($t_{(62)} = 3.068$, $p = 0.003$; PR mean = 4.41 SD = 3.23; GR mean = 2.07 SD = 2.66; Fig. 5D). Furthermore, PR and GR groups differed in the number of errors in both large ($t_{(62)} = 3.697$, $p = 0.0001$; PR mean = 5.11 SD = 4.76; GR mean = 1.52 and SD = 1.93) and small conditions ($t_{(62)} = 3.953$, $p = 0.0001$; PR mean = 7.30 SD = 5.74; GR mean = 2.26 and SD = 2.93) of serial visual search task, but not in execution time (all ps > .84). Importantly, the PR group in T1 exhibited a significant crowding effect, measured as difference in number of errors between small vs. large spacing condition ($t_{(36)} = -2.291$, $p = 0.028$; Fig. 5E), while the GR group did not show crowding ($p > 0.14$).

The results at T2 showed that the two groups differed in the number of errors in the small spacing condition of the serial visual search task ($t_{(55)} = 2.047$, $p = 0.045$; PR mean = 1.89, SD = 3.07; GR mean = 0.70 and SD = 1.49), but not in the large condition and in time (all ps > .43). Moreover, the PR group again displayed a crowding effect, measured as difference in number of errors between small vs. large spacing condition ($t_{(36)} = -2.185$ and $p = 0.035$), whereas the GR group did not show crowding ($p > 0.70$).

To determine the possible relationship between reading abilities (speed and errors), crowding (small spacing condition of serial visual search task) and phonological (visual-to-phonological mapping speed and phonemic recognition) skills, on the entire sample of children, we computed a partial correlation controlling for age, IQ (the standard score in the Vocabulary subtest) and visuo-spatial attention, indexed as number of errors in large spacing condition of serial visual search task. The reading speed (syll/sec) at Grade 1 correlates with the number of errors in small spacing condition of serial visual search task ($r = -0.28$, $p = 0.014$), with the visual-to-phonological mapping speed ($r = -0.27$, $p = 0.017$), and with the number of errors in the phonemic recognition task ($r = -0.25$, $p = 0.025$) measured at T1.

The reading accuracy (number of errors) at Grade 1 correlates only with the visual-to-phonological mapping speed ($r = 0.32$, $p = 0.005$) measured at T1.

To determine the predictive relationship between pre-reading crowding and future reading fluency emergence in a more stringent way, we computed a two-step fixed-entry multiple regression analysis on the entire sample of children. The dependent variable was the reading speed measured as syll/sec in the word text reading and the predictors were: (1) the visual-to-phonological mapping speed and the phonemic recognition skill, and; (2) the number of errors in the small spacing condition of the serial visual search task. The results of this regression analysis showed that phonological skills accounted for 15% of the variance of reading speed ($p = 0.007$) and crowding accounted again for 9% of the unique variance of reading speed ($p = 0.009$).

Individual data analysis shows that the percentages of pre-readers clinically impaired were (T1): (i) 62% (23/37) in the number of errors in the small spacing condition of the serial visual search task; (ii) 43% (16/37) in the phonemic recognition skill; and (iii) 32% (12/37) in the visual-to-phonological mapping speed (i.e., at least 1 SD above the mean of GR group).

To quantify the reliability of three reading predictors, we computed the odds ratios between hits (i.e., PRs with impaired predictor) and false alarms (i.e., GRs with impaired predictor). 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 of visuo-spatial deficit was 13.14 (95% confidence interval from 3.33 to 51.82), indicating that a pre-reading excessive crowding is a strong predictor of future poor reading development. Odds ratio of auditory-phonological deficit was 9.52 (95% confidence interval from 1.96 to 46.25) indicating that also a pre-reading phonemic recognition deficit is a strong predictor of future poor reading development. Odds ratio of cross-modal mapping deficit was 2.11 (95% confidence interval from 0.64 to 6.94) indicating that a pre-reading visual-to-phonological mapping speed deficit is a moderate predictor of future poor reading development.

7. Discussion

In Experiment 1, the main effect of target-to-flankers spacing was absent when attention was preallocated to the target position, demonstrating that crowding can be nullified by an efficient attentional orienting and zooming (e.g., Turatto et al., 2000; Facoetti and Molteni, 2000; Ronconi et al., 2012, 2016, 2018). Although Joo and coll. (2018) did not find any correlation between spatial attention and crowding, our finding confirm several studies showing a direct link between attentional mechanisms and crowding (He et al., 1996; Intriligator and Cavanagh, 2001; Strasburger, 2005; Yeshurun and Rashal, 2010; Grubb et al., 2013; Huckauf and Heller, 2002; Scolari et al., 2007; Yeshurun and Rashal, 2010, but Nazir, 1992; Wilkinson et al., 1997).

The main aim of Experiment 1 was to study the crowding in an unselected group of children with DD and in an age-matched TR control group. In comparison with TRs, children with DD showed stronger crowding in the smaller target-to-flanker spacing at the unattended condition. In contrast, crowding was not different between DD and TR children in the attended condition. These results demonstrate that children with DD present an excessive crowding in the condition in which target and flankers are placed nearby only when the spatial attention is not pre-oriented and focused in the target location. Thus, the findings of Experiment 1 confirm several studies showing an excessive crowding in children with DD (Geiger and Lettvin, 1987; Moores et al., 2011; Callens et al., 2013; Moll and Jones, 2013; see Gori and Facoetti, 2015 for a review) and could partially explain the previous studies that did not find differences in crowding between two groups. In particular, in these studies the attention of participants may have been pre-oriented and focused on the target location, nullifying the possible crowding differences between two groups (e.g., Doron et al., 2015; Sacchi et al., 2018).

However, the cross-sectional design used in Experiment 1 was not enough to disentangle the causal relationship between the excessive crowding and reading difficulties (Goswami, 2015). The difference found in the smaller target-to-flankers spacing at the unattended condition could, indeed, only be the effect of reduced reading experience typically associated to DD.

An initial proof to understand whether this excessive crowding is causally linked to the reading difficulties is to investigate the effect of a manipulation of interletter and interline spacing in a reading task. Indeed, a specific relationship between an excessive crowding and interletter and interline spacing text was found in adults with DD (Joo et al., 2018). To this aim in Experiment 2, we tested children with and without DD in extra-small and extra-large spacing text similarly to Zorzi et al. (2012) and Joo et al. (2018). As in Schneps et al. (2013), the number of syllables per line is the same in two spacing conditions. The findings of Experiment 2 show that a simple visual manipulation of text that reduces crowding by an extra-large spacing was able to improve the reading accuracy only in children with DD. Excluding a possible effect of a different size of noising letters per line (Schneps et al., 2013), this result demonstrates that the reading improvement in children with DD is linked to a pure crowding reduction.

To further investigate the possible causal link between crowding and reading skills, in Experiment 3 children with DD were randomly assigned to an AVG or a NAVG training (Franceschini et al., 2013, 2017a, 2017b; Gori et al., 2016; see Franceschini et al., 2015 for a review). AVGs share an extraordinary emphasis on peripheral processing, speed in terms of multiple transient events and a high degree of perceptual load, enhancing visual-spatial attention mechanisms (see Bediou et al., 2018 for a meta-analysis) and their neural networks (Bavelier et al., 2012; Föcker et al., 2018a, 2018b). Our findings demonstrate that only 12 h of AVG training were able to reduce crowding and enhance reading speed in children with DD, with significant relevance for the clinical setting. The reading improvements after the AVG training were characterized by an improvement in reading speed, without a cost in accuracy. These results are consistent with a selective improvement in processing speed of graphene-to-phoneme mapping previously found in some AVG training studies (e.g., Gori et al., 2016; Franceschini et al., 2013, 2017a, 2017b; Łuniewska et al., 2018; Franceschini and Bertoni, in press in this issue; see for a discussion Vidyasagar, in press in this issue). Importantly, in Experiment 4 we confirm the crowding reduction and reading speed enhancement only in children with DD that are able to efficiently perform the AVG training, improving their game scores (Franceschini and Bertoni, in press in this issue). These findings suggest that crowding and reading speed are improved only when the visual-spatial attention mechanisms indexed by AVG scores are enhanced during the training.

In Experiment 2 we obtained an improvement in reading errors in children with DD by using a simple visual text manipulation able to reduce the perceptual lateral noise increasing the letter and word identification, rather than to work on their underlying sluggish orienting of spatial attention (see Hari and Renvall, 2001; Vidyasagar and Pammer, 2010; Grainger et al., 2016a,b for reviews). With the AVG training in Experiment 3 and 4, we are directly working on the orienting of spatial attention, improving the speed of processing and sampling of visual stimuli (see Bediou et al., 2018 for a meta-analysis). This training allows a faster access to the multiple elements of the text or letter string (Franceschini et al., 2017). Thus, in Experiment 2 we directly manipulated the crowding effect (working on the accuracy rate), whereas in Experiment 3 and 4 we worked on underlying visuo-attentional mechanism crucially linked to phonological decoding speed. It is possible that a beneficial effect also in terms of reading accuracy could be obtained with a longer AVG training able to improve the visual identification as observed in the visual text manipulation (Bediou et al., 2018).

Finally, in Experiment 5, we longitudinally investigated the causal link between crowding and reading development, testing a large cohort of pre-literate children and observing their reading development during the next year of the primary school. Future PRs were characterized at the pre-reading stage by an excessive crowding measured in a more ecological way as the number of errors in the small spacing condition of the serial visual search task. In particular, future PRs show a crowding effect (i.e., difference between number of errors in small and large spacing condition) not only at first grade, but also at pre-reading stage. In contrast, future GRs do not show any crowding effect at first grade or at pre-reading stage. These findings also confirm a visuo-spatial attention deficit at pre-reading stage in future PRs (e.g., Franceschini et al., 2012; Carroll et al., 2016; Gori et al., 2016). More importantly, these findings show that visuo-spatial attention deficits in pre-readers are more evident at small spacing condition, suggesting that measuring visual crowding could be a new and more efficient neurocognitive predictor for an early identification of future reading disorders. Independently from our a priori group classification of reading disorder, pre-reading crowding measured as numbers of errors at small spacing condition in the serial visual search task was able to predict future reading speed even when age, IQ and visuo-spatial attention (i.e., numbers of errors in the large spacing condition of the serial visual search task) are controlled for. Importantly, pre-reading crowding predicts future reading speed also when auditory-phonological (i.e., number of errors in the phonemic recognition task) and cross-modal integration (i.e., the visual-to-phonological mapping speed) skills are controlled for. This result demonstrate that visual crowding is causally linked with reading speed development independently from the auditory-phonological and cross-modal integration processing.

Our five experiments reveal the presence of multiple and independent evidence about a causal link between crowding and reading acquisition, indeed the results show: (i) the presence of an excessive crowding in DD only in the unattend locations, suggesting the crucial role played by visuo-spatial attention in crowding; (ii) an extra-large spaced text that reduces crowding is able to increase reading accuracy in children with DD, suggesting a possible causal link between an excessive crowding and reading difficulties; (iii) an attentional AVG training reduces crowding and accelerates phonological decoding speed in children with DD; (iv) an attentional AVG training reduces crowding and accelerates phonological decoding speed only in children with DD that improve their visuo-spatial attention indexed by an enhancement of game scores, and finally; (v) pre-reading crowding longitudinally predicts future PRs and the future reading speed independently from phonological processing and cross-modal integration. These findings clearly support the probabilistic and multi-factorial nature of neurocognitive deficits at the origin of DD and provide new insights for a more efficient remediation and prevention for DD. Combining innovative visuo-spatial attention trainings with the traditional auditory-phonological and visual-to-phonological mapping trainings in children at risk or with a diagnosis of DD, future studies could develop a more clinically efficient remediation and prevention of DD.

Although several studies have shown the reading (Peters et al., 2019) and attentional (Bediou et al., 2018) effects of AVG training, the small sample in Experiment 3 and 4 could be a possible limit of the present study. Future research should investigate the reading and crowding effects of AVG in a larger sample of children with and without DD also in different orthographies (but see Franceschini et al., 2017b). In Experiment 5, we used a child-friendly crowding task based on serial visual search because it was difficult to test children of 5-years old with the computerized crowding task in an educational setting. Although this choice can appear a methodological limitation of our study, it might really be a positive argument regarding the generalization of similar results using different paradigms to measure crowding effect.

CRediT authorship contribution statement

Sara Bertoni: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Validation, Writing - original draft, Writing - review & editing. **Sandro Franceschini:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Validation, Writing - original draft, Writing - review & editing. **Luca Ronconi:** Conceptualization, Methodology, Validation, Writing - review & editing. **Simone Gori:** Conceptualization, Methodology, Supervision, Validation, Writing - review & editing. **Andrea Facoetti:** Conceptualization, Formal analysis, Methodology, Project administration, Resources, Supervision, Validation, Writing - original draft, Writing - review & editing.

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