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The magnocellular-dorsal pathway dysfunction in developmental dyslexia:

Case-control, longitudinal and intervention studies

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Abstract

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). Although the most common explanation of DD suggest a specific disorder in auditory and phonological processing, several studies show that also a magnocellular-dorsal (MD) pathway dysfunction could be a core deficit in DD. In this thesis will be investigated the MD functioning on children with and without DD by two case-control studies. The causal relationship between MD dysfunction and reading impairment will be investigated through: (i) two longitudinal studies, in which the attentional skills was tested in pre-reading children, and (ii) five intervention studies in which children with DD was treated with a visual-attentional training (i.e., action video game, AVG). The MD functioning was tested with different tasks that are able to capture different skills driven by MD pathway. In particular, the low spatial frequency, processed by MD pathway, will be investigated through Navon tasks in which is important the global perception of the scene. Another aspect linked to the MD pathway, is the signal-to-noise exclusion in which the target is processed filtering the noise, and this will be investigated through a crowding task and visual and auditory attentional noise exclusion tasks.

The findings show that the MD functioning is impaired already at pre-reading stage in future poor readers and that AVG training is able to improve reading speed and attentional skills linked to the MD pathway functioning. For these reason it will be sustain the causal role of MD pathway dysfunction in DD, and the DD as a multifactorial neurodevelopmental disorder.

1. Introduction

1.1 Developmental Dyslexia

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 & Pennington, 2012). DD is characterize by clinical heterogeneity and high level of comorbidity with attentional deficit and hyperactivity, and autism spectrum disorders (APA, 2013; Grinter, Maybery & Badcock, 2010; Behrmann, Thomas & Humphreys, 2006; Van der Hallen, Evers, Brewaeys, Van den Noortgate & Wagemans, 2015; Song & Hakoda, 2015; Gliga, Bedford, Charman & Johnson, 2015).
The most common explanation of DD suggest a specific disorder in auditory and phonological processing (Hornickel & Kraus, 2013; Peterson & Pennington, 2015). Several longitudinal studies have shown that auditory-phonological processing is already impaired at pre-reading stage in future children with DD (e.g., Carroll, Solity & Shapiro, 2016; Franceschini, Gori, Ruffino, Pedrolli & Facoetti et al., 2012; Black, Xia & Hoeft, 2017). Phonological awareness (i.e., the ability to perceive and manipulate the sounds of spoken words) is essential for reading acquisition (Bradley & Bryant, 1978; Gabrieli, 2009). Specific difficulties in phonological awareness are often present in DD (Williams, 1984; Hulme, Hatcher, Nation, Brown, Adams & Stuart, 2002) and phonological deficits are predictive of future reading difficulties (Catts, McIlraith, Bridges, Nielsen, 2017; but Castles & Coltheart, 2004). In the same way, difficulties in the visual-orthographic processing of a written word (i.e., letter-identity and letter-location encoding), could impair the ability in mapping the sequence of graphemes to the previously developed speech-sound auditory forms (Grainger, Dufau & Grainger, 2016).
Although the phonological explanation of DD, several studies show that also difficulties in spatial attention could be a core deficit in DD (Bosse Tainturier & Valdois, 2007; Zorzi, Barbiero, Facoetti, Lonciari, Carrozzi, Montico, Bravar, George, Pech-Georgel, & Ziegler, 2012; Facoetti, Trussardi, Ruffino, Lorusso, Cattaneo, Galli, Molteni &

Zorzi 2010; Franceschini et al., 2012; Franceschini, Gori, Ruffino, Viola, Molteni & Facoetti, 2013), impairing orthographic development (Vidyasagar & Pammer, 2010; Stein, 2014; Grainger et al., 2016).

The ability to extract visual information and combine that with auditory information is considered at the basis of reading acquisition (Blomert, 2011). Letter identification is a fundamental stage in visual word recognition and reading (McClelland & Rumelhart, 1981; Pelli, Farell & Moore, 2003; Perry, Ziegler & Zorzi, 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 & Goswami, 2005). Phonological decoding is also fundamental for a fast access to semantics from print during reading acquisition (Share, 1995). Recently, Grainger and colleagues (2016) described a specialized system for parallel letter processing that assigns letter identities to different locations along the horizontal meridian 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 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, Bertrand, Lété, Beyersmann, & Ziegler 2016).

The act of reading must be sufficiently fast to operate within the constraints of limited capacity and rapid decay of the information processing (Perfetti, 1985). The lack of synchronization among auditory and visual processes could lead to weak consolidation of letter-to-speech sound integration (Breznitz, Shaul, Horowitz-Kraus, Sela, Nevat & Karni, 2013; Blau, van Atteveldt, Ekkebus, Goebel & Blomert, 2009; Boets, Op de Beeck, Vandermosten, Scott, Gillebert & Mantini, 2013).

A mild impairment in the visual magnocellular-dorsal (MD) pathway, with or without a corresponding deficit in the auditory system, has been hypothesized as possible core deficit in DD (Stein, 2018, Gori & Facoetti, 2014, Gori & Facoetti, 2015; Vidyasagar, 2019; Hari & Renvall, 2001; Boden & Giaschi, 2007; Vidyasagar & Pammer, 2010). In particular, performance in coherent dot motion perception - which resulted in a very reliable proxy of the MD pathway - are related to letter feature position encoding, independently from phonological awareness abilities (Cornelissen & Hansen, 1998).

The MD pathway originates in the ganglion cells of the retina, passes through the M-layer of the lateral geniculate nucleus (LGN), and finally reaches the occipital and parietal cortices (Maunsell & Newsome, 1987). The MD pathway is considered blind to colors and responds optimally to contrast differences, low spatial frequencies, high temporal frequencies, and both real and illusory motion (e.g., Gori, Giora, & Stubbs, 2010; Gori, Giora, Yazdanbakhsh, & Mingolla, 2011; Gori, Hamburger, & Spillmann, 2006; Gori & Yazdanbakhsh, 2008; Livingstone & Hubel, 1987; Morrone, Tosetti, Montanaro, Fiorentini, Cioni & Burr, 2000; Ruzzoli, Gori, Pavan, Pirulli, Marzi & Miniussi, 2011; Yazdanbakhsh & Gori, 2011), which is also, surprisingly, perceived by animals without a cortex, such as fish (Gori, Agrillo, Dadda, & Bisazza, 2014a). Individuals with DD are less sensitive than typically reading controls to luminance patterns and motion displays with high temporal and low spatial frequencies (e.g., Eden, VanMeter, Rumsey, Maisog, Woods & Zeffiro, 1996), visual features that are known to be associated with the MD pathway. However, they perform similarly to the controls on tasks preferentially associated with the parvocellular–ventral pathway (Gori, Cecchini, Bigoni, Molteni & Facoetti, 2014b), such as those involving color and form (Merigan & Maunsell, 1993). Moreover, a postmortem study showed that in the brain of individuals with DD the M neurons of the LGN were significantly smaller than those found in typical readers' brains, and the P neurons did not differ between the two groups (Livingstone, Rosen, Drislane & Galaburda, 1991). This study recently received strong support from the first in vivo study (Giraldo-Chica, Hegarty, & Schneider, 2015), showing smaller LGN volume in a larger sample of individuals with DD compared to controls.

A MD visual pathway dysfunction has been causally linked to DD, because: i) pre-reading children that present this type of visual dysfunction will develop poor reading skills in primary school (e.g., Boets, Vandermosten, Cornelissen, Wouters, Ghesquiere, 2011; Gori, Seitz, Ronconi, Franceschini & Facoetti, 2016), and ii) specific and efficient trainings of this visual pathway can improve reading skills in children with DD (e.g., Franceschini et al., 2013; Gori et al., 2016; Lawton, 2016).

The parieto-frontal attentional network is included in the MD pathway (Corbetta & Shulman, 2002; Dosenbach, Fair, Cohen, Schlaggar & Petersen, 2008). Several studies showed perceptual and attentional deficit in DD (e.g. Tallal, 2004; Bosse et al., 2007;

Facoetti, Paganoni, Turatto, Marzola & Mascetti, 2000; Facoetti, Corradi, Ruffino, Gori & Zorzi, 2010; Iles, Walsh & Richardson, 2000; Buchholz & Davies, 2007; Liu, Cheng & Chung, 2015).

Dysfunctional connectivity between frontal and parietal regions inside the attention networks characterizes children with a history of DD (Koyama, Di Martino, Kelly, Jutagir, Sunshine, Schwartz & Milham, 2013). Visual-attentional abilities - mainly controlled by the MD visual pathway - evaluated with visual search, multiple visual target discrimination and rapid orienting of visual attention tasks, not only are impaired in children with DD and in future poor readers at pre-reading stage (e.g., Banfi, Kemeny, Gangl, Schulte-Korne, Moll & Landerl, 2017; Bosse & Valdois, 2009; Carroll et al., 2016; Casco, Tressoldi & Dellantonio, 1998; Facoetti et al., 2010; Franceschini et al., 2012; Gori et al., 2016; Liu, Chen & Wang et al., 2016), but are also partially recovered after efficient reading interventions in children with DD (e.g., Facoetti, Lorusso, Paganoni, Cattaneo, Galli, Umiltà & Mascetti, 2003; Franceschini et al., 2013; Gori et al., 2016) and are extremely efficient in adults with good phonological decoding skills (Antzaka, Lallier, Meyer, Diard, Carreiras & Vadois, 2017).

The low spatial frequency processing, guided by the MD pathway, characterizes the global spatial information analysis (Hughes, Nozawa & Kitterle, 1996). It is suggested that a variety of factors contribute to the precedence of low frequency information, including the high contrast gain of the MD pathway, the amplitude spectra typical of natural images, and inhibitory interactions between the parallel frequency-tuned channels (Hughes et al., 1996).

Neuropsychological, psychophysical, electrophysiological and functional neuroimaging studies have suggested that the right temporo-parietal junction plays a key role in low spatial frequency processing (global perception), while the homologous area in the left hemisphere specifically processes the high spatial frequencies (local details) (Navon, 1977; Hochstein & Ahissar, 2002; Fink, Halligan, Marshall, Frith, Frackowiak & Dolan, 1996; Sergent, 1982; De Schotten, Dell'Acqua, Forkel, Simmons, Vergani, Murphy & Catani, 2011; Corbetta, Patel & Shulman, 2008). Navon (1977) describes global precedence on local perception as an inherent property of the human visual system that usually could not be skipped.

During the orthographic processing - before phonological mapping - perception of the global scene is a useful device for narrowing down the range of candidates in accounting for a certain local region and their location assignments (Vidyasagar & Pammer, 2010; Franceschini et al., 2012; Navon, 1977; Hochstein & Ahissar, 2002; Grainger et al., 2016). Later, sequential scanning of individual letters inside fixation periods is also necessary for effective letters identification (Vidyasagar & Pammer, 2010; Franceschini et al., 2012; Grainger et al., 2016).

Reversing the global to local world perception has been found to be associated with unusual and extraordinary performance in local features extraction in several neurodevelopmental disorders often in comorbidity with DD (Grinter, Maybery & Badcock, 2020; Behrmann et al., 2006; Van der Hallen et al., 2015; Song & Hakoda, 2015; Gliga et al., 2015).

Moreover, MD pathway is involved in an efficient flanked-letter identification (Omtzigt, Hendriks & Kolk, 2002; Omtzigt & Hendriks, 2004), because this pathway drive the rapid orienting of attention (Omtzigt & Hendriks, 2004). Consequently, a MD dysfunction in DD could be related to a greater difficulty in the recognition of an object surrounded by other objects (Omtzigt & Hendriks, 2004).

The greater difficulty to select the relevant information in clutter than when the information is presented in isolation is called crowding (see Pelli, 2008; Pelli & Tillman, 2008; Whitney & Levi, 2011, Rosenholtz, 2016, for reviews). Crowding is a universal phenomenon that selectively impairs the discrimination and the ability to recognize stimuli in clutter (Whitney & Levi, 2011). Some neuroimage studies have shown that the strongest effects of crowding occurred in the earliest stages of cortical processing in V1 (Chen, He, Zhu, Zhou & Fang, 2014; Millin, Arman, Chung, & Tjan, 2014), whereas other studies showed that it could arises at later stages in the visual processing hierarchy (Chicherov, Plomp & Herzog, 2014; Ronconi, Bertoni & Bellaccosa Marotti, 2016; Ronconi & Bellacosa Marotti, 2017). Crowding depends by 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 comparably to when the flankers are absent (Yashar, Chen & Carrasco, 2015). Bouma’s law states that critical spacing is proportional to target eccentricity: the higher the target eccentricity the larger the critical spacing for correctly discriminating the target (Bouma, 1970; Whitney & Levi, 2011). Crowding can occur with simple objects such as oriented gratings (e.g., Greenwood, Bex & Dakin, 2012), and with complex objects such as faces and letters (Pelli & Tillman, 2008; Freeman, Chakravarthi & Pelli, 2012; Whitney & 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, Di Filippo, Spinelli & Zoccolotti, 2009).

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

People with DD appear to suffer from an excessive crowding as compared to typical readers (e.g., Geiger & Lettvin, 1987; Moores, Cassim & Talcott, 2011; Callens, Whitney, Tops & Brysbaert, 2013; Moll & Jones, 2013; see Gori & Facoetti, 2015 for a review; but Doron, Manassi, Herzog & Ahissar, 2015; Sacchi, Mirchin & Laszlo, 2018). An excessive crowding in individuals with DD could be due to sluggish orienting of their spatial attention (Facoetti, Paganoni, Turatto, Marzola & Mascetti, 2000, Facoetti, Turatto, Lorusso & Mascetti, 2001, Facoetti, Ruffino, Peru, Paganoni & Chelazzi, 2008, Facoetti et al., 2010a; 2010b; Lallier, Thierry, Tainturier, Donnadieu, Peyrin, Billard & Valdois, 2009; Lallier, Tainturier, Dering, Donnadieu, Valdois & Thierry, 2010; Ding, Zhao, He, Tan, Zheng & Wang, 2016; see Gori & Facoetti, 2014; Krause, 2015; Grainger et al., 2016 for reviews) induced by a MD pathway dysfunction (see Hari & Renvall, 2001; Vidyasagar & Pammer, 2010; Vidyasagar, 2019 for reviews). Some studies showed that extra-large interletter spacing enhances their reading efficiency on the fly, suggesting a possible causal link (e.g., Spinelli, De Luca, Judica & Zoccolotti, 2002; Zorzi et al., 2012; but Schneps, Thomson, Sonnert, Pomplun, Chen & Heffner-Wong, 2013).

However, the causal link between: (i) the reverse local to global perception, (ii) an excessive crowding and DD is not yet clearly established because group differences between individuals with and without DD might be simple effects of the reduced reading experience associated to DD (Goswami, 2003, 2015).

Therefore, specific deficits in the visual-attention domain could impair the perception of the whole string of symbols (e.g., Bosse et al., 2007; see Valdois et al., 2004 for a review) and, as a consequence, also the resulting serial grapheme-segmentation ability (e.g., Facoetti et al., 2010; see Hari & Renvall, 2001; Vidyasagar & Pammer, 2010 for reviews). A whole-brain neuroimaging study, using data-driven analysis of neural connectivity, demonstrated that typical readers - in contrast to children with DD - are better able to perceive the whole string of symbols and modulate serial visual attention in order to recognize words on the basis of their visual properties (Finn, Shen, Holahan, Scheinost, Lacadie, Papademetris & Constable, 2014).

The MD pathway is a multi-sensory network in which general domain attentional mechanism could be linked not only to visual processing but also to auditory processing in clutter (Ziegler, Pech-Georgel, George, Alario, & Lorenzi 2005; 2010; Geiger, Cattaneo, Galli, Pozzoli, Lorusso, Facoetti & Molteni, 2008).

The auditory-phonological and visual-orthographic deficits which typically characterize children and adults with DD could be linked to earlier mild deficit in the multi-sensory attentional network (e.g., Boets et al., 2008; Boets et al., 2011; Carroll et al., 2016; Facoetti et al., 2010; Franceschini et al., 2012; Gori et al., 2016; Lawton, 2016; Kevan & Pammer, 2008, 2009; Witton, Talcott, Hansen, Richardson, Griffiths, Rees, Green, 1998; see Grainger et al., 2016; Gori & Facoetti, 2014, 2015; Hari & Renvall, 2001; Stein, 2014; Vidyasagar & Pammer, 2010 for reviews). In particular, it has been demonstrated that children with DD also have difficulties in serial processing of rapid auditory stimuli (Farmer & Klein, 1995; Tallal, 2004). Therefore, a sluggish domain-general attentional shifting is an alternative explanation to phonological decoding deficits (Hari & Renvall, 2001; Facoetti et al., 2010; Lallier et al., 2010). This could also explain the typical deficits in perceptual noise exclusion found in visual (Sperling, Lu, Manis & Seidenberg, 2005; Sperling, Lu, Manis & Seidenberg, 2006; Kevan & Pammer, 2009; Dispaldro, Leonard, Corraci, Ruffino, Bronte & Facoetti, 2013) and in auditory stimuli (Ziegler et al., 2005; Geiger et al, 2008) both in children with DD and in children with specific language impairment. Finally, it is crucial to focus on the role played by spatial and temporal attention in multisensory integration (Talsma, Senkowski, Soto-Faraco &Woldorff, 2010) in order to better understand the complex developmental mechanisms involved in reading acquisition (Hari & Renvall, 2001; Wallace & Stevenson, 2014). Similarly to the cross- and multisensory mechanisms that integrate speech and lip movements during language development, the activation of a specific neurocognitive mechanism is at the basis of the integration of congruent letters and speech-sounds in reading acquisition (Blau, van Atteveldt, Ekkebus, Goebel & Blomert, 2009; van Laarhoven, Keetels, Schakel & Vroomen, 2018). These cross- and multisensory integration mechanisms - strictly involved in reading acquisition - are able to change the phonological coding in language-specific cortical areas, such as the left planum temporale (Dehaene, Cohen, Morais & Kolinsky, 2015). Harrar and colleagues (2014) have recently demonstrated that English adults with DD - compared with subjects without DD - exhibit a deficit in multisensory integration and tend to distribute their attention asymmetrically between auditory and visual modalities. In particular, individuals with DD present difficulties in attentional shifting from visual to auditory, but not from auditory to visual stimuli (Harrar et al., 2014).

All the evidence about deficits in DD listed above show that the reading difficulties are a multifactorial, rather than a unifactorial disease. This is an important aspect to understand the causal relationship between various cognitive skills impaired and DD. Recently, Hancock and colleagues (2017) have sustained that the impairment in phonological awareness, in multi-sensory integration of visual symbols with their corresponding speech sound, in sensory processing and in perceptual noise exclusion, described in DD, could be explain by an excess of neural noise (i.e., sources of random variability in the firing activity of neural networks and membrane voltage of single neurons). In particular, some genetics factor linked to DD, such as DCDC2 and KIAA0319, may disrupt neural migration and the formation of local excitatory–inhibitory circuits, thereby increasing neural noise. In particular the intron DCDC2 deletion is mainly linked to the MD pathway deficit in DD (Gori, Mascheretti, Giora, Ronconi, Ruffino, Quadrelli, Facoetti & Marino, 2015). Excess neural noise disrupts neural synchronization across multiple scales, leading to deficits in low-level sensory information processing. Consequently, the downstream effects of an excess of neural noise may lead to impairments in phonological awareness and multi-sensory integration, which are fundamental during reading development (Hancock, Pugh & Hoeft, 2017).

1.2 PhD Project

My PhD project was focused on MD pathway and attentional deficits and their role in DD to answer to some questions about the causal relationship between these deficits and reading development. The Material and Methods section is divided in three main sections based on experimental design to answer to four different questions:

1- Case-control studies: The first question was if my attentional tasks were able to capture the attentional deficit in children with DD. The Experiment 1a, 1b, 2a and 2b are case-control studies in which the attentional skills are evaluated in children with and without DD by two Navon (paper-and-pencil and computerized) and crowding (computerized and extra-large spaced text) tasks.

The second question was if these attentional deficits could be one of the possible causes of DD or a simple effect of reading difficulties. This is a fundamental point of the research, because it is important to understand the relationship between the attentional and multisensory deficits with DD (Goswami, 2005). The longitudinal and intervention studies are the main experimental design to demonstrate whether a deficit in a general-domain skill has a pivotal role in a more specific-domain skill (i.e., reading).

2- Longitudinal studies: The Experiment 3 and 4 are two longitudinal studies in which the attentional skills were evaluated by a computerized Navon task (Experiment 3) and by a computerized crowding task (Experiment 4) during the last year of kindergarten (5 years old), and then I evaluated the reading skills at the end of the Grade 1 (6 years old). A longitudinal study is a good experimental design to understand the causal relationship because the attentional skills are evaluated during the pre-reading stage and for this reason they are not linked to reading difficulties or to a reduced reading exposure typical in children with DD.

3- Intervention studies: Another experimental design to study the causal relationship is the intervention study. The Experiment 5 and 6 are two intervention studies in which I evaluated the effect of a visual-attentional training on reading skills and on visual attentional skills measured by a computerized Navon task (Experiment 5) and a computerized crowding task (Experiment 6). In particular, the visual-attentional training lied in the use of a specific type of video-game called action video-game

(AVG). There are several studies that have extensively studied perceptual and attentional abilities in AVG players and in trained non-video gamers (Green & Bavelier, 2003; Green, Lie & Bavelier; see Green & Bavelier, 2012 for a review and Bediou, Adams, Mayner, Tipton, green & Bavelier, 2018 for a recent meta-analysis). AVG share a set of qualitative features, including extraordinary speed (both in terms of very transient events and in terms of the velocity of moving objects), a high degree of perceptual, cognitive, and motor load in the service of an accurate motor plan (multiple items that need to be tracked and/or kept in memory, multiple action plans that need to be considered and quickly executed typically through precise and timely aiming at a target), unpredictability (both temporal and spatial) and an emphasis on peripheral processing (Green et al., 2010). Playing AVGs requires the use of most of the visual-attention skills and MD pathway functioning often connected to reading skills (Franceschini, Bertoni, Ronconi, Gori, Molteni & Facoetti, 2015). Another important aspect of the use of AVG to treat the DD is that they are not linked to the problems that characterized the most common DD interventions, based on explicit and systematic instruction on letter-to-speech sound integration (McArthur, Eve, Jones, Banales, Kohnen, Anandakumar, Larsen, Marinus, Wang & Castles, 2012): (i) highly demanding, and (ii) the dropout during the training (Gabrieli, 2009). The intervention studies could explain the relationship between attentional skills and DD, because, if a visuo-attentional training is able to improve also the reading skills, this means that attentional mechanism could be the general-domain cognitive skill that has a pivotal role during the reading.

The third question was based on the results of Intervention studies and it was if these reading and attentional improvements, obtained in children with DD with an AVG training, characterized each child that perform this type of training. For this reason in the Experiment 7a and 7b will be analyzed the enhancement of the game scores during the training to evaluate if the children perform actively the training and to understand which children benefit by the training.

The fourth question find an answer with another Intervention study because it was if AVG training is able to produce cross-modal effect. In particular, if this visual training is able to improve also auditory skills and multi-sensory skills. For this reason in Experiment 8 and 9 will be analyzed the effect of AVG on reading skills, multi-sensory, and auditory and visual attentional noise exclusion skills. This is an important aspect, because if a visual training is able to improve also sensory auditory skills this means that AVGs could have cascading effects on audio-visual processing.

2- Material and Methods:

The entire investigation process of each Experiment was conducted according to the principles expressed in the Declaration of Helsinki.
Participants were individually tested in a dimly lit and quiet room for each Experiment.

2.1 Experimental design: Case – control studies

Are my attentional tasks able to capture attentional deficits in children with DD?

2.1.1 Experiment 1a: Global visual perception in children with dyslexia by using a paper and pencil.

(Franceschini, S., Bertoni, S., Gianesini, T., Gori, S., & Facoetti, A. (2017). A different vision of dyslexia: Local precedence on global perception. *Scientific reports*, *7*(1), 17462).

Participants:
Participants were 180 children from the 2nd to the 5th year of primary school (range 7.2–12 years old; 81 males and 99 female). The sample was collected from 4 Italian schools. All the children were native Italian speakers without any documented history of brain damage, hearing or visual (not corrected) deficits, or ADHD diagnosis (APA, 2013).
A series of reading tasks (word and pseudoword lists) and a Navon stimuli task were administered in counterbalanced order. The reading skills of children from the different grades were standardized (Franceschini, Bertoni, Ronconi, Molteni, Gori & Facoetti, 2016). Children were divided into two groups: a child was assigned to the group of children with DD if her/his Z score in the mean of speed and accuracy in words and/or pseudowords reading was below −1.5 SDs (n = 17), all the other children were assigned to the TR group (n = 162). The two groups did not differ in chronological age: $t(177) = 0.683$, $p > 0.496$ (mean children with dyslexia = 9.17, SD = 1.2 and mean TR = 9.37, SD = 1.14).

Navon task:
To investigate local and global perception in a paper and pencil Navon task were administered four different conditions composing the Navon stimuli (Navon, 1977) RAN (Denckla & Rudel, 1976) (global vs. local task and congruent vs. incongruent

condition; Figure 1). On each sheet were represented three lines with geometric figures: a triangle, a circle or a square with features that never varied (for example the triangle has always the same characteristics), for a total amount of 7 targets per line (mean distance between the large figures was 4mm). Each global figure (mean height 38mm; mean width 38mm) was composed of smaller local figures (mean height 4mm; mean width 4mm) of the same (congruent) or different (incongruent) stimuli.

In the congruent and incongruent global tasks, children were invited to name aloud the larger figure, independently from the local figures. In contrast, in the congruent and incongruent local tasks, children were invited to name the smaller figure aloud, independently from the global figure. All the children started the tasks from one of the congruent condition (global/local or local/global), and continued with respective incongruent condition (global/local or local/global). The sheets for global and local tasks contained the same figures. Time and errors were measured.

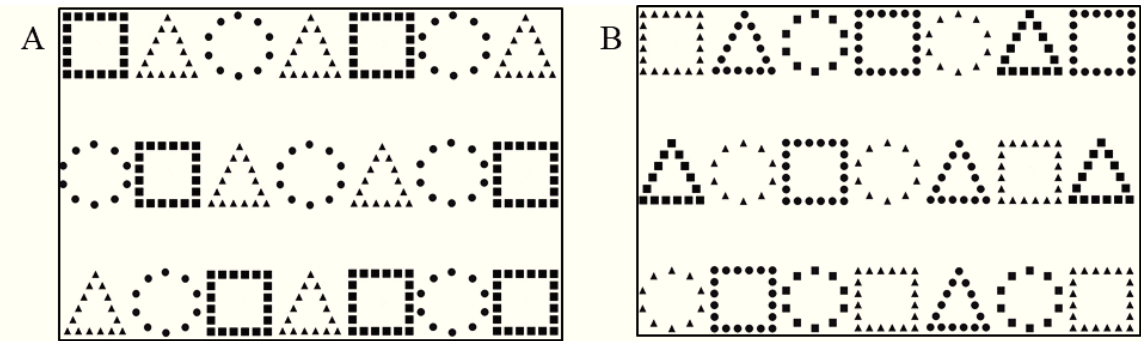

Figure 1: Paper and pencil Navon task. A: Congruent condition; B: Incongruent condition.

Reading tasks:

Words reading: the ability to read aloud was measured using words lists composed by 51 words (separated into 3 lists). Words were composed by 2-5 syllables, for a total amount of 149 syllables (Franceschini et al., 2016).

Pseudowords reading: phonological decoding ability was measured using 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). Texts order administration was counterbalanced between children. All children were invited to read aloud each text as fast and accurate as possible. Words or pseudowords that were wrongly read, were counted as one error independently from the quantity of wrong letters or syllables pronounced. Self-corrections were not classified as errors.

Results:

We excluded from the analysis children performance more than three boxplot lengths from either end of the box (n=1/180).

Similarly to the original version of RAN tasks (Denckla & Rudel, 1976), mean accuracy was at ceiling (rate=.99), consequently it was not further analyzed.

To investigate local and global perception in a paper and pencil Navon task, the corrected response times were analysed with a mixed analysis of variance (ANOVA). Whether a different visual perception characterize the neurodevelopmental disorder of reading acquisition, a reversed global precedence perception, i.e. local before global perception will be expected in children with DD.

Response times (in sec) in the Navon stimuli task were analysed by a mixed ANOVA with a 2 × 2 × 2 design. The two within-subject factors were condition (congruent and incongruent) and task (global and local), while the between-subject factor was group (children with DD and typical readers, TR). Main effect of condition and task were significant ($F_{(1,177)}$=85.96, p=.001, η^2=.327 and $F_{(1,177)}$=17.354, p=.001, η^2=.089, respectively). The condition × task interaction was significant ($F_{(1,177)}$=6.513, p=.012, η^2=.035). Group main effect was also significant ($F_{(1,177)}$=7.1, p=.008, η^2=.039): children with DD group was slower (mean response time=30.42 sec SD=9.28) than TR group (mean response time=25.15 sec SD=7.6). Crucially for our hypothesis, condition × task × group interaction was significant (F(1,177) = 10.472, p = 0.001, η2 = 0.056), indicating that the two groups showed a different condition effect in the two tasks (Figure 2A, B). Within-subject planned comparisons on the condition effect (incongruent vs. congruent) were significant in global (t(161) = -10.67, p = 0.0001, Cohen's d = 0.84) and local (t(161) = -10.289, p = 0.0001, Cohen's d = 0.81) task in TR group, whereas this effect was significant in global (t(16) = -3.522, p = 0.003, Cohen's d = 0.85), but not in local task (t(16) = -1.045, p = 0.312, Cohen's d = 0.25) in the children with DD group.

Between-subject planned comparisons showed that in the global task, the condition effect was significantly increased in the children with DD group (mean = 8.55 sec, SD = 10.01) in comparison to TR group (mean = 4.21 sec, SD = 5.02; t(177) = −3.014, p = 0.001, Cohen's d = 0.58). In contrast, in the local task, the condition effect was significantly decreased in the group with DD (mean = 2.16 sec, SD = 8.55) in comparison to TR group (mean = 4.96 sec, SD = 6.14; t(177) = 1.715, p = 0.044, Cohen's d = 0.38).

In the congruent condition, the group with DD was slower than TR group both in global ($t_{(177)}$=-1.755, p=.04 one tile, Cohen's d=.39) and local ($t_{(177)}$=-3.052, p=.003, Cohen's d=.69) tasks, whereas in the incongruent condition, the group with dyslexia was slower in comparison to TR group in the global task ($t_{(177)}$=-3.527, p=.001, Cohen's d=.74), but not in the local task ($t_{(177)}$=-1.373, p=.172, Cohen's d=.36).

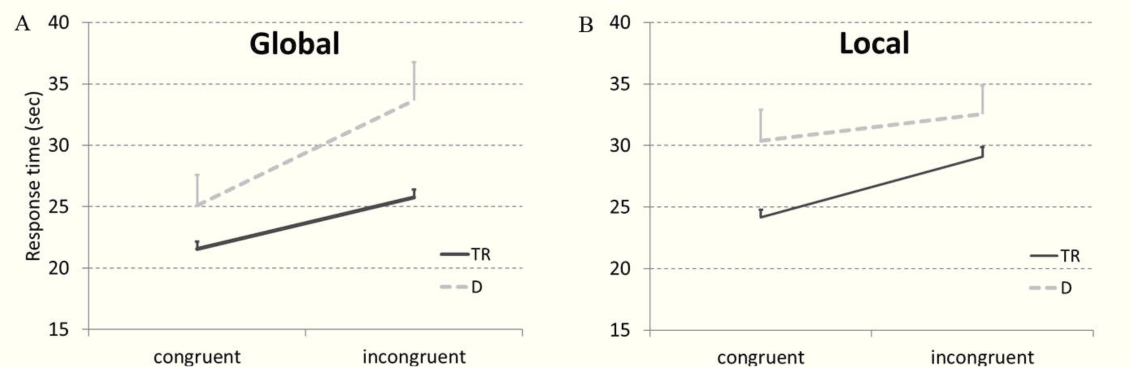

Figure 2: Results of paper and pencil Navon task. A: Children with DD showed greater local interference than TR in global task; B: Children with DD showed lower global interference in local task.

2.1.2 Experiment 1b: Global visual perception in children with dyslexia by using a computerized Navon task.

(Franceschini, S., Bertoni, S., Gianesini, T., Gori, S., & Facoetti, A. (2017). A different vision of dyslexia: Local precedence on global perception. *Scientific reports*, *7*(1), 17462).

Participants:

Participants were thirty-two children (14 female and 18 male) with DD, from the 3rd to 8th school grade, and fifteen children (11 female and 4 male) TR, from the 1st to 8th school grade.

Children with DD were diagnosed by the Italian National Health Service, based on standard exclusion and inclusion criteria (APA, 2013). The reading performance (errors and/or speed) of each individual was at least −1.5 SDs below the age-standardized norm in at least one of the 4 clinical measures (Sartori, Job & Tressoldi, 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 did not differ for chronological age: $t_{(45)}$=.648, p>.521, Cohen's d=.19 (mean children with dyslexia= 10.09, SD=1.49 and mean TR=9.73, SD=2.25). The two groups differed both in words reading time ($t_{(45)}$=3.087, p=.003, Cohen's d=1.1; TR: mean=137.84, SD=98.09; children with dyslexia: mean=291.08, SD=179.42) and errors ($t_{(45)}$=5.131, p=.001, Cohen's d=1.94; TR: mean=2.27, SD=3.06; children with dyslexia: mean=12.16, SD=7.13), and pseudowords reading time ($t_{(45)}$=3.004, p=.004, Cohen's d=1.09; TR: mean=88.32, SD=48.46; children with DD: mean=165.39, SD=93.26) and errors ($t_{(45)}$=4.705, p=.001, Cohen's d=1.74; TR: mean=3.6, SD=3.91; children with DD: mean=14.09, SD=8.18).

To balance the dimension of the two groups, we added 17 children (TR n=32 , children with DD n=32). The two groups did not differ for chronological age: $t_{(62)}$=.081, p>.936, Cohen's d=.02 (mean TR=10.06, SD=1.74). The two groups differed both in words reading time ($t_{(62)}$=5.308, p=.0001, Cohen's d=1.44.; TR: mean=109.06, SD=73.78) and errors ($t_{(62)}$=6.782, p=.0001, Cohen's d=1.86; TR: mean=3, SD=2.74), and pseudowords reading time ($t_{(62)}$=5.041, p=.0001, Cohen's d=1.37; TR: mean=75.81, SD=37.52) and errors ($t_{(62)}$=6.522, p=.0001, Cohen's d=1.79; TR: mean=4.03, SD=3.05).

A series of reading tasks (word and pseudoword lists), and a computerized Navon task were administered in counterbalanced order.

Computerized Navon task:
Participants sat 42 cm away from the pc screen. Geometric figures were shown on a computer screen: a square or a triangle (7.8 x 7.8°) at a global level, which could be formed by small squares or triangles (0.8 x 0.8°) at local level. The experiment included two different tasks, administered in counterbalanced order. Children had to indicate the global or the local figure. Stimuli features were both congruent or incongruent: i) in the congruent condition the global figure had the same shape of local figures (a big triangle composed by little triangles 20 cd/m^2) and ii) in the incongruent condition, instead, the global figure had a different shape from local figures (a big triangle composed by little squares). A small cross (0.1° and .6 cd/m^2) in the centre of the screen served as fixation point. Each trial started with a white screen (119 cd/m^2), after 1500 msec the fixation point appeared for 350 msec, then one of the four possible figures appeared (a square or triangle, made of congruent or incongruent figures) and did not disappear until the children pressed the button (C or M on a keyboard) or max 5 seconds, to indicate the triangle(s) or the square(s), respectively (Figure 3). Each condition consisted of 20 trials, for a total amount of 80 trials.

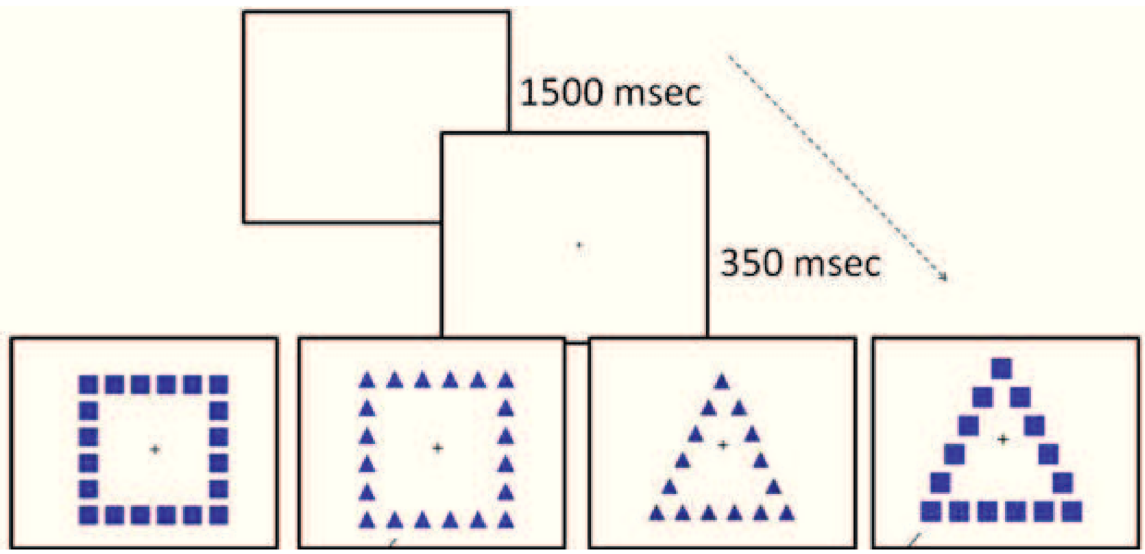

Figure 3: Computerized Navon task: Congruent (e.g., big and small squares) and incongruent (e.g., big square and small triangles) conditions.

Reading tasks:
Phonological decoding abilities were measured using a standardized list of pseudowords (Sartori et al., 2007). Reading abilities were measured using a standardized list of words (Sartori et al., 2007).

Results:
Response times in global and local tasks were analyzed with a mixed ANOVA. As found in Experiment 1a, an atypical local before global perception was expected also in this new and unselected sample of children with DD.

Mean accuracy (rate=.95) was at ceiling, consequently it was not further analyzed.

Response times (in msec) in the computerized Navon task were analyzed by means of a mixed ANOVA with a 2 × 2 × 2 design. The two within-subject factors were condition (congruent and incongruent) and task (global and local), while the between-subject factor was group (children with dyslexia and TR).

Main effect of condition and task were significant ($F_{(1,45)}$=43.48, p=.001, η^2=.491 and $F_{(1,45)}$=6.113, p=.017, η^2=.120, respectively). Crucially for our hypothesis, condition × task × group interaction was significant (F(1,45) = 5.697, p = 0.021, η2 = 0.112), indicating that the two groups showed a different condition effect in the two tasks (Figure 4B).

Since the main results were found in global perception, we collected further 17 TR children only in global task (n = 32) to balance the different sample size of two groups originally studied and we re-ran an ANOVA on the Navon global task with a 2 x 2 design. Again, mean accuracy was at ceiling (.97).

The within-subject factors was condition (congruent and incongruent), while the between-subject factor was group (children with DD and TR). Main effect of condition ($F_{(1,62)}$=27.994, p=.0001, η^2=.311) and condition x group interaction were significant ($F_{(1,62)}$=19.214, p=.0001, η^2=.237; Figure 4A).

Within-subject planned comparisons on the condition effect (incongruent vs. congruent) were not significant in global (t(31) = 0.667, p = 0.51, Cohen's d = 0.03), but were significant in local (t(14) = 3.873, p = 0.002, Cohen's d = 0.17) task in TR group, whereas this effect was significant in global (t(31) = 6.599, p = 0.0001, Cohen's d = 0.37), but not in local task (t(31) = 1.719, p = 0.096, Cohen's d = 0.15) in children with

DD. Moreover, in global task, the condition effect was significantly increased in children with DD (mean = 111 msec, SD = 95) in comparison to TR group (mean = 10 msec, SD = 88; t(62) = 4.383, p = 0.0001, Cohen's d = 1.10). In contrast, in local task, the condition effect was decreased in children with DD (mean = 33 msec, SD = 109) in comparison to TR group (mean= 77 msec, SD= 77; but t(45)= −1.402, p= 0.168, Cohen's d = 0.47).

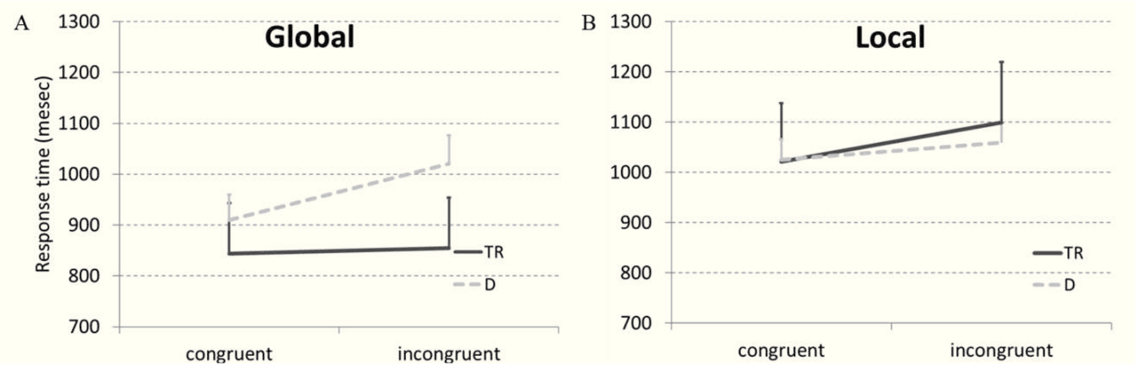

Figure 4: Results of computerized Navon task. A: Children with DD showed greater local interference than TR in global task; B: Children with DD showed lower global interference in local task.

Discussion:

The results of Experiment 1a and 1b show that children with DD have a deficit in the global perception of a visual scene. In particular, they have difficulties to ignore the local information when they have to perceive the global one and local and global information are different. This global perception deficit is present in both a paper and pencil and computerized Navon tasks.

2.1.3 Experiment 2a: Crowding in Attended and Unattended Location.

(Bertoni, S., Franceschini, S., Ronconi, L., Gori, S. & Facoetti, A. Is Excessive Visual Crowding Causally Linked to Developmental Dyslexia? In press in Neuropsychologia).

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 ($\geq$85), normal or corrected-to-normal vision, absence of neurological deficit and ADHD diagnosis (APA, 2013). The two groups (DD and TR) were not different ($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 sec., SD=31.17 sec.; DD: mean=298.08 sec., SD=170.42 sec.) 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 sec., SD=15.11 sec.; DD: mean=174.46 sec., SD=44.43 sec.) 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.

Computerized 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 & Rashal, 2010) or at the center of the screen (unattended condition) in order to induce visual attention to remain at the fixation location (Figure 5). 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.

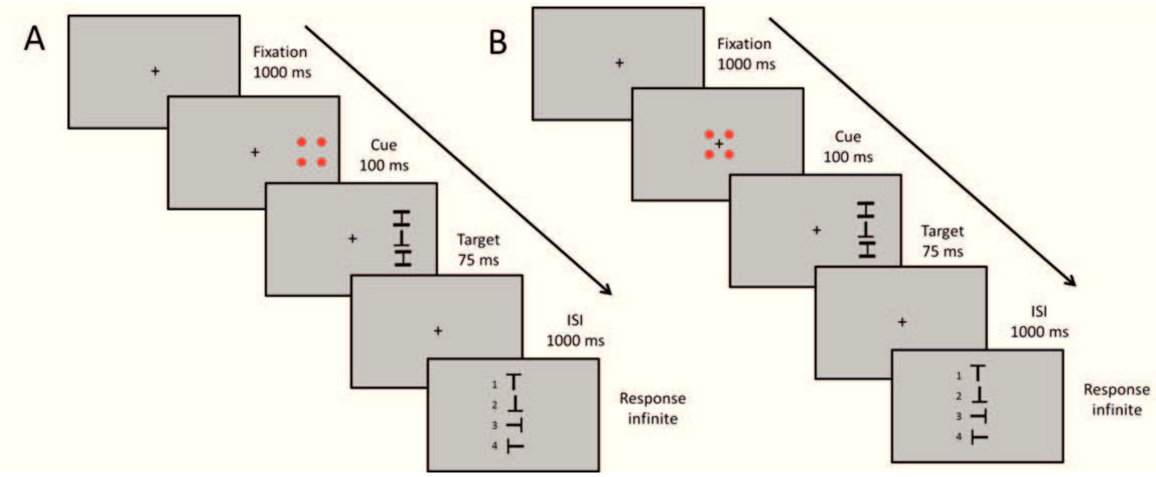

Figure 5: Computerized crowding task. A: Attended location condition; B: Unattended location condition.

Reading tasks:

Words and pseudowords reading tasks were the same as those used in the Experiment 1b.

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 x 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 ($F(2,66)=5.864$, $p=.005$, $\eta 2=.151$) and a group main effect ($F(1,33)=5.050$, $p=.031$, $\eta 2=.133$; see Figure 6A). Although the T-F S and group interaction was not significant ($F(2,66),=1.314$, $p=.276$), 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=.65, SD=.19 and DD mean=.48, SD=.22) and at the 2.5° ($t(33)=-1.853$, $p=0.037$; TR mean=.67, SD=.18 and DD mean=.56, SD=.18), but not at the 2.8° ($t(33)=-0.746$, $p>0.461$; TR mean=.72, SD=.17 and DD mean=.67, SD=.21; see Figure 6B).

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

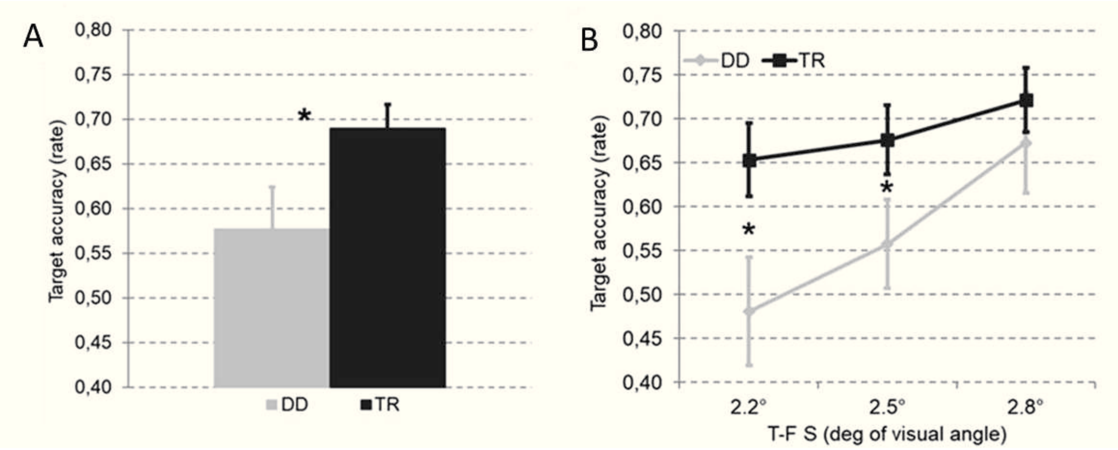

Figure 6: A: Target accuracy (in rate) in typical readers (TR) and children with developmental dyslexia (DD) groups. B: Target accuracy (in rate) in DD and TR groups at different target to flanker spacing (T-F S). Bars represent standard errors.

2.1.4 Experiment 2b: Reading Extra-large Spacing Word Text.

(Bertoni, S., Franceschini, S., Ronconi, L., Gori, S. & Facoetti, A. Is Excessive Visual Crowding Causally Linked to Developmental Dyslexia? In press in Neuropsychologia).

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 2a were used. The two groups (DD and TR) did not differ ($t(48)=-.439$, $p>0.662$) 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 sec, SD=40; DD: mean=146 sec, 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 sec., SD=26; DD: mean=107 sec., SD=42) and errors ($t(48)=5.78$, $p=0.0001$; TR: mean=3.7, SD=2.77; DD: mean=9, SD=3.64).

Extra-small and extra-large reading tasks to measure crowding effect:

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 (Figure 7 A and B).

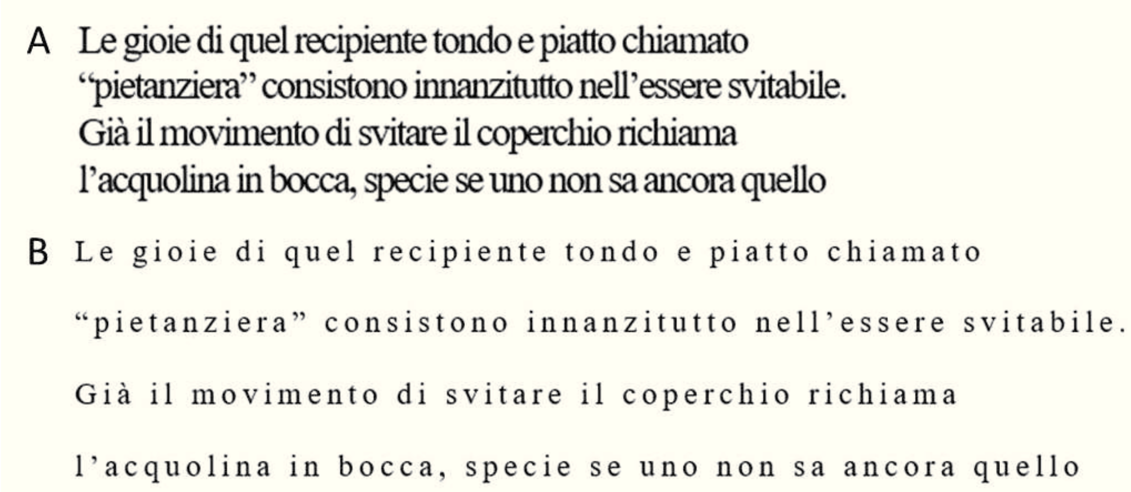

Figure 7: Extra-small (A) and extra-large (B) word text reading tasks.

Results:

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

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

The ANOVA on errors showed a spacing condition main effect ($F(1,48)=16.132$, $p=.0001$, $\eta 2=.252$), a group main effect ($F(1,48)=22.919$, $p=.0001$, $\eta 2=.323$), and a significant spacing condition × group interaction ($F(1,48)=4.488$, $p=0.039$ $\eta 2=0.086$; see Figure 8). 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 ($F(1,48)=8.231$, $p=.006$, $\eta 2=.146$), but neither main effect of spacing condition or spacing condition × group interaction were significant (all $ps>.107$).

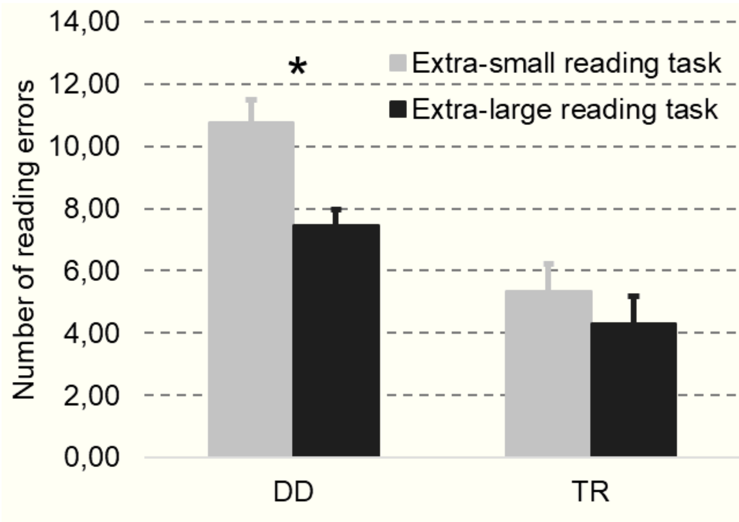

Figure 8: Number of reading errors in extra-small and extra-large spacing tasks in children with developmental dyslexia (DD) and typical readers (TR).

Discussion:

The results of Experiment 2a and 2b show that children with DD suffered of crowding more than children without DD both when crowding is measured by a computerized and by a paper and pencil task (i.e., word text with different spacing). In particular, in the computerized crowding task, children with DD have deficits to select the target when the attention is not pre-oriented and the target-to-flankers spacing is smaller. In the paper and pencil crowding task, children with DD improve their reading accuracy in an extra-large spacing text, showing more crowding than children with without DD in the extra-small spacing text.

The results of the Experiment 1a, 1b, 2a and 2b show that these attentional tasks are able to capture the attentional deficits of children with DD.

These attentional deficits are a possible cause or only an effect of DD?

Longitudinal and intervention studies to answer to this question.

2.2 Experimental design: Longitudinal studies

2.2.1 Experiment 3: Pre-reading global visual perception in future children with reading disorders.

(Franceschini, S., Bertoni, S., Gianesini, T., Gori, S., & Facoetti, A. (2017). A different vision of dyslexia: Local precedence on global perception. *Scientific reports*, *7*(1), 17462).

Participants:

Ninety-six (44 female and 52 male) 5-year-old children attending the last year of 4 kindergartens in Northern Italy, took part in the present longitudinal study. In the Italian school system, formal reading instruction starts in grade 1. Consequently, Italian preschoolers are also pre-readers. We excluded the few children that were able to read at the kindergarten stage and the children with ADHD diagnosis. All children were native Italian speakers without any documented history of brain damage, hearing or visual deficits. The performance IQ level was estimated through the The performance IQ level was estimated through the administration of block design subtest of the WPPSI scale (Wechsler, 2002). The T2 sample was composed by 82 (34 female and 48 male, 14 children moved to other school and become unavailable for testing) children (mean age = 68.5 months, SD = 5.1 and mean Performance IQ = 10.1, SD = 3.5).

Computerized Navon task (T1: kindergarten and T2: grade 1):

The global and local perceptual abilities were measured with the same task used in Experiment 1b, but for each condition 14 trials were presented, for a total amount of 56 trials. Moreover, also the size of stimuli was changed. Geometric figures were shown on a computer screen: A square or a triangle (11.5 × 11.5°) at a global level, which could be formed by small squares or triangles (1.4 × 1.4°) at local level. A small cross (0.2° and 0.6 cd/m2) in the centre of the screen served as fixation point.

Auditory-phonological processing (T1 and T2):

Phonological skills at the syllabic level were tested by using one task included in the Italian “Phonological Awareness Battery” (Marotta, Trasciani & Vicari, 2004), that is the “Syllabic blending”, measuring the ability to blend segmented syllables into a word (15 words; e.g., “fi”, “o” and “re”=“fiore” (flower in Italian)). The number of errors was recorded.

Visual-to-phonological mapping task (T1 and T2):

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.

Words text reading task (T2).

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

Results:

We divided our pre-reading sample in future poor readers (PR, n = 14) and TR (n = 68) on the basis of their future standardized reading performance at the end of grade 1 (Franceschini et al., 2012). A child was assigned to the PR group if her/his z score for average 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 TR group.

The two groups were significantly different in text reading skills (PR mean=-2.92, SD=1.1; TR mean=-0.14, SD=.71 $t_{(80)}$=11.89, p=.001, Cohen’s d=3.07; see Franceschini et al. 2012 for details). These two groups did not differ for chronological age (PR mean=5.65 years, SD=.53; TR mean=5.73 years, SD=.41 $t_{(80)}$=.624, p=.535, Cohen’s d=.17), performance IQ (PR mean=10.07, SD=2.87; TR mean=10.09, SD=3.69; $t_{(80)}$=.016, p=.987, Cohen’s d=.01), auditory-phonological skills (syllabic blending: PR mean=2.07 errors, SD=1.39; TR mean=1.97 errors, SD=1.63; $t_{(80)}$=-.207, p=.837, Cohen’s d=.07) and visual-to-phonological mapping (RAN of colors: PR mean=19.04

sec, SD=6.4; TR mean=18.67 sec, SD=7.57; $t_{(80)}$=-.168, p=.867, Cohen's d=.05).

Accuracy and reaction times in the computerized Navon task were analyzed with two mixed ANOVAs. We predicted a selective local before global perception at pre-reading stage only in future PR children. Accuracy and response times (in msec) in the computerized Navon task were analyzed by two ANOVAs with a 2 × 2 × 2 design. The two within-subject factors were condition (congruent and incongruent) and task (global and local) and the between-subject factor was group (PR and TR). In the ANOVA about accuracy, only a main effect of condition was significant: $F_{(1,80)}$=9.747, p=.003 η^2=.109 (congruent condition rate=.95, SD=.07 and incongruent condition rate=.90, SD=.12). In the ANOVA about response times, a main effect of condition was significant: $F_{(1,80)}$=23.749, p=.0001 η^2=.229 (congruent condition mean=651 msec, SD=330 and incongruent condition, mean=764 msec, SD=453). Crucially for our causal hypothesis, the condition × task × group interaction was significant only on response times ANOVA: F(1,80) = 11.55, p = 0.001 η2 = 0.126 (Figure 9A and B).

Within-subject planned comparisons on the condition effect (incongruent vs. congruent) showed a significant effect both in global (t(67) = 3.276, p = 0.002, Cohen's d = 0.28) and in local (t(67) = 5.203, p = 0.0001, Cohen's d = 0.48) tasks in future TR group, whereas in future PR group this effect was significant in global (t(13) = 2.964, p = 0.011, Cohen's d = 0.76), but not in local task (t(13) = 0.271, p = 0.791, Cohen's d = 0.05). The TR group showed a significantly greater condition effect in local than in global task (t(67) = 2.428, p = 0.018, Cohen's d = 0.43), whereas the PR group showed a significantly greater condition effect in global than in local task (t(13) = 2.623, p = 0.021, Cohen's d = 1.08). Between-subject planned comparisons showed that in the global task, the condition effect was significantly stronger in PR (mean = 362 msec, SD = 458) in comparison to TR group (mean = 118 msec, SD = 298; t(80) = 2.525, p = 0.014, Cohen's d = 0.65). In contrast, in the local task the condition effect was present in the TR group (mean = 277 msec, SD = 440) that showed a greater condition effect in comparison to the PR group (mean = −17 msec, SD = 245; t(80) = 2.427, p = 0.017, Cohen's d = 0.86).

In addition, paired-sample t-tests revealed that the two groups significantly differed only in the global incongruent condition (t(80) = 3.304, p = 0.001, Cohen's d = 0.93).

After we established that future PR, at the pre-reading stage, already showed a local before global visual perception, we further investigated the causal link between individual measures of neurocognitive functioning at T1 (kindergarten) and reading emergence (T2 = grade 1), across our entire sample of children (n = 82), independently of our a priori group classification of reading disorder. Using two five blocks fixed entry linear regression analysis, we showed that after controlling for chronological age, performance IQ (i.e., Block Design standard score; Wechsler, 2002), auditory-phonological (errors in the syllabic blending; Marotta et al., 2004) and cross-modal mapping (i.e., speed in sec in the RAN of colours; Franceschini et al., 2012) skills, only the global task condition effect (incongruent vs. congruent) measured at pre-reading stage predicted a significant unique variance ($R2 = 0.07$, $p = 0.017$) of future text reading skills (mean between speed and accuracy z scores) in T2.

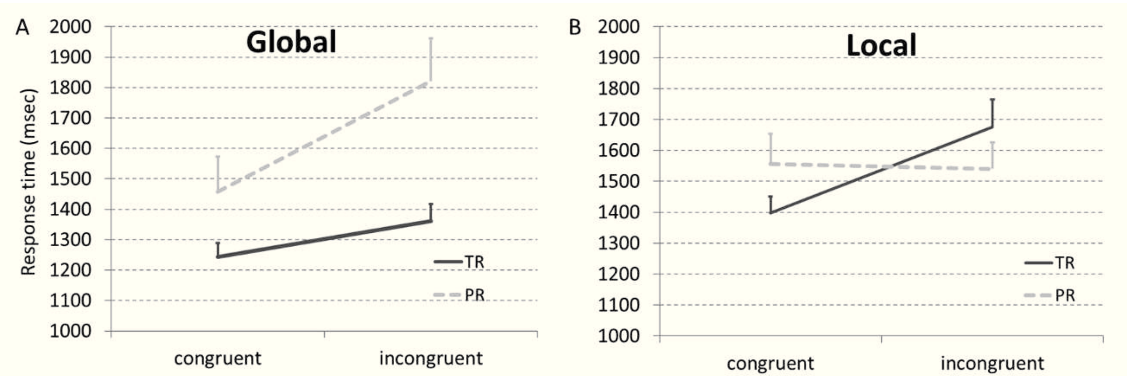

Figure 9: A: Future PR showed already at pre-reading stage a greater local interference than future TR in the global task; B: Future PR showed already at pre-reading stage a lower global interference in the local task.

Discussion:

The results of Experiment 3 show that the global perception deficit of children with DD could be one of the causes of DD because the children that show reading difficulties at the end of the Grade 1, during the last year of kindergarten already showed a deficit in the global perception when the local information is different.

2.2.2 Experiment 4: Longitudinally Testing the Causal Hypothesis Between Excessive Crowding and DD.

(Bertoni, S., Franceschini, S., Ronconi, L., Gori, S. & Facoetti, A. Is Excessive Visual Crowding Causally Linked to Developmental Dyslexia? In press in Neuropsychologia).

Participants:

In this Experiment, I 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 preschoolers 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 performance IQ level was estimated through the administration of the Vocabulary subtest of the WPPSI scale (Wechsler, 2002).

Written informed consent was obtained by parents of children, and all procedures were jointly approved by the Ethics Committee of the University of Padua.

Crowding task (T1: kindergarten and T2: grade 1)::

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 x 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 Figure 10 A and B). Time (in sec) and errors were measured.

Figure 10: Serial visual search task to measure crowding in an ecological setting: the large spacing (A) and the small spacing (B) conditions.

Phonemic recognition task (T1 and T2):

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).

Visual-to-Phonological Mapping Task (T1 and T2):

The task was the same as that used in the Experiment 2a.

Words text reading task (T2).

The task was the same as that used in the Experiment 2a.

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 & 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= .34; GR mean= 5.84 years SD= .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 ($t(62)=2.29$, $p=.026$; PR mean=11.75 sec. SD=6.54; GR mean=8.67 sec. SD=2.89; Figure 11A), and in the number of errors in the phonemic recognition task ($t(62)= 3.068$, $p= .003$; PR mean= 4.41 SD=3.23; GR mean= 2.07 SD= 2.66; Figure 11B). Furthermore, PR and GR groups differed in the number of errors in both large ($t(62)=3.697$, $p=.0001$; PR mean=5.11 SD=4.76; GR mean=1.52 and SD=1.93) and small conditions ($t(62)=3.953$, $p=.0001$; 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 ($t(36)=-2.291$, $p=.028$; Figure 11C), while the GR group did not show crowding ($p > .14$).

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 ($t(55)=2.047$, $p=.045$; PR mean=1.89, SD=3.07; GR mean= .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 $p=.035$), whereas the GR group did not show crowding ($p > .70$).

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 visuospatial 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 ($r=-.28$, $p=.014$), with the visual-to-phonological mapping speed ($r=-.27$, $p=.017$), and with the number of errors in the phonemic recognition task ($r=-.25$, $p= .025$) measured at T1.

The reading accuracy (number of errors) at Grade 1 correlates only with the visual-to-phonological mapping speed ($r=.32$, $p=.005$) 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=.007) and crowding accounted again for 9% of the unique variance of reading speed (p=.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.

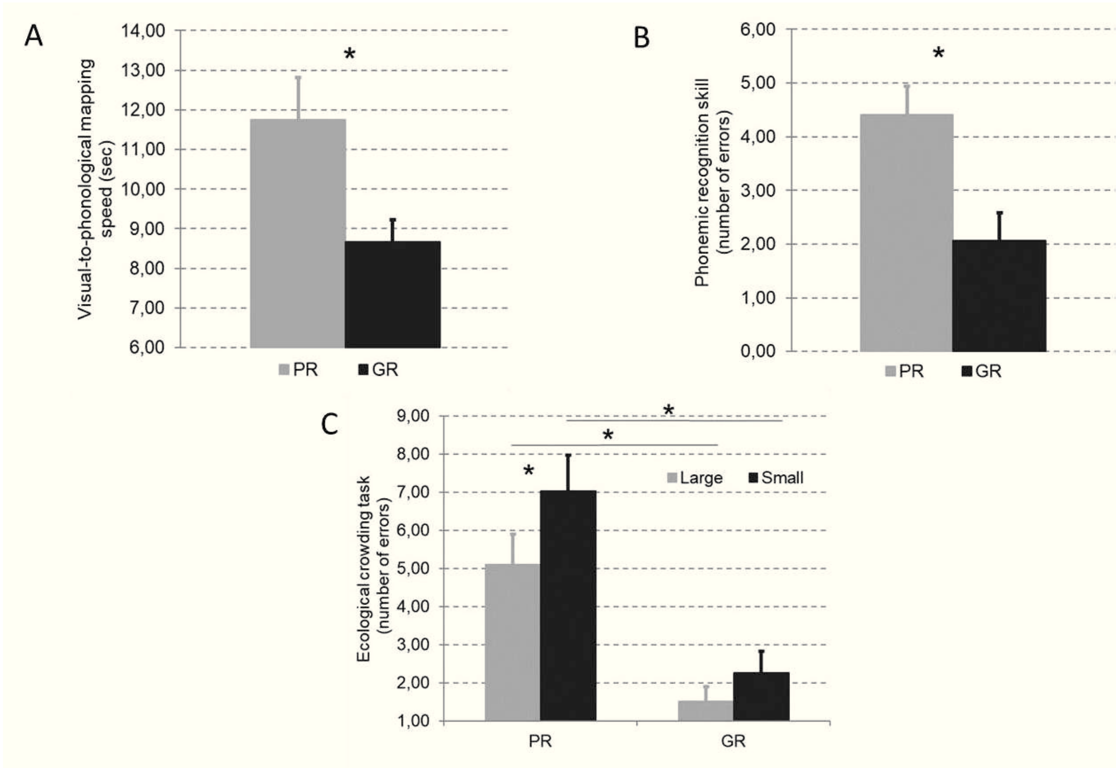

Figure 11: A: Visual-to-phonological mapping speed (sec.) in kindergarten (T1) in future poor readers (PR) and good readers (GR). B: Number of errors in phonemic recognition task in T1 in future PR and GR. C: Number of errors in ecological crowding task in kindergarten (T1) in large and small spacing condition in future PR and GR.

Discussion:

The results of Experiment 4 show that the ability to extract the visual relevant information (i.e., target) embedded in noise (i.e., flankers) measured by crowding task, could be one of the causes of DD. Indeed, the children that show reading difficulties at the end of the Grade 1, during the last year of kindergarten already showed an excessive crowding in comparison to children without reading difficulties.

2.3 Experimental design: Intervention studies

2.3.1 Experiment 5: Global visual perception in children with dyslexia after an action video game Training.

(Franceschini, S., Bertoni, S., Gianesini, T., Gori, S., & Facoetti, A. (2017). A different vision of dyslexia: Local precedence on global perception. *Scientific reports*, *7*(1), 17462).

Participants:

Participants were fourteen children (6 female and 8 male; mean age = 10.41 years, SD = 1.71) with DD of Experiment 1b that agreed to be involved to a video game training. 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 as AVG or NAVG (Franceschini et al., 2013). Seven children with DD were assigned to AVG and seven to NAVG training. Information about video game experience were collected during–interviews with parents during pre-informative briefing about the experimental training. Children with DD did not know the aim of the training and in the previous six months did not play action any video game (AVG) for more than 1 hour per month. The attentional and reading performance of the participants were evaluated before (T1) and after (T2) the two different video game trainings.

Reading and phonological skills were similar in the two groups (all ps > 0.392). The two groups did not differ at T1 in both reading (speed and accuracy) and global and local visual perception measurements (all ps > 0.06). Each child was individually treated by playing the commercial Wii ™ video game for a total of 12 hours. The single minigames were selected to create the AVG and NAVG trainings (Gori et al., 2016; Franceschini et al., 2013).

Computerized Navon task:

The task was the same as that used in the Experiment 1b.

Reading tasks:

Words text reading task was the same as that used in the Experiment 2a and 2b (Cornoldi & Colpo, 2004).

Pseudowords reading tasks: phonological decoding abilities were measured using two pseudowords texts (Franceschini et al., 2016), and two lists, of 15 pseudowords each, composed of 2-4 syllables (the same syllables in different order for both lists; Franceschini et al., 2016). Pseudowords texts and lists order administration were counterbalanced between children in T1 and T2.

Training procedure:

Participants were individually trained in a dimly lit and quiet room.

Participants were tested before 3 to 5 days the start of treatment and re-tested between one and three days after the end of training. Video games were played standing 200 cm from a 27-in TV screen. In order to classify the mini-games, we followed the checklist developed by Green et al. (2010): 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 (Figure 12).

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 minutes per day distributed across a period of two weeks (Gori et al., 2016; Franceschini et al., 2013; Franceschini et al., 2017).

Figure 12: An example of Action Video-Game (AVG) on the left; and of Non Action Video-Game (NAVG) on the right.

Results:

Response times (in msec) in the global and local computerized Navon task (Fig. 2a) were analyzed by means of two mixed ANOVAs with a 2 times (T1 = before and T2 = after) × 2 conditions (congruent and incongruent) design for each treated group.

In the AVG group, in global task, main effect of condition was significant ($F(1,6) = 11.28$, $p = 0.015$, $\eta 2 = 0.653$). Crucially for our hypothesis, time × condition interaction was also significant ($F(1,6) = 9.379$, $p = 0.022$, $\eta 2 = 0.61$). Planned comparison showed that AVG group presented a significant response times reduction in incongruent condition ($t(6) = 2.521$, $p = 0.045$, Cohen's d = 1.12, B01 = 2.12; Fig. 2d). The same ANOVA on NAVG did not show any significant effect (time × condition effect $F(1,6) = 0.180$, $p = 0.686$, $\eta 2 = 0.029$).

In local task, both groups showed only a main effect of condition (AVG: $F(1,6) = 6.921$, $p = 0.039$, $\eta 2 = 0.536$; NAVG: $F(1,6) = 9.959$, $p = 0.02$, $\eta 2 = 0.624$). Planned comparison showed that in children with DD, the condition effect (incongruent vs. congruent) became significant only after AVG treatment ($t(6) = 3.264$ $p = 0.017$, Cohen's d = 0.40 Figure 13A, whereas after NAVG $t(6) = 1.472$ $p = 0.19$, Cohen's d = 0.27).

Reading speed (syllables per second) improvement was evaluated in AVG and NAVG groups by two separate ANOVAs 2 times (T1 = before and T2 = after) × 3 tasks (words text, pseudowords lists and pseudowords texts). Results showed a significant main effect of time ($F(1,6) = 7.78$, $p = 0.032$ $\eta 2 = 0.565$; T1 mean = 1.59 SD = 0.41, T2 mean = 1.86, SD = 0.49) only in the AVG training group (NAVG time effect $F(1,6) = 1.097$, $p = 0.335$ $\eta 2 = 0.155$ T1 mean = 1.29 SD = 0.73, T2 mean = 1.37, SD = 0.65). The same ANOVAs considering as dependent variable the number of errors, did not show any significant effect (AVG time effect $F(1,6) = 1.931$, $p = 0.214$ $\eta 2 = 0.243$; T1 mean = 4.48 SD = 2.99, T2 mean = 4.21, SD = 3.09; NAVG time effect $F(1,6) = 0.692$, $p = 0.437$ $\eta 2 = 0.103$; T1 mean = 7.02 SD = 4.68, T2 mean = 6.99, SD = 3.42). The reading improvements after the AVG training were characterized by the increased reading speed without any cost in accuracy (Gori et al., 2016; Franceschini et al., 2013; Franceschini et al., 2017) and this result is in agreement with the improved speed of processing already found associated with AVG (Dye et al., 2009).

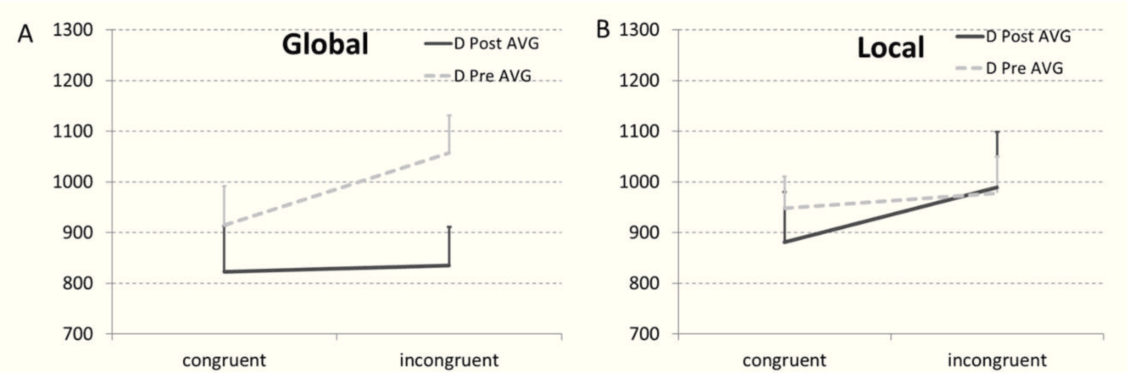

Figure 13: Only after the AVG training children with DD showed a significant reduction of local interference effect in the global task (**A**) and a significant increase of global interference effect in the local task (B).

Discussion:

The results of Experiment 5 show that the global perception deficit could be one of the causes of DD because with a visual attentional training (i.e., AVG) children with DD improve the global perception and, more importantly, their reading speed.

2.3.2 Experiment 6: AVG Training Reduces Crowding and increase Reading Speed.

(Bertoni, S., Franceschini, S., Ronconi, L., Gori, S. & Facoetti, A. Is Excessive Visual Crowding Causally Linked to Developmental Dyslexia? In press in Neuropsychologia).

Participants:

The participants were the same as in the Experiment 5.

Computerized Crowding task:

Crowding was measured with a similar task used in Experiment 1c, but I 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.

Reading tasks:

The pseudowords reading tasks were the same as those used in Experiment 5.

Training procedure:

The training procedure was the same as that used in the Experiment 5.

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). Reading speed improvement (syll/sec) was evaluated by a mixed ANOVA with a 2 x 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 ($F(1,12)=9.012$, $p=0.011$ $\eta2=0.429$), and a significant time × group interaction ($F(1,12)=5.889$, $p=0.032$ $\eta2=0.329$; see Figure 14A). 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=.23; T2 mean=1.47 syll/sec, SD=.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 hr of AVG training were higher than the mean improvements expected in a child with DD (0.15 syll/sec) after 1 year (8760 hr) of spontaneous reading development.

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

In Experiment 2a the difference between children with 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 children with DD 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=.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 Figure 14B).

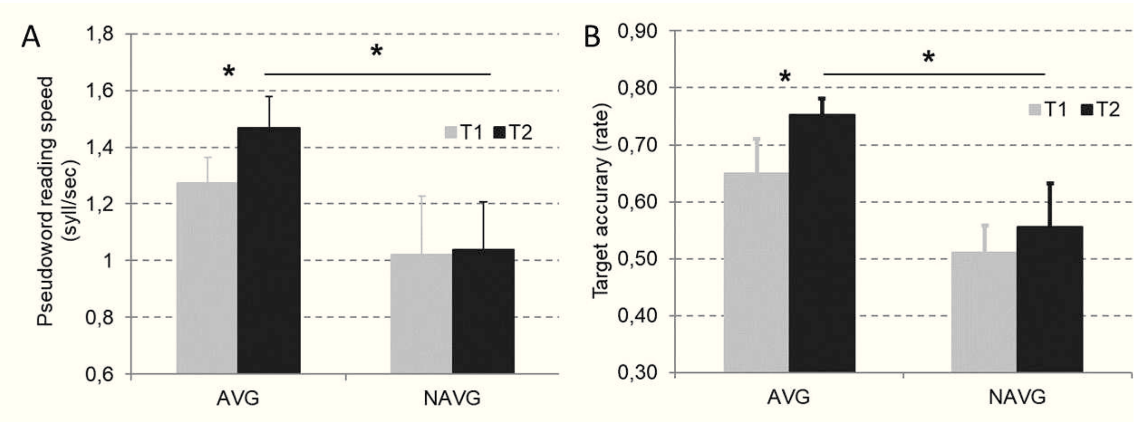

Figure 14: A: Reading speed (syll/sec) in pseudoword tasks before (T1) and after (T2) action video game (AVG) or non-action video game (NAVG) training. B: Target accuracy (in rate) in crowding task before (T1) and after (T2) AVG or NAVG training in the small spacing condition.

Discussion:

The results of Experiment 6 show that an excessive visual crowding could be one of the possible causes of DD, because with a visual attentional training (i.e., AVG) children with DD improve the ability to extract the relevant information ignoring the distractors, reducing the crowding and improving their reading speed.

The results of longitudinal (Experiment 3 and 4) and intervention (Experiment 5 and 6) studies show that these attentional deficits are a possible cause of DD and not only an effect.

Is it possible that each child with DD could improve his/her attentional and reading skills with an AVG training?

2.3.3 Experiment 7a: AVG Training Increase Reading Speed Only in High Learning DD Players

(Franceschini, S., & Bertoni, S. (2018). Improving action video games abilities increases the phonological decoding speed and phonological short-term memory in children with developmental dyslexia. In press in Neuropsychologia.)

Participants:

Eighteen children (8 females and 10 males) with DD, from the 3rd to 8th school grade (mean age=9.79 years, SD=1.33), took part to our clinical AVG training study. Children received the diagnosis of DD by the Italian National Health Service, based on standard exclusion and inclusion criteria (APA, 2013). Specifically, the reading performance (errors and/or speed) of each individual was at least −1.5 SD below the age-standardized norm in at least one of 2 clinical reading tasks (i.e., words and pseudowords reading; Sartori et al., 2007). Other inclusion criteria for this study were normal IQ (≥85), normal or corrected-to-normal vision, absence of neurological deficits and ADHD diagnosis. Furthermore, children had played no AVG or no more than one hour in the last six

months. This piece of information was taken from a specific questionnaire filled in by the parents of the participants. Informed written consent was obtained from parents of each child, and the Scientific Institute E. Medea ethic committee approved the research protocol.

Reading tasks:

The pseudowords reading tasks were the same as those used in Experiment 5 and 6.

Phonological short-term memory:

Children listened to a series of pseudo-words trigrams. Children had to repeat every trigram in the correct order. Two lists of trigrams were presented. If the children repeated correctly at least one of them, a new series with an additional list of trigrams was proposed. If both lists of trigrams were wrongly reported, the task was interrupted.

One point for each phoneme correctly repeated was assigned. The series started with a list of two trigrams and continued up to a maximum of eight trigrams.

Training procedure:

The training procedure was the same of Experiment 3, but the children were trained for 12 sessions of 60 minutes 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 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; see Table 1), 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, $t(7)=.099$, $p=.924$), nor in the “Nanostray 2” group (HL score mean=10212, SD=13809; LL mean=12875 SD=11903, $t(7)=.307$, $p=.769$) 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; $t(7)=4.103$, $p=.005$) and “Nanostray 2” (HL mean= 97600 SD= 21842; LL mean= 38218 SD= 20582; $t(7)=4.189$, $p=.004$).

Results:

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., 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.

For each group, the one trained with Plants vs Zombies (four females and five males), and the one trained with Nanostray 2 (four females and five males), the median game score improvement was calculated. To differentiate between children that acquired good abilities in AVG performance and those that did not reach high game score, since we did not have a reference average score, we divided the total group of players with DD in those who showed a game score improvement greater than the median score (high learning player, HL, n=8: 1 female and 3 males for Plants vs zombies, 1 female and 3 males for Nanostray 2) and those who showed an improvement lower or equal than the median score (low learning player, LL, n=10: 3 female and 2 males for Plants vs zombies, 3 female and 2 males for Nanostray 2; see Fig. 1 panel A e B). The initial game score in Plants vs Zombies (HL score mean=403, SD=181; LL mean=394 SD=95, U=8, p=.624), and in Nanostray 2 sub-groups (HL score mean=10212, SD=13809; LL mean=12875 SD=11903, U=9, p=.806) compared using the non-parametric Mann-Whitney U Test showed no significant differences. Based on our a priori classification, the game score improvements in HL and LL groups were significantly different both in Plants vs Zombies (HL mean=428 SD=215; LL mean=9 SD= 76; U=0, p=.016) and Nanostray 2 (HL mean=97,600 SD=21,842; LL mean= 38,218 SD=20,582; U=0, p=.016). The HL (n=8) and LL

(n=10) sub-groups trained with the two AVGs did not differ in age (U=21.5, p=.101), in standardized reading tasks (i.e., time and errors; see Table 1), neither in experimental reading task syll/sec reading speed (U=37, p=.829) and error rate (U=33, p=.573) or phonological skills (U=30.5, p=.408).

Due to the small number of participants and variables distribution, pseudo-words reading ability improvements were analyzed using the Wilcoxon Signed-Rank Test non-parametrical analysis.

To obtain a unique data from the two tasks of different length (i.e., pseudo-words text and list), we used as dependent variables the syllables per second (syll/sec) and the mean of errors on the total number of items for each task (i.e., error rate; errors/46 items and errors/16 items for the two tasks, respectively). As expected, the two tasks were highly correlated (r Spearman=0.86, $p < .0001$ for execution time and r Spearman=0.55, p=.017 for the error rate); consequently, the mean of the two performance was used as dependent variable. A Wilcoxon signed-rank test showed that in the HL group, there was a significant improvement in syll/sec reading rate between pre- and post-training (Z=-2.24, p=.025). The clinical relevance of this result can be fully appreciated by noting that the pseudo-words decoding improvements obtained by this clinical AVG trainings in HL group of children with DD (mean 0.11 syll/sec) were not significantly different (Z=-0.98, p=.327) than the mean improvements expected in a DD child (0.15 syll/sec) after 1 year of spontaneous reading development (Tressoldi et al., 2001). Thus, only in the HL group the AVG trainings (i.e., 12 h) effect was similar to a year of spontaneous reading speed development (i.e., 8760 h). In contrast, the error rate did not show significant change between pre- and post-training performance (Z=-1.82, p=.069; see Fig. 15A).

Conversely, the LL group, did not show significant changes either in terms of syll/sec reading rate (Z=-0.612, p=.541), or in error rate (Z=459, p=.646; see Fig. 15A). To explore the possible differences related to the type of game (Plants vs Zombies or Nanostray 2), we compared the change obtained by the two HL sub-groups (HL in Plant vs Zombies and HL in Nanostray 2) in syll/sec and in error rate, but in both cases, there were not significant differences (U=1, p=.057 and U=7, p=.886 respectively). Improvements observed in syll/sec were not correlated with the game scores in Plants vs Zombies (r Spearman=0.28, p=.46). Game

score improvements in this group of children were correlated to age (r Spearman=0.67, p=.047) and in the speed of the standardized pseudowords reading task measured in pre training (r Spearman=-0.67, p=.045). These correlations indicate that older children improved in this game more than the younger ones, and the ones with more difficulties in phonological decoding improved in the game more than those with fewer difficulties. More importantly, both age and the speed of the standardized pseudowords reading task measured in pre training were not correlated with each other or with speed improvements after AVG trainings (all ps>.173). In the group that played Nanostray 2, syll/sec improvements were significantly positively correlated (r Spearman= 0.65, p=.029 one-tailed) with the game score improvements: higher the game score improvements, higher the syll/sec improvements. All the other correlations were not significant (all ps>.286).

Finally, considering that the HL group did not show any significant growth in error rate, in order to control for a possible speed accuracy trade off, for each participant we calculated the rate of improvement in terms of syll/sec rate (i.e., the ratio between difference pre and post training performance in syll/sec and pre training syll/sec performance) and compared with error rate change (i.e., the mean of difference between pre- and post-training error rate). Correlation between the syll/sec rate and the error rate variations was significant ($r=-0.44$ $p=.035$ one-tailed), indicating a possible speed accuracy trade off (see Figure 16). To analyze the effects of this correlation, we measured the dimensions of performance variation. In the HL group the rate of speed improvement in terms of syll/sec (mean=0.13) was statistically different from zero ($Z=-2.24$, $p=.025$), whereas the reduction of error rate (mean=0.04), was not ($Z=-1.82$, $p=.069$). In the LL group, neither the variation in syll/sec nor in error rate was significantly different from zero ($Z=-0.459$, $p=.646$ and $Z=-0.612$, $p=.541$ respectively).

Phonological short term memory improvements were also evaluated using the Wilcoxon Signed-Rank Test statistical analysis. In this case the dependent variable was the number of correct phonemes. The HL group had a significant performance improvement (pre-training mean=32.5, SD=10.25; post-training mean=45.13, SD=16.4; $Z=-2.103$, $p=.035$). In contrast, the performance in the phonological short-term memory was not significantly changed in LL players (pre-training mean=27.3, SD=4.55 and post-training mean=28.5, SD=7.99; $Z=-0.141$, $p=.888$; see Figure 15B). Analyzing the game score improvements separately for the two video games, we observed that in Plants vs Zombies group, phonological improvements were positively correlated (r Spearman=0.72, $p=.028$) with the game score improvements as well as with the standardized pseudo-words (r Spearman =-0.83, $p=.006$) and words (r Spearman=-0.65, $p=.03$ one-tailed) reading speed. Greater game score improvement and greater severity in reading performance were positively connected to larger short term memory improvement. The same correlations were not significant with improvements in Nanostray 2 game score (all ps>0.14).

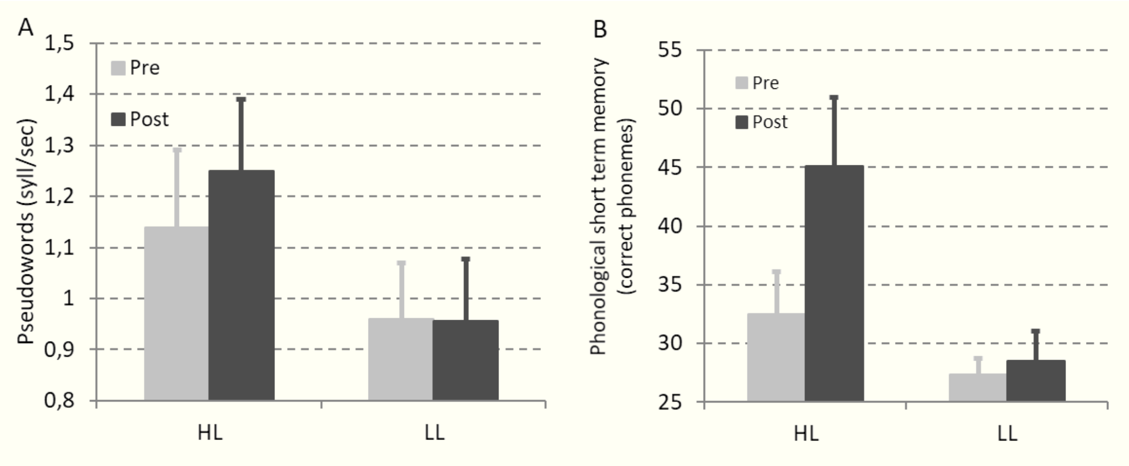

Figure 15: A: Pseudo-words reading speed (syll/sec) for high learning (HL) and low learning (LL) players are represented before (pre-) and after (post-) the training. B: The performance (number of correct phonemes) in the short term memory task are reported for HL and LL groups. Error bars represent SEM.

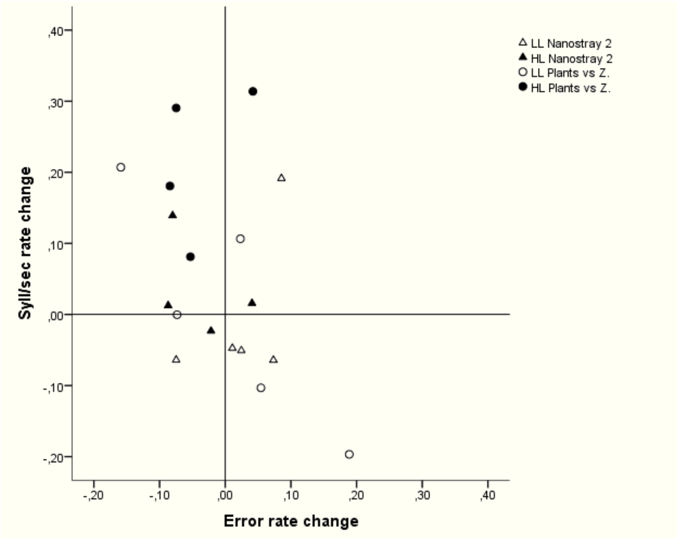

Figure 16: For both groups (HL and LL) the changes in terms of syll/sec rate (syllables for second post-pre performance/ the initial syllable for second performance) and the error rate (post- minus pre-training) are shown.

2.3.4 Experiment 7b: AVG Training Reduces Crowding Only in High Learning DD Players

(Bertoni, S., Franceschini, S., Ronconi, L., Gori, S. & Facoetti, A. Is Excessive Visual Crowding Causally Linked to Developmental Dyslexia? In press in Neuropsychologia).

Participants:

The participants were the same as in the Experiment 3c.

Crowding tasks:

The crowding task was the same as that used in the Experiment 3b.

Reading tasks:

The reading tasks were the same as those used in the Experiment 3c.

Training procedure:

The training procedure was the same as that used in the Experiment 3c.

Results:

As in Experiment 4, 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 Figure 17), but not in the large spacing condition ($t(7)=-1.173$, $p=.140$), while the children of the LL group did not improve their performance in both spacing conditions (all $ps>0.1$).

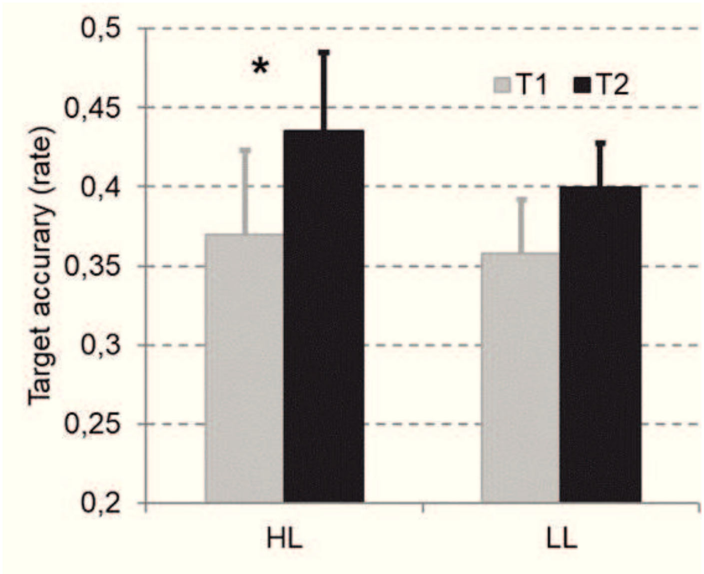

Figure 17: Target accuracy (in rate) in crowding task before (T1) and after (T2) AVG training in HL and LL groups in the small spacing condition.

Discussion:

The results of Experiment 7a and 7b answer to the question "*Is it possible that each child with DD could improve his/her attentional and reading skills with an AVG training?*" showing that to improve the reading speed and the attentional skills, measured by crowding, children with DD have to participate actively the AVG training and they have to be able to sustain the training improving their performance measured by game scores.

Is it possible that a visual-attentional training have a cross-modal effect improving also auditory skills in children with DD?

2.3.5 Experiment 8: Action video games improve reading abilities and visual-to-auditory attentional shifting in English-speaking children with dyslexia.

(Franceschini, S., Trevisan, P., Ronconi, L., Bertoni, S., Colmar, S., Double, K., ... & Gori, S. (2017). Action video games improve reading abilities and visual-to-auditory attentional shifting in English-speaking children with dyslexia. Scientific Reports, 7(1), 5863).

Participants:

Twenty-eight dyslexic children (8 females and 20 males), mean age 10.1 years (range 7.8–14.3) were involved in the experiment. All the children were recruited through school newsletters or dyslexia associations. The inclusion criteria were the same as those in Experiment 5. Children were randomly allocated to either AVG (n = 16) or NAVG training (n = 12).

Visual, auditory, audio-visual processing and cross-sensory attentional shifting task:.

The experimental procedure and data acquisition were controlled with E-prime 2.0 (Psychology Software, Inc.) running on a 23-in Dell Optiplex 9030 VAIO Screen. The viewing distance was set to 50 cm, with the vertical body midline aligned with the screen center by using the chinrest. The visual target stimulus was a black square (2.5 × 2.5°) presented on a light grey background at an eccentricity of 16° from the fixation point (0.5 × 0.5°). The sound target stimulus was a 500-Hz sound (pure tone) and was presented in one of the 2 (left or right) external speakers. Speakers were positioned close to the left and right screen borders, and were elevated so that the center of the speakers was aligned with the monitor horizontal median line, where the visual stimulus was presented. This way we ensured that visual and auditory stimuli were presented close together in space. On each trial, the fixation point appeared for a random duration between 1000 and 2500 msec., in order to avoid the possibility that participants might build a prediction about the target onset time over the course of the trials. Subsequently, the target stimulus appeared according to the 3 possible experimental conditions. In the "visual" condition, the visual stimulus was presented alone for 200 msec. in the left or right visual hemifield. In the "auditory", the sound was presented alone for 200 msec. in the left or right speaker. In the "audio-visual" condition, a synchronized combination of

the visual and auditory stimulus was presented for 200 msec., always on the same side (left visual hemifield/left speaker or right visual hemifield/right speaker). Participants were asked to respond as fast and as accurately as possible by pressing the letter “Z” for any stimulus appearing on their left side and the letter “M” for any stimulus appearing on their right side. The maximum time for response was set to 2000 msec. The experimenter controlled the transition from one trial to the next. After 10 practice trials, participants performed 90 experimental trials (3 conditions × 2 sides × 15 repetitions) and 10 catch trials (where no visual or auditory stimulus occurred), randomly intermixed, for a total duration of approximately 15 min.
Informed written consent was obtained from the parents of each child; the University of Sydney ethic committee approved the research protocol (p. n. 2015/059).

Reading tasks:
Word reading: The Sight Words task, form “A” of Towre 267 was used in T1, form “B” in T2. In both cases, participants were asked to read the first three columns (81 words; “long” lists) as fast and accurately as possible. In addition, the first column of form “C” (including 27 words “short” list) was used in T1 and the first column of form “D” (including 27 words; “short” list) was used in T2. Again, participants were asked to read as fast and accurately as possible. We selected different reading tests in T1 and T2 evaluations to exclude the test-retest effect. Time (in sec.) and numbers of errors were recorded. Performance in the two lists were mediated for the statistical analysis. One error was assigned if the word was not pronounced entirely correctly. Self-corrections were not considered errors. The tasks were administered in about 10 minutes.
Phonological decoding: The Phonemic Awareness task, form “A” of Towre 267 was used in T1, form “B” in T2. In both cases, participants were asked to read the first two columns (44 pseudowords; “long” lists) as fast and accurately as possible. In addition, the first column of form “C” (including 22 pseudowords; “short” list) was used in T1 and the first column of form “D” (including 22 pseudowords; “short” list) was used in T2. We selected different reading tests in T1 and T2 evaluations to exclude the test-retest effect. Time (in sec.) and numbers of errors were recorded. Performance in the two lists were mediated for the statistical analysis. One error was assigned if the

pseudoword was not pronounced entirely correctly. Self-corrections were not considered errors. The tasks were administered in about 10 minutes.

Auditory-phonological working memory:

Children listened to a series of pseudoword trigrams using headphones. Children had to repeat each trigram in the correct sequence. Two lists of trigrams were presented. If the children repeated correctly at least one of them, a new series with an additional couple of trigram lists was proposed. If both lists were wrongly reported, the task was interrupted. One point for each correctly repeated item was assigned. The series started with two trigrams and continued up to a maximum of eight trigrams.

Phoneme blending: Two lists of words (10 + 10) were presented. The first list differed in T1 and T2 (the same sound but in reversed order was presented in T1 and T2: T1 "day" and T2 "aid"; T1 "tar" and T2 "art"), the second list was the same. The two lists were counterbalanced among subjects. The instructions for children were: "your task is to put some sounds together to create a word. If I pronounced the sounds /D/-/A/-/D/ what word would be created? Try to blend those sounds together to figure out the word". The sounds were recorded by an Australian native speaker and the children were required to put together the sounds (delivered to them by means of professional headphones) in order to figure out a word. One point was assigned if the word was recognized, zero points if the word was not recognized. The tasks were administered in about 10 minutes.

Training procedure:

The training procedure was the same as that used in the Experiment 5 and 6.

Results:

Word reading ability improvements were analyzed using a 2 (time: pre vs. post) × 2 (intervention group: AVG vs. NAVG) analysis of Covariance (ANCOVA). In the first ANCOVA, the dependent variable was execution time. To exclude the possible effects of educational experience and reading impairment TOWRE-2 *z*-scores) in T1 were controlled by entering them as covariates. The time × group interaction was significant ($F(1,24) = 4.81$, $p = 0.038$ $\eta 2 = 0.17$; see Figure 18). Post-hoc comparisons showed that participants in the AVG group significantly decreased their reading time (pre-training mean = 88, SE = 13; post-training mean = 74, SE = 13 p = 0.024, Cohen's d, using the formula: mean in T1- mean in T2/pooled SD, was 0.27), whereas NAVG group did not show any significant differences between pre- (mean = 97, SE = 16) and post-training (mean = 103, SE = 15). We also calculated the Cohen's d comparing the changes (T2-T1) of each group, using the formula for independent sample (mean of AVG group) − (mean of NAVG)/(pooled standard deviation) which resulted 0.86.

The same ANCOVA model was performed using number of errors as the dependent variable. No main effect or interaction was significant.

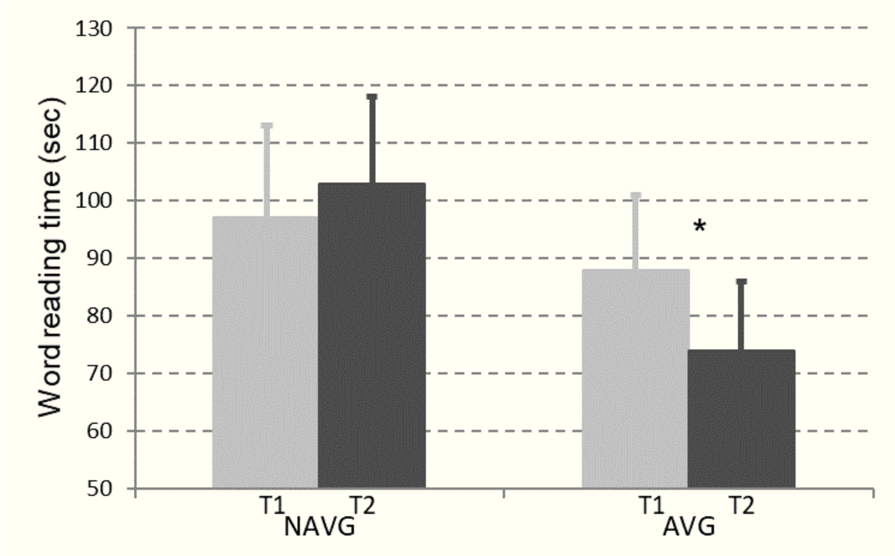

Figure 18: The time for word recognition was significantly reduced only after Action Video-Game (AVG) training. Error bars represent standard errors.

The ANCOVA model described above was applied to pseudoword reading abilities. Using reading time (in sec.) as the dependent variable. The time × group interaction was significant ($F(1,24) = 6.162$, $p = 0.02$ $\eta2 = 0.204$; see Figure 19). Post-hoc comparisons showed that children with DD in the AVG group significantly decreased their phonological reading time (pre-training mean = 86, SE = 9; post-training mean = 69, SE = 10, p = 0.003, Cohen's d = 0.45), whereas participants in the NAVG group did not show any significant difference between pre- (mean = 79, SE = 10) and post-training (mean = 82, SE = 12). Comparing the mean changes between AVG and NAVG groups, Cohen's d was = 0.98.

We ran a similar ANCOVA, differing only in the dependent variable (number of errors). No main effect or interaction was significant.

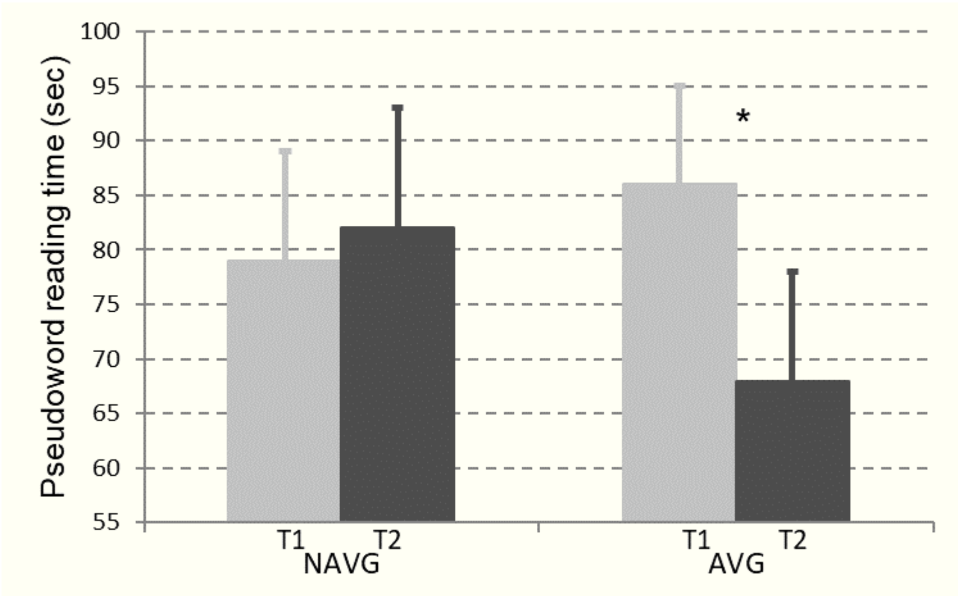

Figure 19: The time for phonological decoding was significantly reduced only after Action Video-Game (AVG) training. Error bars represent standard errors.

Auditory-phonological working memory. The number of correct items in the phonological short-term memory and phoneme blending task were analyzed to measure the effect of the two different trainings on auditory-phonological working memory.

Accuracy in auditory-phonological working memory was analyzed using a 2 (time: pre vs. post) X 2 (task: memory and blending) × 2 (intervention group: AVG vs. NAVG) ANCOVA. To exclude the possible effect of educational experience, chronological age was controlled by entering it as covariate.

The time × group interaction was significant ($F(1,25) = 5.277$, $p = 0.03$ $\eta2 = 0.174$; see Figure 20). Post-hoc comparisons showed a significant improvement in the accuracy of the AVG group (pre-training mean = 11.28; SE = 0.97; post-training mean = 15.12; SE = 0.8, $p = 0.002$, Cohen's d = 1.09), whereas the NAVG group did not show any significant improvement (pre-training mean = 11.13; SE = 1.12; post-training mean = 10.85; SE = 0.93). Comparing the mean changes between AVG and NAVG groups, Cohen's d was = 0.9.

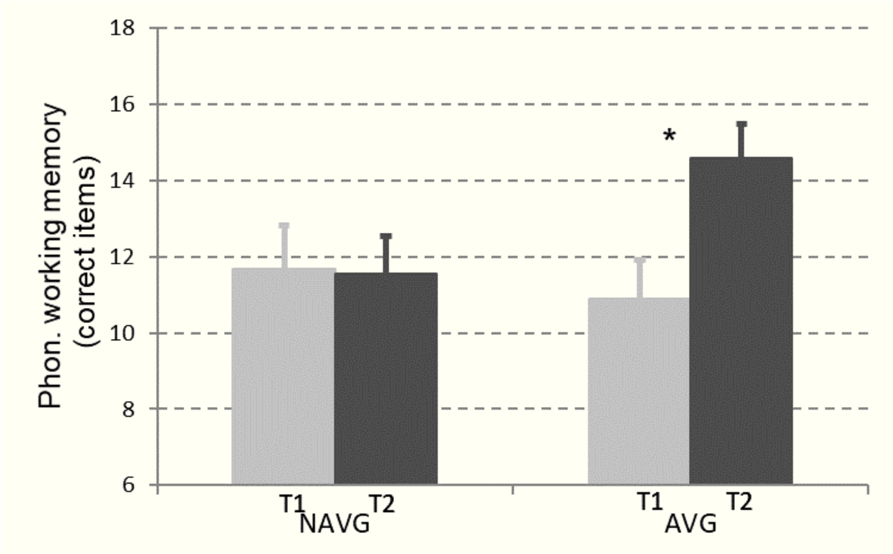

Figure 20: Significant improvement in auditory-phonological working memory was observed only after Action Video-Game (AVG) training. Error bars represent standard errors.

Visual, auditory and audio-visual processing. The inefficiency index (speed to accuracy ratio, i.e., msec./accuracy rate) in the localization of auditory, visual and audio-visual stimuli, was analyzed to measure the effect of the two different trainings on the unisensory and multisensory processing. The inefficiency index was analyzed using two mixed ANCOVAs with 2 (time: pre vs. post) × 2 (intervention group: AVG and NAVG) design.

In both the unisensory and multisensory ANCOVAs no main effect or interaction were significant. The planned comparisons with age as a covariate for both Unisensory and Multisensory modalities indicate that only AVG training can improve both Unisensory and Multisensory processing (AVG mean T1= 762.20, SE= 60.16; mean T2= 597.93, SE= 24.64, p=.004; and mean T1= 511.63, SE= 31.07; mean T2= 448.232, SE= 24.85, p=.011; vs. NAVG mean T1= 683.80, SE= 69.98; mean T2= 592.55, SE= 28.67, p=.148; and mean T1= 474.20, SE= 36.14; mean T2= 472.02, SE= 28.90, p=.936; respectively).

Cross-sensory attentional shifting. Similarly to Harrar and colleagues's analysis (2014), we calculated unisensory accurate reaction times (RTs) for each child both, when the previous stimulus was the same (e.g., two successive visual trials) and when it was different (e.g., a visual trial followed by an auditory trial). Visual (i.e. from auditory to visual) and auditory (i.e. from visual to auditory) shift costs were calculated by computing the difference between RTs on consecutive trials with the same target, and

RTs when the previous trial was different. Cross-sensory shift costs were analyzed using a mixed 2 (time: pre vs. post) × 2 (target modalities: visual-to-auditory vs. auditory-to-visual) × 2 (intervention group: AVG and NAVG) ANCOVA. To exclude that differences in educational experience and pre-training cross-sensory attentional shifting abilities could drive the observed results, chronological age as well as attentional shift performance in T1 were controlled by entering them as covariates. The three-way time × target modality × intervention group interaction was significant when the cross-sensory attentional shifting was measured as shift costs ($F(1,23) = 8.923$, $p = 0.007$, $\eta 2 = 0.280$).

For each group a mixed ANOVA with a 2 times (time: pre vs. post) × 2 (target modalities: visual-to-auditory vs. auditory-to-visual) design was performed. The time × target modality interaction was significant only in the AVG group ($F(1,15) = 4.782$, $p = 0.045$, $\eta 2 = 0.242$). Within-subject planned comparisons showed that only the visual-to-auditory shift cost was significantly reduced after the AVG training (pre-training mean = 115 msec., SE = 41.90 and post-training mean = 24 msec., SE = 28.57; $t(15) = 1.765$, $p = 0.049$, Cohen's $d = 0.65$; see Figure 21), indicating that AVG training improved the attentional shifting from visual to auditory modality. Comparing the mean changes between AVG and NAVG groups, Cohen's d was = 0.47.

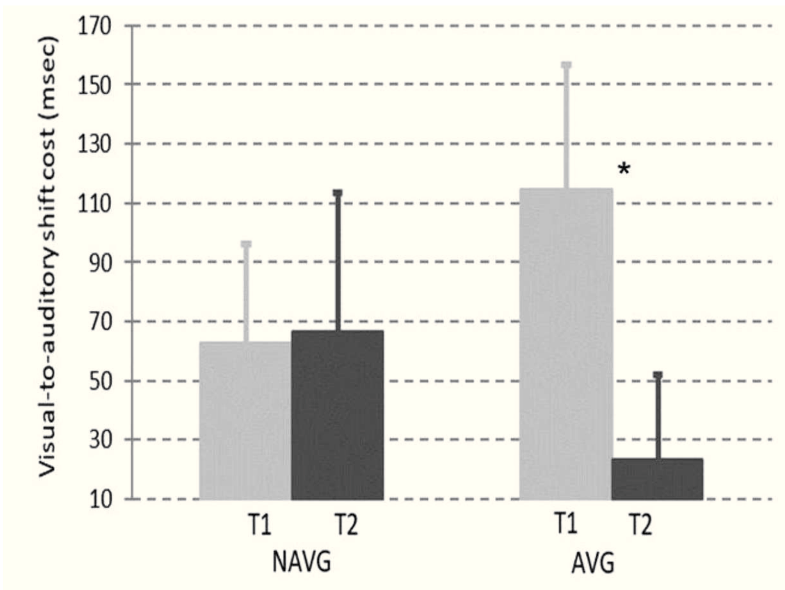

Figure 21: Visual to auditory shift cost (in msec) significantly decreased only after AVG training. Error bars represent standard errors.

Discussion:

The results of Experiment 8 show that the AVG training improve reading and attentional skills not only in transparent orthography (i.e., Italian) but also in a deep orthography (i.e., English). This result is possible because AVG training trains general-domain skills as spatial attention. In this study, there is an important cross-modal effect of the AVG training, because children with DD improve also auditory skills measured by phonological working memory and by the ability to shift the attention from visual to auditory sensory modality.

2.3.6 Experiment 9: The effect of AVG training on visual and auditory attentional noise exclusion.

Participants:

Participants were fourteen children (4 female and 10 male; mean age = 8.93 years, SD = .99) with DD. The participants were tested before and after an AVG and a NAVG training. This experiment was run as a cross-over study in which each participant was treated both with AVG and NAVG (2 children did not participate in the NAVG training) in counterbalance order. As in the above intervention studies, information about video game experience was collected during interviews with parents during pre-informative briefing about the experimental training. Children with DD did not know the aim of the training and in the previous six months did not play AVG for more than 1 hour per month. The attentional and reading performance of the participants were evaluated before (T1) and after (T2 and T3) the two different video game trainings.
Each child was individually treated by playing the commercial Wii ™ video game for a total of 24 hours (i.e., 12 hours with AVG and 12 hours with NAVG). The single minigames were selected to create the AVG and NAVG trainings (Franceschini et al., 2013; Gori et al., 2016).

Visual attentional noise exclusion task (i.e., Visual Search):

The experimental procedure and data acquisition were controlled with E-prime 2.0 (Psychology Software, Inc.) Participants were seated 60 cm away from the screen. The children' task were to indicate the presence or absence of the target ignoring the distractors with a button press (Y or B on a keyboard respectively). The stimuli (little puppets) were shown at two eccentricities: at 4.30° and 9.07° around of the center of the screen. To control that children were focused at the centre of the screen, the target was shown at the center in eight trials. The target and distractors were similar for color but they differed for the shape. After a small cross (0.1° and 0.6 cd/m2) appeared at the center of the screen for 500 msec, target and distractors (both of 2.86°×3.82°) were shown for 2000 msec. The task was composed by four different display size conditions (2, 4, 8 or 12 distractors and the presence or absence of the target). A total amount of 208 trials were presented (see Figure 22).

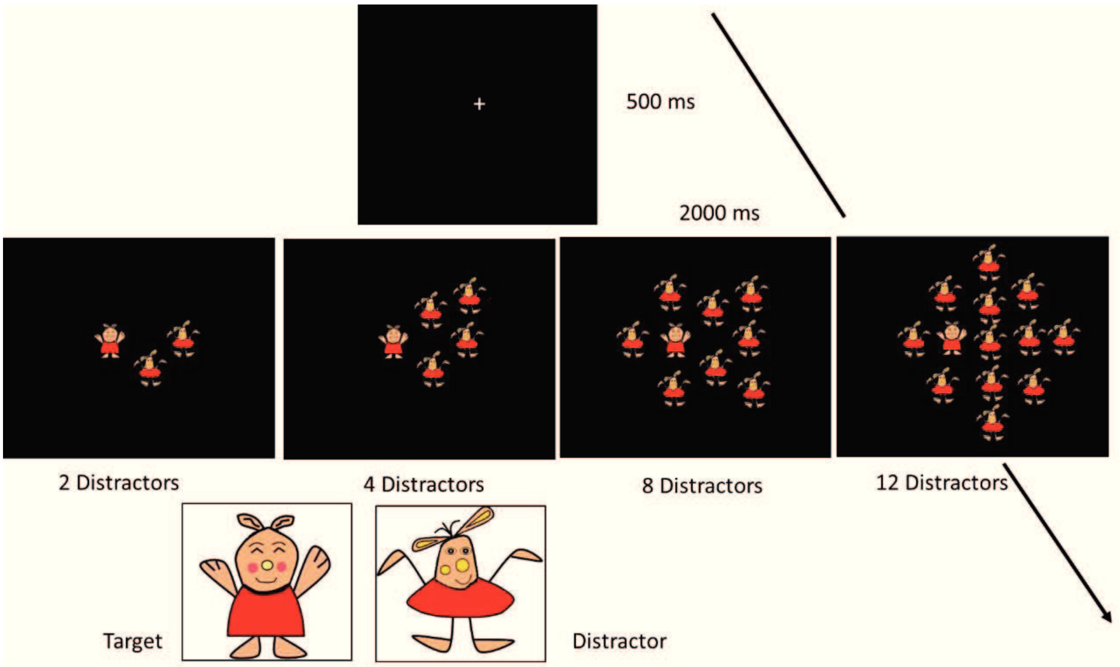

Figure 22: Visual attentional noise exclusion task (i.e., visual search).

Auditory attentional noise exclusion task:

The experimental procedure and data acquisition were controlled with E-prime 2.0 (Psychology Software, Inc.) Participants were seated 60 cm away from the screen. The task was similar to Green, Pouget & Bavelier (2010). A small cross (0.1° and 0.6 cd/m2) appeared at the center of the screen for the total duration of the trial. A pure tone embedded in a white noise mask was presented in one ear, while white noise alone was presented in the other by headphones. The auditory stimuli were presented for 2500 msec. The children' task were to indicate with a button press on a keyboard the ear in which the tone was present (Z for the left and M for the right) as quickly and accurately as possible. The auditory stimuli were created with Audacity 2.3.0 version.

The signal-to-noise ratio amplitude was manipulated in order to test accuracy and reaction times at different level of difficulty. In particular, there were ten signal-to-noise ratio conditions in which the -21 signal-to-noise ratio was the lowest tone amplitude and was the more difficult condition; while the +12 signal-to-noise ratio, was the highest tone amplitude and was the simplest condition. The other signal-to-noise ratio conditions were: -15, -12, -9, -6, -3, +3, +6, +9.

Reading tasks:

The pseudowords reading tasks were the same as those used in Experiment 5.

Training procedure:

The training procedure was the same as that used in the Experiment 5.

Results:

The reaction times (in msec) and accuracy (in rate) in the visual attentional noise exclusion task (Figure 22) were analyzed by two mixed ANOVAs with a 2 times (T1 = before and T2 = after) × 2 conditions (target present and target absent) × 4 display size (number of distractor) design for each training (AVG and NAVG).

In the ANOVA of reaction times in the AVG training the main effects of display size ($F(1,13) = 138.11$, $p = 0.0001$, $\eta2 = 0.914$) was significant. Crucially for our hypothesis, time × display size interaction was also significant ($F(1,13) = 5.56$, $p = 0.035$, $\eta2 = 0.30$). Planned comparison showed that the response times reduction was present in the more difficult display size condition (12 distractors: $t(13)= 2.192$, $p= 0.047$; T1 mean= 1222 SD= 170; T2 mean= 1106 SD= 157; see Figure 23A). In the ANOVA of reaction times in the NAVG training only the main effect of display size ($F(1,11) = 118.99$, $p = 0.0001$, $\eta2 = 0.915$) was significant.

In the ANOVA of accuracy in the AVG training, main effects of time ($F(1,13) = 7.25$, $p = 0.018$, $\eta2 = 0.358$) and display size ($F(1,13) = 9.75$, $p = 0.008$, $\eta2 = 0.429$) were significant. Crucially for our hypothesis, time × display size interaction was also significant ($F(1,13) = 4.68$, $p = 0.048$, $\eta2 = 0.265$). Planned comparison showed that the AVG training nullify the display size effect measured as the accuracy difference between the smaller (i.e., 2 distractors) and the larger (i.e., 12 distractors) display size conditions (T1: $t(13)= 3.941$, $p= 0.002$; 2 distractors: mean=.87 SD= .08; 12 distractors: mean= .79 SD= .09; T2: $t(13)= 1.418$, $p= 0.18$; 2 distractors: mean=.89 SD= .07; 12 distractors: mean= .85 SD= .08). Moreover, planned comparison showed that the accuracy improvement was present in the more difficult display size conditions (8 distractors: $t(13)= 3.312$, $p= 0.006$; T1 mean=.82 SD= .09; T2 mean= .88 SD= .07; 12 distractors: $t(13)= 2.877$, $p= 0.013$; T1 mean=.79 SD= .09; T2 mean= .85 SD= .08; see Figure 23B).

In the ANOVA of accuracy in the NAVG training only the main effect of the display size was significant (F(1,11) = 13.99, p = 0.003, η2 = 0.56).

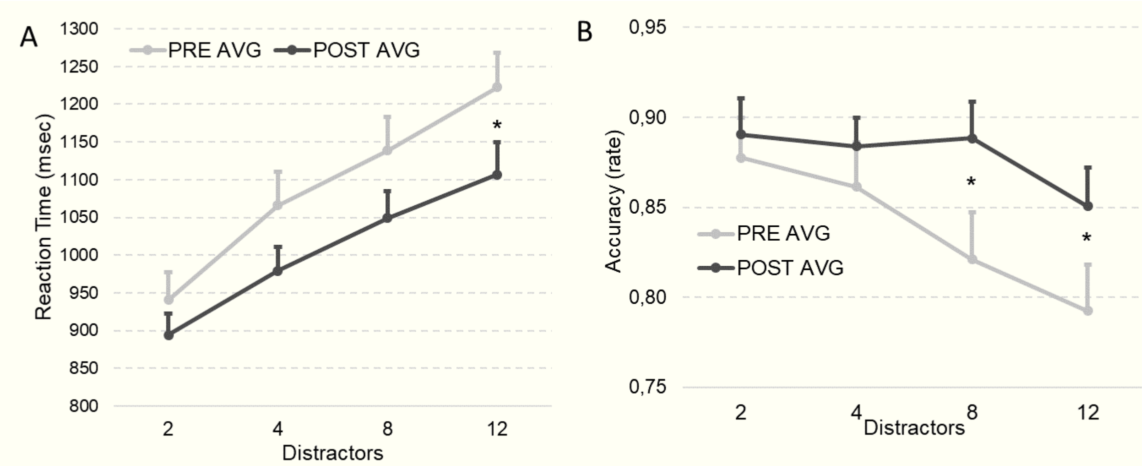

Figure 23: A: Reaction time (in msec) in visual attentional noise exclusion task before (PRE AVG) and after (POST AVG) Action Video-Game training. B: Accuracy in visual attentional noise exclusion task before (PRE AVG) and after (POST AVG) Action Video-Game training.

The response times (in msec) and the accuracy in the auditory attentional noise exclusion task were analyzed by two mixed ANOVAs with a 2 times (T1 = before and T2 = after) × 2 ear location (right and left ears) × 10 signal-to-noise ratio (-21, -15, -12, -9, -6, -3, 3. 6, 9, 12) design for each training (AVG and NAVG).

In the ANOVA of response times in the AVG training the main effects of time (F(1,13)= 7.136, p= 0.019, η2= 0.354), ear location (F(1,13)= 7.005, p= 0.020, η2= 0.35) and signal-to-noise ratio (F(9,117) = 32.354, p = 0.0001, η2 = 0.713) were significant. Crucially for our hypothesis time × ear location × signal-to-noise ratio was significant (F(9,117) = 4.280, p = 0.0001, η2 = 0.248). To better understand this interaction was run an ANOVA for the extreme signal-to-noise ratio value: -21 and -15 as the more difficult conditions, and +9 and +12 as the easier conditions. In the ANOVAs of more difficult conditions (i.e., -21 and -15), time × ear location were significant (F(1,13)= 5.915, p= 0.03, η2= 0.313; F(1,13)= 7.637, p= 0.016, η2= 0.37, respectively). These results showed that, after AVG training there was a greater reaction time reduction in the more difficult conditions of signal-to-noise ratio at the left ear (-21: t(13)= 2.182, p= 0.048; T1 mean=1672 SD= 362; T2 mean= 1361 SD= 345; -15: t(13)= 2.607, p= 0.022; T1 mean=1639 SD= 370; T2 mean= 1341 SD= 335; Figure 24A).

Conversely, in the ANOVAs of easier conditions (i.e., +9 and +12), time × ear location was not significant (p> .51; Figure 24B).

In the ANOVA of response times in the NAVG training only the main effect of signal-to-noise ratio (F(9,99)= 26.488, p= 0.0001, η2= 0.707) was significant.

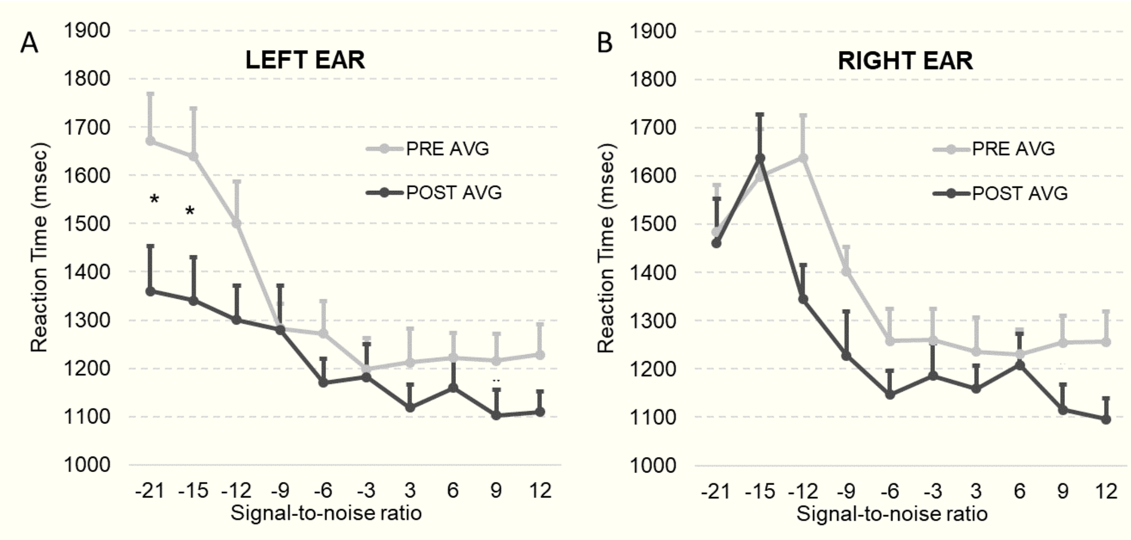

Figure 24: A: Reaction time (in msec) in auditory attentional noise exclusion task at the left ear before (PRE AVG) and after (POST AVG) Action Video-Game training. B: Reaction time (in msec) in auditory attentional noise exclusion task at the right ear before (PRE AVG) and after (POST AVG) Action Video-Game training.

In the ANOVA of accuracy in the AVG training only the main effect of signal-to-noise ratio was significant (F(9,117)= 57.85, p= 0.0001, η2= 0.817). In the same ANOVA in the NAVG training the signal-to-noise ratio (F(9,99)= 32.834, p= 0.0001, η2= 0.749) was significant.

Reading speed (syllables per second) improvement was evaluated in AVG and NAVG training by two separate ANOVAs 2 times (T1 = before and T2 = after) × 2 tasks (pseudowords lists and pseudowords texts). Results showed a significant main effect of time (F(1,13) = 8.982, p = 0.010 η2 = 0.409; T1 mean = .95 SD = 0.23, T2 mean = 1.06, SD = 0.31) only in the AVG training (NAVG time effect F(1,11) = 1.558, p = 0.238 η2 = 0.124 T1 mean = 1.07 SD = 0.31; T2 mean = 1.11, SD = 0.34). The same ANOVAs considering as dependent variable the number of errors, did not show any significant effect both in AVG and NAVG trainings (all ps> .67). The reading improvements after the AVG training were characterized by the increased reading speed without any cost in accuracy (Gori et al., 2016; Franceschini et al., 2013, see for a review Peters, De Losa, Bavin & Crewther, 2019).

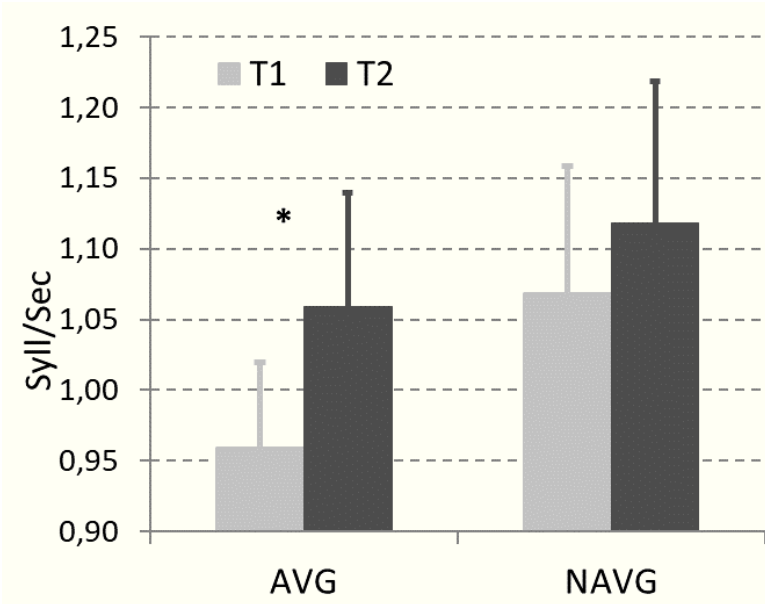

Figure 25: Reading speed (syll/sec) in pseudoword tasks before (T1) and after (T2) action video game (AVG) or non-action video game (NAVG) training.

Discussion:

The results of Experiment 9 show that AVG training improve the ability to extract the information when it is presented in a noise contest. In particular, children with DD after an AVG training improve not only the reading speed, but also the ability to detect the target in both visual and auditory attentional noise exclusion task.

The results of Experiment 8 and 9 show that AVG training that is a visual training, produce croos-modal effect improving visual and auditory attention.

3. Discussion

In this thesis, the attentional mechanisms guided by MD pathway, were analysed, with different tasks and different experimental studies design, in children with and without DD to understand the possible causal relationship between MD pathway dysfunction and reading impairment.

In Experiment 1a, the typical global before local perception in an unselected group of children with DD and in TR of primary school was studied. In comparison with TR, children with DD showed no interference from the global information during the rapid naming in the local task. In contrast to TR performance, children with DD presented a larger interference of the local incongruent feature during the rapid naming in the global perception task. This result is a first demonstration that children with DD present a local before global perception.

In Experiment 1b a new group of children with DD and a new group of TR were tested by a computerized Navon task. This Navon task did not involve the presence of more than one target at a time, reducing the possible role of perceptual load and serial attentional processing dysfunctions (Zorzi et al., 2012; Franceschini et al., 2012; 2013). In addition, there was no involvement of speech sound processing in response measurement, excluding the influence of other neurocognitive functions known to be predictive of future reading abilities (Goswami, 2015; Franceschini et al., 2012). Contrary to the typical global before local perception found in TR (Navon, 1977), children with DD showed greater local interference in the global task in comparison to the global interference during the local task. Moreover, children with DD showed a greater local interference effect than the TR in the global incongruent condition, confirming that they present a local before global perception even when possible perceptual, attentional and linguistic effects were excluded.

In Experiment 2a, 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, Benso, Facoetti, Galfano, Mascetti & Umiltà, 2000; Facoetti & Molteni, 2000; Ronconi, Basso, Gori & Facoetti, 2012, Ronconi, Franchin, Valenza, Gori & Facoetti, 2016, Ronconi, Devita, Molteni, Gori & Facoetti, 2018). Although Joo and colleagues (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 & Cavanagh, 2001; Strasburger, 2005; Yeshurun & Rashal, 2010; Grubb et al., 2013, Huckauf & Heller, 2002; Scolari et al., 2007; Franceschini et al., 2012, but Nazir, 1992; Wilkinson et al., 1997). The main aim of Experiment 2a 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 2a confirm several studies showing an excessive crowding in children with DD (Geiger & 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).

These results are confirmed in the Experiment 2b, in which was investigated 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 2b, children with and without DD were tested with extra-small and extra-large spacing texts similarly to Zorzi and colleagues (2012) and Joo and colleagues (2018). As in Schneps and colleagues (2013), the number of syllables per line is the same in two spacing conditions. The findings of Experiment 2b 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.

However, the case-control design used in these four Experiments was not enough to disentangle the causal relationship between the local before global perception, and the excessive crowding and reading difficulties (Goswami, 2015). The difference found in the visuo-attentional skills, indeed, could only be the effect of reduced reading experience typically associated to DD.

To investigate the possible causal link between attentional dysfunction and reading skills in Experiment 3 and 4 were run two longitudinal studies, and in Experiment 5 and 6 were run two intervention studies.

In Experiment 3 and 4, the global and local perception and crowding were longitudinally investigated in two large cohort of pre-literate children and their reading development was observed during the next year of the primary school. The results of Experiment 3 show that future PRs were characterized by a local before global perception at pre-reading stage. Moreover, independently of our a priori group classification of reading disorder, pre-reading global before local perception was able to predict future efficient reading skills in grade 1 even when chronological age, IQ, visual-to-phonological mapping and pure phonological skills were controlled for. In sum, the global visual perception of preliterate children was linked to reading abilities one year after the first evaluation, demonstrating a causal connection between global before local perception and reading emergency and development. Similarly to the group of children with DD of Experiment 1a and 1b, the future PR children showed visual perceptual skills that seem to proceed without an initial automatic and unskippable global processing (Bosse et al., 2007; Navon, 1977; Hochstein & Ahissar, 2002; Corbetta et al., 2008; Grainger et al., 2016). This lack of a global perception bias leads to a facilitation in local features extraction (Navon, 1977; Hochstein & Ahissar, 2002). In children with DD and future PRs the local relevant incongruent information appears perceived simultaneously or before the salient global configuration of the visual scene (Corbetta et al., 2008).

The results of Experiment 4 show that 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.

In Experiment 5 and 6, the global and local perception and crowding were investigated in a sample of children with DD, before and after an AVG or a NAVG (Gori et al. 2016; Franceschini et al., 2013; Green & Bavelier, 2003). As write above, AVGs share an extraordinary emphasis on peripheral processing and global perception, speed in terms of multiple transient events and moving objects and a high degree of perceptual and motor load (Green & Bavelier, 2003; Kim et al., 2015; Dye et al., 2009; Franceschini et al., 2015). The findings of Experiment 5, demonstrate that only the AVG training was able to increase reading speed in children with DD (Gori et al., 2016; Franceschini et al., 2013; Franceschini et al., 2015) and only AVG training increased the global before local perception in the computerized Navon task. In particular, children with DD treated with 12 hours of AVG showed a significant decrease of local interference in the global task and a significant increase of global interference in the local task. A causal connection between local before global perception and reading disabilities is demonstrated, excluding any possible influence of visual-to-phonological access (Dehaene et al., 2015) and indirect phonological (Bradley & Bryant, 1983; Boets et al., 2013) or orthographic (Grainger et al., 2016) stimulation.

The findings of Experiment 6, demonstrate that only 12 hours 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, in contrast to the phonological interventions that improve word accuracy and letter-sound knowledge, but not reading fluency (Peters at el., 2019). These results are consistent with a selective improvement in processing speed of grapheme-to-phoneme mapping previously found in some AVG training studies (e.g., Gori et al., 2016; Franceschini et al., 2013; Łuniewska, Chyl, Debska, Kacprzak, Plewko, Szczerbinski, Scewczyk, Grabowska & Jednorog et al., 2018; see for a review Peters et al., 2019; see for a discussion Vidyasagar, 2019).

To understand if each child can benefit from the AVG training in Experiment 7a and 7b have been analyzed the enhancement of the game scores during the training because it appears clear that a clinical treatment for DD that does not produce adequate improvements in the targeted skill, will not be able to produce any improvement in the reading skills.

The findings of Experiment 7a show that not all the children with DD obtained the same beneficial effects from commercial AVG trainings. Phonological decoding speed and phonological short-term memory were increased only in children with DD that improved their video game scores. Moreover, the findings of Experiment 7b confirm the crowding reduction only in children with DD that are able to efficiently perform the AVG training, improving their game scores. 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. The connection between the video game scores and the reading-related improvements could confirm the causal role of visual attentional skills trained by the AVG on the reading outcome (Franceschini et al., 2013, 2015). AVG training enhances the efficiency of visual processing, and the higher is the level of attentional plasticity showed by the acquisition of good gaming ability, the higher are also the chances to improve the reading speed and phonological short-term memory. In this apparently obvious result could be found a possible explanation of the high variability observed in the effectiveness of different behavioral trainings for DD remediation (e.g., McArthur et al., 2011; Galuschka et al., 2014).

The findings of Experiment 8 show an improvement in word reading and phonological decoding speed, without any cost in accuracy also in English-speaking children. These findings demonstrate that, even in a language with deep orthography, AVG training improves reading skills without a direct targeting of phonological, orthographic or grapheme-to-phoneme decoding. These results are in line with the improved speed of processing and reading speed already found with AVG (Dye et al., 2009), also in patients with amblyopia (Vedamurthy, Nahum, Huang, Zheng, Bayliss, Bavelier & Levi, 2015). Thus, in children with DD, AVG training enables an enhancement of processing speed and reading and increased phonological short-term memory and phoneme blending skills. Consequently, playing AVG may also improve the phonological working memory deficit usually associated with DD (Jorm, 1983). Indeed, no phonological information was presented during the training, therefore no direct training of phonological working memory was carried out.

These findings demonstrated that a visual attentional training could produce a general beneficial effect also on cognitive functions that were not directly trained by AVG, such as the auditory processing, and, consequently, phonological short term memory. Harrar and colleagues (2014) interpreted the multisensory integration deficit as a tendency to extend the time spent on visual stimuli when attention has to be shifted from visual to auditory stimuli. The findings of Experiment 8 in the cross-sensory attentional shifting analysis demonstrate that English-speaking children with DD treated with AVG specifically improve their cross-sensory attentional shifting ability from visual to auditory stimuli.

The cross-modal effect of the AVG is present also in the Experiment 9, in which the findings show an improvement in the reading speed, in the speed of auditory attentional noise exclusion, and in the speed and accuracy of visual attentional noise exclusion. In particular, the improvement in the speed of processing in the auditory attentional noise exclusion task, is greater for the stimuli in the more difficult signal-to-noise ratio conditions presented at the left ear, which is elaborated by right hemisphere.

These findings are compatible with behavioral, psychophysical, and neuroimaging studies demonstrating the possible role of a right dysfunction of the fronto-parietal network in children and adults with DD (Facoetti et al., 2001; Hari et al., 2001; Hoeft et al., 2006; 2011). Facoetti and colleagues (2001) showed an asymmetric distribution of visual spatial attention in children with DD. In the same vein, Hari and colleagues (2001) in a psychophysical study showed that adults with DD processed stimuli in the left visual hemifield significantly more slowly than TR, indicating a left-sided mini-neglect, possibly related with a deficit in the right fronto-parietal network. In addition, greater right prefrontal activation during a reading task and greater right superior longitudinal fasciculus white-matter organization significantly predicted future reading outcomes in a longitudinal study on children with DD (Hoeft et al., 2006). The greater functional activation and structural organization of the right fronto-parietal network could indicate a faster global perception of the stimuli (Van der Hallen et al., 2015) and consequently a greater improvement of reading skills in children with DD (Hoeft et al., 2006). Accordingly, a direct high frequency repetitive transcranial magnetic stimulation over the right parietal cortices improved phonological decoding in adults with DD (Costanzo, Menghini, Caltagirone, Oliveri & Vicari, 2013). A dysfunction in the right parietal network could impair the simultaneous processing that is responsible for poor reading outcomes (Bosse et al., 2007). TR activate parietal areas more strongly for multiple than single element processing. In contrast, the stronger right parietal areas activation for multiple elements processing was absent in participants with DD (Lobier, Peyrin, Pichat, Le Bas & Valdois, 2014).

These evidence led to hypothesize that a direct cognitive stimulation of the right global perception network by using a visuo-attentional training could improve attentional and reading skills, and that the variable manipulated during the training (i.e., the multi-sensory spatio-temporal attention; see Bediou et al., 2018 for a recent meta-analysis) is causally related to the reading skills.

The findings of these longitudinal and intervention studies show that DD is not only characterized by phonological deficits, as described by O'Brien and colleagues (2012) in which around 38 – 53% of children with DD do not present phonological deficits, and that the MD pathway dysfunction could be a cause of DD rather than an effect.

In summary, these nine Experiments reveal the presence of multiple and independent evidence about a causal link between MD pathway dysfunction and reading acquisition. In particular, the results suggest an impairment in MD pathway functioning because: (i) children with DD show a dysfunctional local before global perception, which is linked to an impairment in the processing of low spatial frequency driven by MD pathway; and (ii) the children with DD show an excessive crowding only in the unattended locations, that is the condition in which a good MD pathway functioning reduce crowding accelerating the rapid selection of attention (Omtzigt & Hendriks, 2004), improving the signal-noise exclusion. Subsequently, the findings of longitudinal studies show that this MD pathway dysfunction is already present at pre-reading stage (Gori et al., 2016), and that this attentional deficits are predictive of the future reading skills. The intervention studies show that with a visuo-attentional training (i.e., AVG), children with DD, improved their reading speed and their attentional skills linked to the MD pathway, underling that an efficient MD pathway functioning is essential during reading development. Importantly, the reading and attentional improvements are possible only in the children that are able to perform actively the AVG training.

It is important to underlie also the cross-modal effect of an AVG training that improve the multi-sensory perception and the signal-to-noise exclusion both in visual and auditory modality, especially in the right hemisphere, whose functional activation and structural organization drive a faster global perception of the stimuli.

References

American Psychiatric Association Diagnostic and statistical manual of mental disorders (DSM-5®) (2013), American Psychiatric Pub.

Antzaka, A., Lallier, M., Meyer, S., Diard, J., Carreiras, M., & Valdois, S. (2017). Enhancing reading performance through action video games: the role of visual attention span. *Scientific reports*, *7*(1), 14563.

Banfi, C., Kemény, F., Gangl, M., Schulte-Körne, G., Moll, K., & Landerl, K. (2017). Visuo-spatial cueing in children with differential reading and spelling profiles. *PloS one*, *12*(7), e0180358.

Bediou, B., Adams, D. M., Mayer, R. E., Tipton, E., Green, C. S., & Bavelier, D. (2018). Meta-analysis of action video game impact on perceptual, attentional, and cognitive skills. *Psychological bulletin*, *144*(1), 77.

Behrmann, M., Thomas, C., & Humphreys, K. (2006). Seeing it differently: visual processing in autism. *Trends in cognitive sciences*, *10*(6), 258-264.

Black, J. M., Xia, Z., & Hoeft, F. (2017). Neurobiological bases of reading disorder part II: The importance of developmental considerations in typical and atypical reading. *Language and linguistics compass*, *11*(10), e12252.

Blau, V., van Atteveldt, N., Ekkebus, M., Goebel, R., & Blomert, L. (2009). Reduced neural integration of letters and speech sounds links phonological and reading deficits in adult dyslexia. *Current Biology*, *19*(6), 503-508.

Boden, C., & Giaschi, D. (2007). M-stream deficits and reading-related visual processes in developmental dyslexia. *Psychological bulletin*, *133*(2), 346.

Boets, B., de Beeck, H. P. O., Vandermosten, M., Scott, S. K., Gillebert, C. R., Mantini, D., ... & Ghesquière, P. (2013). Intact but less accessible phonetic representations in adults with dyslexia. *Science*, *342*(6163), 1251-1254.

Boets, B., Vandermosten, M., Cornelissen, P., Wouters, J., & Ghesquière, P. (2011). Coherent motion sensitivity and reading development in the transition from prereading to reading stage. *Child development*, *82*(3), 854-869.

Boets, B., Wouters, J., Van Wieringen, A., De Smedt, B., & Ghesquiere, P. (2008). Modelling relations between sensory processing, speech perception, orthographic and phonological ability, and literacy achievement. *Brain and language*, *106*(1), 29-40.

Blomert, L. (2011). The neural signature of orthographic–phonological binding in successful and failing reading development. *Neuroimage*, *57*(3), 695-703

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

Bosse, M. L., & Valdois, S. (2009). Influence of the visual attention span on child reading performance: a cross- sectional study. *Journal of Research in Reading*, *32*(2), 230-253.

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature*, *226*(5241), 177.

Bradley, L., & Bryant, P. E. (1978). Difficulties in auditory organisation as a possible cause of reading backwardness. *Nature*, *271*(5647), 746.

Breznitz, Z., Shaul, S., Horowitz-Kraus, T., Sela, I., Nevat, M., & Karni, A. (2013). Enhanced reading by training with imposed time constraint in typical and dyslexic adults. *Nature communications*, *4*, 1486.

Buchholz, J., & Davies, A. A. (2007). Attentional blink deficits observed in dyslexia depend on task demands. *Vision Research*, *47*(10), 1292-1302.

Callens, M., Whitney, C., Tops, W., & Brysbaert, M. (2013). No deficiency in left-to-right processing of words in dyslexia but evidence for enhanced visual crowding. *The Quarterly Journal of Experimental Psychology*, *66*(9), 1803-1817.

Carroll, J. M., Solity, J., & Shapiro, L. R. (2016). Predicting dyslexia using prereading skills: the role of sensorimotor and cognitive abilities. *Journal of Child Psychology and Psychiatry*, *57*(6), 750-758.

Casco, C., Tressoldi, P. E., & Dellantonio, A. (1998). Visual selective attention and reading efficiency are related in children. *Cortex*, *34*(4), 531-546.

Castles, A., & Coltheart, M. (2004). Is there a causal link from phonological awareness to success in learning to read?. *Cognition*, *91*(1), 77-111.

Catts, H. W., McIlraith, A., Bridges, M. S., & Nielsen, D. C. (2017). Viewing a phonological deficit within a multifactorial model of dyslexia. *Reading and Writing*, *30*(3), 613-629.

Chen, J., He, Y., Zhu, Z., Zhou, T., Peng, Y., Zhang, X., & Fang, F. (2014). Attention-dependent early cortical suppression contributes to crowding. *Journal of Neuroscience*, *34*(32), 10465-10474.

Chicherov, V., Plomp, G., & Herzog, M. H. (2014). Neural correlates of visual crowding. *Neuroimage*, *93*, 23-31.

Corbetta, M., Patel, G., & Shulman, G. L. (2008). The reorienting system of the human brain: from environment to theory of mind. *Neuron*, *58*(3), 306-324.

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature reviews neuroscience*, *3*(3), 201.

Cornelissen, P. L., & Hansen, P. C. (1998). Motion detection, letter position encoding, and single word reading. *Annals of Dyslexia*, *48*(1), 155-188.

Costanzo, F., Menghini, D., Caltagirone, C., Oliveri, M., & Vicari, S. (2013). How to improve reading skills in dyslexics: the effect of high frequency rTMS. *Neuropsychologia*, *51*(14), 2953-2959.

De Schotten, M. T., Dell'Acqua, F., Forkel, S. J., Simmons, A., Vergani, F., Murphy, D. G., & Catani, M. (2011). A lateralized brain network for visuospatial attention. *Nature neuroscience*, *14*(10), 1245.

Dehaene, S., Cohen, L., Morais, J., & Kolinsky, R. (2015). Illiterate to literate: behavioural and cerebral changes induced by reading acquisition. *Nature Reviews Neuroscience*, *16*(4), 234.

Denckla, M. B., & Rudel, R. G. (1976). Rapid 'automatized'naming (RAN): Dyslexia differentiated from other learning disabilities. Neuropsychologia, 14(4), 471-479.

Dye, M. W., Green, C. S., & Bavelier, D. (2009). Increasing speed of processing with action video games. *Current directions in psychological science*, *18*(6), 321-326.

Ding, Y., Zhao, J., He, T., Tan, Y., Zheng, L., & Wang, Z. (2016). Selective impairments in covert shifts of attention in Chinese dyslexic children. *Dyslexia*, *22*(4), 362-378.

Dispaldro, M., Leonard, L. B., Corradi, N., Ruffino, M., Bronte, T., & Facoetti, A. (2013). Visual attentional engagement deficits in children with specific language impairment and their role in real-time language processing. *Cortex*, *49*(8), 2126-2139.

Doron, A., Manassi, M., Herzog, M. H., & Ahissar, M. (2015). Intact crowding and temporal masking in dyslexia. *Journal of Vision*, *15*(14), 13-13.

Dosenbach, N. U., Fair, D. A., Cohen, A. L., Schlaggar, B. L., & Petersen, S. E. (2008). A dual-networks architecture of top-down control. *Trends in cognitive sciences*, *12*(3), 99-105.

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*(6586), 66.

Facoetti, A., Corradi, N., Ruffino, M., Gori, S., & Zorzi, M. (2010a). Visual spatial attention and speech segmentation are both impaired in preschoolers at familial risk for developmental dyslexia. *Dyslexia*, *16*(3), 226-239.

Facoetti, A., Lorusso, M. L., Paganoni, P., Cattaneo, C., Galli, R., Umilta, C., & Mascetti, G. G. (2003). Auditory and visual automatic attention deficits in developmental dyslexia. *Cognitive brain research*, *16*(2), 185-191.

Facoetti, A., & Molteni, M. (2000). Is attentional focusing an inhibitory process at distractor location?. *Cognitive Brain Research*, *10*(1-2), 185-188.

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

Facoetti, A., Ruffino, M., Peru, A., Paganoni, P., & Chelazzi, L. (2008). Sluggish engagement and disengagement of non-spatial attention in dyslexic children. *cortex*, *44*(9), 1221-1233.

Facoetti, A., Turatto, M., Lorusso, M. L., & Mascetti, G. G. (2001). Orienting of visual attention in dyslexia: evidence for asymmetric hemispheric control of attention. *Experimental Brain Research*, *138*(1), 46-53.

Facoetti, A., Trussardi, A. N., Ruffino, M., Lorusso, M. L., Cattaneo, C., Galli, R., ... & Zorzi, M. (2010b). Multisensory spatial attention deficits are predictive of phonological decoding skills in developmental dyslexia. *Journal of cognitive neuroscience*, *22*(5), 1011-1025.

Facoetti, A., Trussardi, A. N., Ruffino, M., Lorusso, M. L., Cattaneo, C., Galli, R., ... & Zorzi, M. (2010). Multisensory spatial attention deficits are predictive of phonological decoding skills in developmental dyslexia. *Journal of cognitive neuroscience*, *22*(5), 1011-1025.

Farmer, M. E., & Klein, R. M. (1995). The evidence for a temporal processing deficit linked to dyslexia: A review. *Psychonomic bulletin & review*, *2*(4), 460-493.

Finn, E. S., Shen, X., Holahan, J. M., Scheinost, D., Lacadie, C., Papademetris, X., ... & Constable, R. T. (2014). Disruption of functional networks in dyslexia: a whole-brain, data-driven analysis of connectivity. *Biological psychiatry*, *76*(5), 397-404.

Fink, G. R., Halligan, P. W., Marshall, J. C., Frith, C. D., Frackowiak, R. S. J., & Dolan, R. J. (1996). Where in the brain does visual attention select the forest and the trees?. *Nature*, *382*(6592), 626.

Franceschini, S., Bertoni, S., Ronconi, L., Molteni, M., Gori, S., & Facoetti, A. (2015). “Shall we play a game?”: Improving reading through action video games in developmental dyslexia. *Current Developmental disorders reports*, *2*(4), 318-329.

Franceschini, S., Bertoni, S., Ronconi, L., Molteni, M., Gori, S., & Facoetti, A. (2016). Batteria De. Co. Ne. Per la lettura: Strumenti per la valutazione delle abilità di lettura nelle scuole primarie. *Dislessia*, *13*(3), 319-337.

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

Franceschini, S., Gori, S., Ruffino, M., Viola, S., Molteni, M., & Facoetti, A. (2013). Action video games make dyslexic children read better. *Current Biology*, *23*(6), 462-466.

Freeman, J., Chakravarthi, R., & Pelli, D. G. (2012). Substitution and pooling in crowding. *Attention, Perception, & Psychophysics*, *74*(2), 379-396.

Gabrieli, J. D. (2009). Dyslexia: a new synergy between education and cognitive neuroscience. *science*, *325*(5938), 280-283.

Geiger, G., Cattaneo, C., Galli, R., Pozzoli, U., Lorusso, M. L., Facoetti, A., & Molteni, M. (2008). Wide and diffuse perceptual modes characterize dyslexics in vision and audition. *Perception*, *37*(11), 1745-1764.

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

Geiger, G., Cattaneo, C., Galli, R., Pozzoli, U., Lorusso, M. L., Facoetti, A., & Molteni, M. (2008). Wide and diffuse perceptual modes characterize dyslexics in vision and audition. *Perception*, *37*(11), 1745-1764.

Giraldo-Chica, M., Hegarty II, J. P., & Schneider, K. A. (2015). Morphological differences in the lateral geniculate nucleus associated with dyslexia. *NeuroImage: Clinical*, *7*, 830-836.

Gliga, T., Bedford, R., Charman, T., Johnson, M. H., Baron-Cohen, S., Bolton, P., ... & Gammer, I. (2015). Enhanced visual search in infancy predicts emerging autism symptoms. *Current Biology*, *25*(13), 1727-1730.

Gori, S., Agrillo, C., Dadda, M., & Bisazza, A. (2014). Do fish perceive illusory motion?. *Scientific reports*, *4*, 6443.

Gori, S., Cecchini, P., Bigoni, A., Molteni, M., & Facoetti, A. (2014a). Magnocellular-dorsal pathway and sub-lexical route in developmental dyslexia. *Frontiers in human neuroscience*, *8*, 460.

Gori, S., & Facoetti, A. (2014b). Perceptual learning as a possible new approach for remediation and prevention of developmental dyslexia. *Vision research*, *99*, 78-87.

Gori, S., & Facoetti, A. (2015). How the visual aspects can be crucial in reading acquisition: The intriguing case of crowding and developmental dyslexia. *Journal of vision*, *15*(1), 8-8.

Gori, S., Giora, E., & Stubbs, D. A. (2010). Perceptual compromise between apparent and veridical motion indices: The Unchained-Dots illusion. *Perception*, *39*(6), 863-866.

Gori, S., Giora, E., Yazdanbakhsh, A., & Mingolla, E. (2011). A new motion illusion based on competition between two kinds of motion processing units: The Accordion Grating. *Neural networks*, *24*(10), 1082-1092.

Gori, S., & Hamburger, K. (2006). A new motion illusion: The Rotating-Tilted-Lines illusion. *Perception*, *35*(6), 853-857.

Gori, S., Mascheretti, S., Giora, E., Ronconi, L., Ruffino, M., Quadrelli, E., ... & Marino, C. (2014). The DCDC2 intron 2 deletion impairs illusory motion perception unveiling the selective role of magnocellular-dorsal stream in reading (dis) ability. *Cerebral Cortex*, *25*(6), 1685-1695.

Gori, S., Seitz, A. R., Ronconi, L., Franceschini, S., & Facoetti, A. (2016). Multiple causal links between magnocellular–dorsal pathway deficit and developmental dyslexia. *Cerebral Cortex*, *26*(11), 4356-4369.

Gori, S., & Yazdanbakhsh, A. (2008). The riddle of the Rotating-Tilted-Lines illusion. *Perception*, *37*(4), 631-635.

Goswami, U. (2003). Why theories about developmental dyslexia require developmental designs. *Trends in cognitive sciences*, *7*(12), 534-540.

Grainger, J., Dufau, S., & Ziegler, J. C. (2016). A vision of reading. *Trends in Cognitive Sciences*, *20*(3), 171-179.

Grainger, J., Bertrand, D., Lété, B., Beyersmann, E., & Ziegler, J. C. (2016). A developmental investigation of the first-letter advantage. *Journal of Experimental Child Psychology*, *152*, 161-172.

Green, C. S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature*, *423*(6939), 534.

Green, C. S., & Bavelier, D. (2012). Learning, attentional control, and action video games. *Current biology*, *22*(6), R197-R206.

Green, C. S., Li, R., & Bavelier, D. (2010). Perceptual learning during action video game playing. *Topics in cognitive science*, *2*(2), 202-216.

Green, C. S., Pouget, A., & Bavelier, D. (2010). Improved probabilistic inference as a general learning mechanism with action video games. *Current biology*, *20*(17), 1573-1579.

Greenwood, J. A., Bex, P. J., & Dakin, S. C. (2012). Crowding follows the binding of relative position and orientation. *Journal of vision*, *12*(3), 18-18.

Grinter, E. J., Maybery, M. T., & Badcock, D. R. (2010). Vision in developmental disorders: is there a dorsal stream deficit?. *Brain research bulletin*, *82*(3-4), 147-160.

Grubb, M. A., Behrmann, M., Egan, R., Minshew, N. J., Heeger, D. J., & Carrasco, M. (2013). Exogenous spatial attention: Evidence for intact functioning in adults with autism spectrum disorder. *Journal of vision*, *13*(14), 9-9.

Hancock, R., Pugh, K. R., & Hoeft, F. (2017). Neural noise hypothesis of developmental dyslexia. *Trends in cognitive sciences*, *21*(6), 434-448.

Hari, R., & Renvall, H. (2001). Impaired processing of rapid stimulus sequences in dyslexia. *Trends in cognitive sciences*, *5*(12), 525-532.

Harrar, V., Tammam, J., Pérez-Bellido, A., Pitt, A., Stein, J., & Spence, C. (2014). Multisensory integration and attention in developmental dyslexia. *Current Biology*, *24*(5), 531-535.

He, S., Cavanagh, P., & Intriligator, J. (1996). Attentional resolution and the locus of visual awareness. *Nature*, *383*(6598), 334.

Hochstein, S., & Ahissar, M. (2002). View from the top: Hierarchies and reverse hierarchies in the visual system. *Neuron*, *36*(5), 791-804.

Hoeft, F., Hernandez, A., McMillon, G., Taylor-Hill, H., Martindale, J. L., Meyler, A., ... & Whitfield-Gabrieli, S. (2006). Neural basis of dyslexia: a comparison between dyslexic and nondyslexic children equated for reading ability. *Journal of Neuroscience*, *26*(42), 10700-10708.

Hoeft, F., McCandliss, B. D., Black, J. M., Gantman, A., Zakerani, N., Hulme, C., ... & Gabrieli, J. D. (2011). Neural systems predicting long-term outcome in dyslexia. *Proceedings of the National Academy of Sciences*, *108*(1), 361-366.

Hornickel, J., & Kraus, N. (2013). Unstable representation of sound: a biological marker of dyslexia. *Journal of Neuroscience*, *33*(8), 3500-3504.

Huckauf, A., & Heller, D. (2002). Spatial selection in peripheral letter recognition: In search of boundary conditions. *Acta Psychologica*, *111*(1), 101-123.

Hughes, H. C., Nozawa, G., & Kitterle, F. (1996). Global precedence, spatial frequency channels, and the statistics of natural images. *Journal of cognitive neuroscience*, *8*(3), 197-230.

Hulme, C., Hatcher, P. J., Nation, K., Brown, A., Adams, J., & Stuart, G. (2002). Phoneme awareness is a better predictor of early reading skill than onset-rime awareness. *Journal of experimental child psychology*, *82*(1), 2-28.

Iles, J., Walsh, V., & Richardson, A. (2000). Visual search performance in dyslexia. *Dyslexia*, *6*(3), 163-177.

Joo, S. J., White, A. L., Strodtman, D. J., & Yeatman, J. D. (2018). Optimizing text for an individual's visual system: The contribution of visual crowding to reading difficulties. *Cortex*, *103*, 291-301.

Jorm, A. F. (1983). Specific reading retardation and working memory: A review. *British journal of Psychology*, *74*(3), 311-342.

Lobier, M. A., Peyrin, C., Pichat, C., Le Bas, J. F., & Valdois, S. (2014). Visual processing of multiple elements in the dyslexic brain: evidence for a superior parietal dysfunction. *Frontiers in human neuroscience*, *8*, 479.

Kevan, A., & Pammer, K. (2008). Visual deficits in pre-readers at familial risk for dyslexia. *Vision research*, *48*(28), 2835-2839.

Kevan, A., & Pammer, K. (2009). Predicting early reading skills from pre-reading measures of dorsal stream functioning. *Neuropsychologia*, *47*(14), 3174-3181.

Kim, Y. H., Kang, D. W., Kim, D., Kim, H. J., Sasaki, Y., & Watanabe, T. (2015). Real-time strategy video game experience and visual perceptual learning. *Journal of Neuroscience*, *35*(29), 10485-10492.

Koyama, M. S., Di Martino, A., Kelly, C., Jutagir, D. R., Sunshine, J., Schwartz, S. J., ... & Milham, M. P. (2013). Cortical signatures of dyslexia and remediation: an intrinsic functional connectivity approach. *PloS one*, *8*(2), e55454.

Krause, M. B. (2015). Pay Attention!: sluggish multisensory attentional shifting as a core deficit in developmental dyslexia. *Dyslexia*, *21*(4), 285-303.

Lallier, M., Tainturier, M. J., Dering, B., Donnadieu, S., Valdois, S., & Thierry, G. (2010). Behavioral and ERP evidence for amodal sluggish attentional shifting in developmental dyslexia. *Neuropsychologia*, *48*(14), 4125-4135.

Lallier, M., Thierry, G., Tainturier, M. J., Donnadieu, S., Peyrin, C., Billard, C., & Valdois, S. (2009). Auditory and visual stream segregation in children and adults: An assessment of the amodality assumption of the 'sluggish attentional shifting'theory of dyslexia. *Brain research*, *1302*, 132-147.

Lawton, T. (2016). Improving dorsal stream function in dyslexics by training figure/ground motion discrimination improves attention, reading fluency, and working memory. *Frontiers in human neuroscience*, *10*, 397.

Livingstone, M. S., & Hubel, D. H. (1987). Psychophysical evidence for separate channels for the perception of form, color, movement, and depth. *Journal of Neuroscience*, *7*(11), 3416-3468.

Livingstone, M. S., Rosen, G. D., Drislane, F. W., & Galaburda, A. M. (1991). Physiological and anatomical evidence for a magnocellular defect in developmental dyslexia. *Proceedings of the National Academy of Sciences*, *88*(18), 7943-7947.

Liu, D., Chen, X., & Chung, K. K. (2015). Performance in a visual search task uniquely predicts reading abilities in third-grade Hong Kong Chinese children. *Scientific Studies of Reading*, *19*(4), 307-324.

Liu, D., Chen, X., & Wang, Y. (2016). The impact of visual-spatial attention on reading and spelling in Chinese children. *Reading and Writing*, *29*(7), 1435-1447.

Łuniewska, M., Chyl, K., Dębska, A., Kacprzak, A., Plewko, J., Szczerbiński, M., ... & Jednoróg, K. (2018). Neither action nor phonological video games make dyslexic children read better. *Sci. Rep.* 8, 549.

Marotta, L., Trasciani, M., & Vicari, S. (2004). Valutazione delle competenze metafonologiche–CMF. *Trento: Edizioni Erickson*.

Martelli, M., Di Filippo, G., Spinelli, D., & Zoccolotti, P. (2009). Crowding, reading, and developmental dyslexia. *Journal of vision*, *9*(4), 14-14.

Maunsell, J. H., & Newsome, W. T. (1987). Visual processing in monkey extrastriate cortex. *Annual review of neuroscience*, *10*(1), 363-401.

McArthur, G., Eve, P. M., Jones, K., Banales, E., Kohnen, S., Anandakumar, T., ... & Castles, A. (2012). Phonics training for English- speaking poor readers. *Cochrane Database of Systematic Reviews*, (12).

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: I. An account of basic findings. *Psychological review*, *88*(5), 375.

Merigan, W. H., & Maunsell, J. H. (1993). How parallel are the primate visual pathways?. *Annual review of neuroscience*, *16*(1), 369-402.

Millin, R., Arman, A. C., Chung, S. T., & Tjan, B. S. (2013). Visual crowding in V1. *Cerebral Cortex*, *24*(12), 3107-3115.

Moll, K., & Jones, M. (2013). Naming fluency in dyslexic and nondyslexic readers: Differential effects of visual crowding in foveal, parafoveal, and peripheral vision. *The Quarterly Journal of Experimental Psychology*, *66*(11), 2085-2091.

Moores, E., Cassim, R., & Talcott, J. B. (2011). Adults with dyslexia exhibit large effects of crowding, increased dependence on cues, and detrimental effects of distractors in visual search tasks. *Neuropsychologia*, *49*(14), 3881-3890.

Morrone, M. C., Tosetti, M., Montanaro, D., Fiorentini, A., Cioni, G., & Burr, D. C. (2000). A cortical area that responds specifically to optic flow, revealed by fMRI. *Nature neuroscience*, *3*(12), 1322.

Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive psychology*, *9*(3), 353-383.

Nazir, T. A. (1992). Effects of lateral masking and spatial precueing on gap-resolution in central and peripheral vision. *Vision research*, *32*(4), 771-777.

O'Brien, B. A., Wolf, M., & Lovett, M. W. (2012). A taxometric investigation of developmental dyslexia subtypes. *Dyslexia*, *18*(1), 16-39.

Omtzigt, D., & Hendriks, A. W. (2004). Magnocellular involvement in flanked-letter identification relates to the allocation of attention. *Vision Research*, *44*(16), 1927-1940.

Omtzigt, D., Hendriks, A. W., & Kolk, H. H. (2002). Evidence for magnocellular involvement in the identification of flanked letters. *Neuropsychologia*, *40*(12), 1881-1890.

Pelli, D. G. (2008). Crowding: A cortical constraint on object recognition. *Current opinion in neurobiology*, *18*(4), 445-451.

Pelli, D. G., Farell, B., & Moore, D. C. (2003). The remarkable inefficiency of word recognition. *Nature*, *423*(6941), 752.

Pelli, D. G., & Tillman, K. A. (2008). The uncrowded window of object recognition. *Nature neuroscience*, *11*(10), 1129.

Perfetti, C. A. (1985). *Reading ability*. Oxford University Press.

Perry, C., Ziegler, J. C., & Zorzi, M. (2007). Nested incremental modeling in the development of computational theories: the CDP+ model of reading aloud. *Psychological review*, *114*(2), 273.

Peters, J. L., De Losa, L., Bavin, E. L., & Crewther, S. G. (2019). Efficacy of dynamic visuo-attentional interventions for reading in dyslexic and neurotypical children: A systematic review. *Neuroscience & Biobehavioral Reviews*, *100,* 58-76.

Peterson, R. L., & Pennington, B. F. (2015). Developmental dyslexia. *Annual review of clinical psychology*, *11*, 283-307.

Ronconi, L., Basso, D., Gori, S., & Facoetti, A. (2012). TMS on right frontal eye fields induces an inflexible focus of attention. *Cereb. Cortex,* 24, 396-402.

Ronconi, L., Bertoni, S., & Marotti, R. B. (2016). The neural origins of visual crowding as revealed by event-related potentials and oscillatory dynamics. *Cortex*, *79*, 87-98.

Ronconi, L., Devita, M., Molteni, M., Gori, S., & Facoetti, A. (2018). When Large Becomes Slow: Zooming-Out Visual Attention Is Associated to Orienting Deficits in Autism. *J. Autism Dev. Disord,* 48, 2577-2584.

Ronconi, L., Franchin, L., Valenza, E., Gori, S., & Facoetti, A. (2016). The attentional 'zoom- lens' in 8- month- old infants. *Dev. Sci*. 19, 145-154.

Ronconi, L., & Marotti, R. B. (2017). Awareness in the crowd: Beta power and alpha phase of prestimulus oscillations predict object discrimination in visual crowding. *Consciousness and cognition*, *54*, 36-46.

Rosenholtz, R. (2016). Capabilities and limitations of peripheral vision. *Annual Review of Vision Science*, *2*, 437-457.

Ruzzoli, M., Gori, S., Pavan, A., Pirulli, C., Marzi, C. A., & Miniussi, C. (2011). The neural basis of the Enigma illusion: A transcranial magnetic stimulation study. *Neuropsychologia*, *49*(13), 3648-3655.

Sacchi, E., Mirchin, R., & Laszlo, S. (2018). An Event-Related Potential study of letter spacing during visual word recognition. *Brain research*, *1684*, 9-20.

Sartori, G., & Job, R. (2007). *DDE-2: Giunti OS Organizzazioni Speciali: batteria per la Valutazione della Dislessia e della Disortografia Evolutiva-2: manuale*. Giunti OS, Organizzazioni Speciali.

Schneps, M. H., Thomson, J. M., Sonnert, G., Pomplun, M., Chen, C., & Heffner-Wong, A. (2013). Shorter lines facilitate reading in those who struggle. *PloS one*, *8*(8), e71161.

Scolari, M., Kohnen, A., Barton, B., & Awh, E. (2007). Spatial attention, preview, and popout: Which factors influence critical spacing in crowded displays?. *Journal of Vision*, *7*(2), 7-7.

Sergent, J. (1982). The cerebral balance of power: Confrontation or cooperation?. *Journal of Experimental Psychology: Human Perception and Performance*, *8*(2), 253.

Share, D. L. (1995). Phonological recoding and self-teaching: Sine qua non of reading acquisition. *Cognition*, *55*(2), 151-218.

Song, Y., & Hakoda, Y. (2015). Lack of global precedence and global-to-local interference without local processing deficit: A robust finding in children with attention-deficit/hyperactivity disorder under different visual angles of the Navon task. *Neuropsychology*, *29*(6), 888.

Sperling, A. J., Lu, Z. L., Manis, F. R., & Seidenberg, M. S. (2005). Deficits in perceptual noise exclusion in developmental dyslexia. *Nature neuroscience*, *8*(7), 862.

Sperling, A. J., Lu, Z. L., Manis, F. R., & Seidenberg, M. S. (2006). Motion-perception deficits and reading impairment: it's the noise, not the motion. *Psychological Science*, *17*(12), 1047-1053.

Spinelli, D., De Luca, M., Judica, A., & Zoccolotti, P. (2002). Crowding effects on word identification in developmental dyslexia. *Cortex*, *38*(2), 179-200.

Stein, J. (2014). Dyslexia: the role of vision and visual attention. *Current developmental disorders reports*, *1*(4), 267-280.

Stein, J. (2018). The current status of the magnocellular theory of developmental dyslexia. *Neuropsychologia*.

Strasburger, H. (2005). Unfocussed spatial attention underlies the crowding effect in indirect form vision. *Journal of Vision*, *5*(11), 8-8.

Tallal, P. (2004). Improving language and literacy is a matter of time. *Nature Reviews Neuroscience*, *5*(9), 721.

Talsma, D., Senkowski, D., Soto-Faraco, S., & Woldorff, M. G. (2010). The multifaceted interplay between attention and multisensory integration. *Trends in cognitive sciences*, *14*(9), 400-410.

Turatto, M., Benso, F., Facoetti, A., Galfano, G., Mascetti, G. G., & Umiltà, C. (2000). Automatic and voluntary focusing of attention. *Perception & Psychophysics*, *62*(5), 935-952.

Valdois, S., Bosse, M. L., & Tainturier, M. J. (2004). The cognitive deficits responsible for developmental dyslexia: Review of evidence for a selective visual attentional disorder. *Dyslexia*, *10*(4), 339-363.

Van der Hallen, R., Evers, K., Brewaeys, K., Van den Noortgate, W., & Wagemans, J. (2015). Global processing takes time: A meta-analysis on local–global visual processing in ASD. *Psychological bulletin*, *141*(3), 549.

van Laarhoven, T., Keetels, M., Schakel, L., & Vroomen, J. (2018). Audio-visual speech in noise perception in dyslexia. *Developmental science*, *21*(1), e12504.

Vedamurthy, I., Nahum, M., Huang, S. J., Zheng, F., Bayliss, J., Bavelier, D., & Levi, D. M. (2015). A dichoptic custom-made action video game as a treatment for adult amblyopia. *Vision research*, *114*, 173-187.

Vidyasagar, T. R., & Pammer, K. (2010). Dyslexia: a deficit in visuo-spatial attention, not in phonological processing. *Trends in cognitive sciences*, *14*(2), 57-63.

Vidyasagar, T. R. (2019). Visual attention and neural oscillations in reading and dyslexia: are they possible targets for remediation?. *Neuropsychologia*.

Yashar, A., Chen, J., & Carrasco, M. (2015). Rapid and long-lasting reduction of crowding through training. *Journal of Vision*, *15*(10), 15-15.

Yazdanbakhsh, A., & Gori, S. (2011). Mathematical analysis of the accordion grating illusion: a differential geometry approach to introduce the 3D aperture problem. *Neural networks*, *24*(10), 1093-1101.

Yeshurun, Y., & Rashal, E. (2010). Precueing attention to the target location diminishes crowding and reduces the critical distance. *Journal of Vision*, *10*(10), 16-16.

Wallace, M. T., & Stevenson, R. A. (2014). The construct of the multisensory temporal binding window and its dysregulation in developmental disabilities. *Neuropsychologia*, *64*, 105-123.

Wechsler, D. (2002). Wechsler primary and preschool scale of intelligence. *San Antonio, TX: The Psychological Corporation*.

Whitney, D., & Levi, D. M. (2011). Visual crowding: A fundamental limit on conscious perception and object recognition. *Trends in cognitive sciences*, *15*(4), 160-168.

Wilkinson, F., Wilson, H. R., & Ellemberg, D. (1997). Lateral interactions in peripherally viewed texture arrays. *JOSA A*, *14*(9), 2057-2068.

Williams, J. P. (1984). Phonemic analysis and how it relates to reading. *Journal of Learning Disabilities*, *17*(4), 240-245.

Witton, C., Talcott, J. B., Hansen, P. C., Richardson, A. J., Griffiths, T. D., Rees, A., ... & Green, G. G. R. (1998). Sensitivity to dynamic auditory and visual stimuli predicts nonword reading ability in both dyslexic and normal readers. *Current biology*, *8*(14), 791-797.

Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: a psycholinguistic grain size theory. *Psychological bulletin*, *131*(1), 3.

Ziegler, J. C., Pech-Georgel, C., George, F., Alario, F. X., & Lorenzi, C. (2005). Deficits in speech perception predict language learning impairment. *Proceedings of the National Academy of Sciences*, *102*(39), 14110-14115.

Zorzi, M., Barbiero, C., Facoetti, A., Lonciari, I., Carrozzi, M., Montico, M., ... & Ziegler, J. C. (2012). Extra-large letter spacing improves reading in dyslexia. *Proceedings of the National Academy of Sciences*, *109*(28), 11455-11459.