The role of visual-spatial attention in reading development: A meta-analysis

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Abstract

The association between visual attention and reading development has been investigated as a possible core causal deficit in dyslexia, as well as phonological awareness (Bosse& Valdois, 2009). The present review aims to provide a meta-analytic review of the studies that have analysed attentional processes and their relation to reading development. The studies included have considered the visual spatial attention orienting that sustains the serial visual analysis involved in the phonological pathway of decoding (Facoetti et al., 2006), and the visual attention span that supports the multielement parallel processing that is thought to be important for lexical processing (Ans et al., 1998). This study aims to summarise data from studies with participants of up to 18 years of age, following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines. The objective is to provide a comprehensive analysis of the association between visual attention skills and reading proficiency and to examine the possible influence of orthographic depth, age, and attentional tasks (interpreted as serial or parallel processing indices) on this relationship between visual attention and reading. All papers that met the criteria were included in the meta-analysis. The results confirm a strong association between visual attention and reading development; we evaluate the evidence and discuss the possibility that visual attention processes play a causal role in determining individual differences in learning to read.

Keywords: visual-spatial attention, reading development, visual search, dyslexia, visual attention span, serial visual processing, parallel visual processing

1. Introduction

Reading is a complex ability that requires the integration of several different cognitive and perceptual processes (Christopher et al., 2012). For reading research, a major goal has been understanding what factors underlie individual differences during the period of reading development. Thus, research has focused on finding possible early 'markers', that could predict future reading disability, and on finding the cognitive deficit/s that cause dyslexia (Christopher et al., 2013; Thompson et al., 2015). Research on reading development has been dominated by the idea that phonological skills represent the foundation of reading; as a consequence, phonological deficits have been considered the core deficit in dyslexia (see Melby-Lervåg et al., 2012; Vellutino et al., 2004 for review). However, besides the phonological awareness hypothesis, there is a growing body of evidence supporting the contribution of visual attention to reading development (see Krause, 2015 for a review).

Visual analysis of a written word is a component of every type of neuropsychological or computational model of reading. However, the specific nature of the relationship between visual attentional processing and reading development is still debated. Although the potential causal role of visual attention in the development of reading skills is still controversial (Banfi et al., 2018; Goswami, 2015; Kronbichler et al., 2002; Olulade et al., 2015; Steinbrink et al., 2014), this hypothesis receives support from the reading impairment literature where many different types of attentional deficits have been associated with reading impairment, from visual spatial attention orienting (Franceschini et al., 2012; Ruffino et al., 2014; Vidyasagar & Pammer, 1999), to visual attention span (Lobier et al., 2012; Van Den Boer et al., 2015) and rapid temporal processing (Farmer & Klein, 1995; Meilleur et al., 2020; Ronconi et al., 2020). As regards the neural basis of the influence of attentional deficits on reading, it has been hypothesised that it could be mediated by a magnocellular transmission deficit (Benassi et al., 2010; Gori et al., 2016; Hari & Renvall, 2001; Stein & Walsh, 1997).

Previous reviews have summarized the evidence on the association between temporal order judgment and reading (Badcock & Kidd, 2015; Krause, 2015; Meilleur et al., 2020), and on the association between magnocellular processing and dyslexia (Benassi et al., 2010, Eden et al., 1996). The present work summarizes the evidence on the association of visual attentional processing and reading proficiency throughout the reading acquisition period.

Visual attention represents the mechanism for selecting relevant information within one of the most complex and cluttered environments there is: written text. This both enables prioritization of the stimuli to be processed and, permits filtering of those stimuli that are irrelevant (Carrasco, 2011; White et al., 2019). Spatial attention, which is crucial to reading, is a selective process, due to our limited capacity to process visual information (Carrasco, 2011; Lennie, 2003). Written text provide a large number of stimuli to be processed, stimuli that compete for processing resources, and spatial attention enhances this selection by offering better processing, similar to a concentrated spotlight (Posner, 1980). But what role does visual attention play during reading development?

Various theories have conceptualised reading acquisition as a sequence of stages related to a child’s cognitive development (Marsh et al., 1981) depending on the strategies used in word recognition (Frith, 1985). The connectionist dual route model of reading aloud, conceptualizes the acquisition of reading as a two-stage process (e.g., Perry et al., 2014). The first stage, called phonological decoding, consists of a visual serial analysis of the word, by parsing the letter chain into constituent graphemes, followed by grapheme-to-phoneme mapping (Hutzler et al., 2004; Ziegler et al., 2014). In a second stage, repeated associations between the orthographic structure of words and the spoken language support the development of an orthographic „lexicon. As the child's orthographic lexicon expands, more and more words are automatically recognised globally (the lexical stage of reading acquisition) (Perry et al., 2014; Ziegler et al., 2014). This connectionist model has made it possible to simulate the way in which, visual deficits in the first stage of learning could determine the reading impairment seen in dyslexic children (Ziegler et al., 2014).

The different rates of reading development in different languages are related to the orthographic complexity of the language (see the grain-size theory, Ziegler & Goswami, 2005) and have also been simulated (Hutzler et al., 2004). Furthermore, the orthographic features of languages influence the dimension of the attentional window needed for word processing: while in transparent languages the ratio is more or less 'one letter – one sound', in opaque languages it is possible to find one or more letters for one sound.

The 'Multiple-trace memory model of reading' - MTM (Ans et al., 1998) maintains that visual attention is modulated during text processing, through a visual-attentional window which controls the quantity of information to be processed, assuming two processing modes: global versus analytic. During the mature stage of reading development, when words are familiar, their recognition occurs globally. This takes place through parallel processing of graphemes, so the attentional window will expand to the entire word array. Visual attention span (VAS) is defined as the number of visual elements that can be processed simultaneously (at a glance) in a visual multielement array (Lallier et al., 2013b; Lobier et al., 2012). It represents a mechanism that supports the development of the orthographical lexicon and also “enhances the recognition of previously unfamiliar words” (Lallier et al., 2013a). Based on this definition, visual attention span (VAS) is involved in both stages of reading development referred to earlier (the Perry et al. model). On the other hand, when the orthographic form of the word is not familiar, or during the phonological stage of reading development, word processing is serial and requires 'contraction' of the visual-attentional window. This modulation process depends on the orthographic grain-size, so that deeper orthographies rely more on parallel processing, even from the early stages of learning to read (Goswami et al., 2003; Paulesu et al., 2001; Wimmer & Goswami, 1994).

1.1. Visual-spatial attention

According to the dual-route model of reading, when the phonological route of decoding is activated, a graphemic parser analyses the letter string into constituent graphemic units and their positions that are represented in the graphemic buffer (Coltheart, 2005; Perry et al., 2014). Visual attention is needed to focus on every sub-lexical unit. Furthermore, because the written text is a very crowded environment, flankers should be inhibited to reduce noise and to improve target stimulus processing. Neuropsychological evidence suggests that there is an atypical pattern of visual-spatial attention functioning in dyslexic children consisting of an atypical distribution of attentional focus across the visual field - left-mini neglect (Facoetti, Trussardi, et al., 2010; Sireteanu et al., 2005), sluggish attentional shifting (Facoetti et al., 2005; Facoetti & Turatto, 2000; Krause, 2015; Lallier et al., 2010), and impaired performance on visual search tasks (Roach & Hogben, 2007; White et al., 2019).

1.1.1. The specific distribution of attention over the visual field in reading impaired children

The line bisection task protocol has demonstrated that normal subjects have an asymmetric perception of space, in the form of a left bias, when the subject is asked to estimate the centre of a line (Chokron & De Agostini, 1995; Jewell & McCourt, 2000). The line bisection task has been used to test the left -mini-neglect hypothesis of dyslexia (Reinhart et al., 2013; Sireteanu et al., 2005). Another method used to gather information about this hypothesis is the Posner cueing paradigm (Posner, 1980) - a way of comparing performance when attention is directed by a visual cue to the target position (attended condition) or is directed in a different direction (unattended condition). This paradigm assumes that when the stimulus is in the attended condition, its detection should occur faster and more accurately. It is generally accepted that during text reading, visual information is processed during fixations, not during saccades (Quercia, 2010). As the amplitude of a saccade is about seven characters (Gautier et al., 2000), this means that covert spatial attention (in the absence of eye movements) would facilitate the processing of the 'skipped' characters. The gain in perception efficiency due to covert attention (evaluated by the Posner cueing paradigm) could improve text processing during fixation. Indeed, Facoetti & Turatto (2000) found atypical asymmetry in attention distribution in dyslexic children. They reported that dyslexics did not show any benefit when the flanker was in the left visual hemifield, which was interpreted as a sign of left mini-neglect. This particularity was found (Facoetti, Trussardi, et al., 2010) in pre-schoolers with a family risk of dyslexia, suggesting that it was not caused by the difference in reading experience between children with dyslexia and typically developing peers. In terms of its relationship to reading performance, visual-spatial attention deficit was found to be mainly related to nonword reading difficulties (Facoetti et al., 2006).

1.1.2. Sluggish attentional shifting observed in children with dyslexia

Text visual processing requires the rapid analysis of the letter string within a crowded visual field. While the visual-spatial attention paradigms aim to evaluate the efficiency (in terms of reaction time and accuracy) of visual attention orientation, the Sluggish Attentional Shifting (SAS) deficit theory in dyslexia (Hari & Renvall, 2001) exploits the attentional blink (AB) phenomenon (Badcock & Kidd, 2015) according to which when asked to identify two stimuli inside a rapid visual serial presentation, the recognition of the second stimulus is impaired, to a varying extent, in relation to stimulus onset asynchrony (SOA) (see MacLean & Arnell, 2012, for review). A deficit in dyslexic children's rapid serial stimuli processing was found to be amodal, involving auditory and visual modalities (Facoetti et al., 2005; Hari et al., 1999; Hari & Renvall, 2001; Lallier et al., 2010). Additional data (Ruffino et al., 2010, Hari et al., 1999) reveal that the sluggish attentional shifting (SAS) in subjects with left-mini-neglect demonstrates differences between the two visual hemifields, with the attentional blink being more evident on the left side. The importance of SAS in differentiating dyslexic children from typically developing readers could be explained within the model of spatial perception proposed by Rucci et al. (2018), based on the integration of spatial and temporal information at the level of retinal cells. Impaired temporal processing of visual stimuli could impair efficient processing of visual space and consequently, it could interfere with decoding fluency.

1.2. Attention and the visual search task

In visual search tasks, subjects are asked to detect the presence of specific stimuli (targets) among a large number of irrelevant stimuli (distractors) (Carrasco, 2011). Search performance is influenced by the target position inside the visual field: however, detection of targets positioned at the periphery is less efficient (Carrasco, 2011; Carrasco & Chang, 1995). In visual search tasks, attention can improve performance by enhancing spatial resolution (Carrasco, 2011; Morgan et al., 1998) and reducing interference. The visual search paradigm (Treisman & Gelade, 1980) involves two types of processing: parallel, which permits a fast scan of an array of elements, and serial, which is slower, based on focused attention. According to the four-stage model proposed by Eimer (2014), both types of visual processing are involved in performing visual search tasks. A spatial global attentional guide provides data for target selection. This parallel visual processing provides high-level stimulus perception that is followed by attention-focusing on specific details of the target (Hochstein& Ahissar, 2002).

The selection of the target is based on attention focusing and serial processing of stimulus features.

Visual search skills are important in reading because of their contribution to maintaining the continuity of visual processing of the text string from one saccade to the next. The performance of dyslexics, compared to typical readers, in a visual search task has shown that dyslexics have a higher orientation discrimination threshold. When a peripheral cue was introduced, it reduced the orientation discrimination threshold for typical readers, but not for dyslexic participants (Roach & Hogben, 2007). White and colleagues (White et al., 2019) repeated the study and added the age dimension to the analysis. They reported that individuals with dyslexia had a higher orientation discrimination threshold and a weaker spatial cueing effect than controls. They also found that reading ability was correlated with the cueing effect, this correlation being higher in participants under 20 years of age (White et al., 2019). They hypothesized that some individuals with dyslexia have a delay in visual attention development, and that this deficit impedes the normal acquisition of reading skills.

To sum up, most of the research shows, that differences in reading acquisition are associated with variability in the ability to efficiently orient attention within the visual field. Delay in visual attention development has also been hypothesized (White et al., 2019) to impact reading acquisition. Further knowledge is needed to understand the evolution of this delay and its influence within stages of reading development.

1.3. Visual attention span

Three partially overlapping concepts are associated with the experimental paradigms used to assess the amount of information (the number of letters) that can be processed within a fixation. Visual span - (Kwon et al., 2007; Legge et al., 2007; O'Regan, 1991) and perceptual span (Rayner et al., 1980, 2010) are both related to the physiology of vision and to reading speed. Visual attention span, the amount of information that can be processed in parallel without moving the eyes (Frey & Bosse, 2018), has been hypothesized to be a core skill which influences reading speed during literacy acquisition (Frey & Bosse, 2018; Onochie-Quintanilla et al., 2017).

In the context of reading, *perceptual span* (often measured by the moving-window paradigm – see Rayner, 2014 for review) applies to both letters and spaces, is asymmetric (right-shifted,) allowing information to be pre-processed from the right of the fixation point (Frey &Bosse, 2018). Its dimensions can vary, decreasing with the growth of the foveal processing load (processing load depends on word frequency, length and structure). Thus perceptual span can determine eye movements and fixation duration while reading, as it is influenced by top-down processes: several studies (e.g., Inhoff & Rayner, 1986; Rayner et al., 2003) have shown that perceptual span increases with reading experience(Choi et al., 2015), and decreases when the words processed are complex, ambiguous, or less frequent.

Visual span, which can be measured by a trigram method(Frey & Bosse, 2018; Legge et al., 2007), represents the capacity for representation of of visual elements during reading (the number of letter slots to the left and right of fixation point). There is an increase in the visual span with age during school years, that is associated with an increase in reading speed (Kwon et al., 2007). Visual span is influenced by text characteristics: letter size, crowding, letter spacing, and spatial orientation (Pelli & Tillman, 2007).

Visual attention span is a concept that adds a processing dimension to the visual aspects of visual and perceptual spans, specifying the number of characters that can be processed simultaneously. The experimental paradigm that is typically used to estimate visual attention span is based on a letter report task in which participants are asked to report a string of five letters (global report) or one cued letter from that string (partial report) (Bosse et al., 2014; Valdois et al., 2012). The letters used are only consonant series, incompatible with any real word skeleton. This aimed to prevent potential aggregation of the elements and to avoid top-down interference (Zoubrinetzky et al., 2016).

The neural theory of visual attention and short-term memory (NTVA) proposed by Bundesen, Habekost, and Kyllingsbæk (Bogon et al., 2014; Bundesen et al., 2005, 2011, 2015) supports a weighted distribution of visual attention during visual multi-element processing, based either on stimulus driven (bottom-up), or on intentional (top-down) factors (Bogon et al., 2014) . In parallel processing tasks, the elements to be processed compete due to the limited storage capacity of the short-term memory. Since the first to be recognised are those elements that are processed faster, visual processing speed is related to visual attention capacity. Some studies have used the theory of visual attention and short-term memory (NTVA) to investigate a possible deficit of multi-element parallel processing in children with dyslexia (Bogon et al., 2014; Dubois et al., 2010; Stefanac et al., 2019). Based on the correlation between auditory/ visual search and visual attention span skills, Lallier, suggested that dyslexic children with low VA span capacity may suffer from a high perceptual load during reading which impedes both auditory and visual multi-element processing (Lallier et al., 2013b).

1.5. The present study

The main goal of this study was to estimate the strength of the relationship between reading proficiency and visuo-attentional skills. It reports a systematic meta-analysis - an overall approach that allows one to obtain a pooled estimation of the magnitude of this relationship and counters the low statistical power of small studies. In addition, to our knowledge, no previous study has analysed whether the relationship between reading proficiency and visuo-attentional skills is affected by orthographic depth and stage of reading acquisition. According to the dual-route model of learning to read, word recognition evolves from an analytical strategy to a global one, which could involve a change in visual attentional processing strategies, a prediction this study allows us to examine. A secondary goal was to evaluate the extent to which variability in the effect size of the relationship between reading proficiency and visuo-attentional skills is affected by several potential moderator variables: orthographic depth, age, and type of task used to measure visuo-spatial attention. Finally, we also evaluated if differences in this effect size were related to the type of study: correlational or group comparison (dyslexics vs. typically developing readers).

Data derived from correlational or group differences studies cannot be the basis for establishing a causal relationship between two variables. Only intervention studies or studies that include a reading age control group can provide data relevant to a causal hypothesis. Because, in many of the studies included, the authors considered that visual attention has a causal influence on the development of reading skills, in the General Discussion we consider whether or not the existing findings provide support for the hypothesis that visual attention deficits can play a causal role in dyslexia.

2. METHOD

2.1 Search strategy

The review was designed following the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA)(Moher et al., 2010). The studies included were identified by searching PsycInfo, Medline, Web of Science, and ERIC databases up until late December 2020, using a combination of search terms related to visual attention (*visual-spatial attention* OR *visual search* OR *visual attention span* OR *visual attention orienting* OR *visual attention*) crossed with *dyslexia* OR *reading development* OR *reading acquisition*. After this, a manual search was conducted in some journals: *Dyslexia, Scientific Studies of Reading, Reading and Writing, Annals of Dyslexia, Journal of Learning disabilities* to identify studies that included data relevant to our study but were not focused on attention issue; 15 additional studies were found.

2.2 Study selection

We included all studies examining the relationship between visual spatial attention and reading development, published in English before 31st December 2020. The criteria for study inclusion were as follows: studies that included populations of school age (mean age of the group was less than 18 years) with an alphabetic language, and with a left to right writing direction.

Of the eighty-four effect sizes included in the meta-analysis, twenty-one were based on correlational studies, using unselected samples, for a total number of 2863 participants and sixty-three compared groups of children with dyslexia with typical readers, for a total number of 3914 participants. Studies that compared children with dyslexia with typical readers were included only if they specified the selection criteria as being either a previous clinical diagnosis or, reading impairment scores. Where the various groups were compared, they were similar in terms of mean age and intellectual ability; the criterion adopted was that the disabled readers group did not report other comorbidities (ex. ADHD). Only studies that included enough information to compute the magnitude of the effects were included.

When a study reported multiple effect sizes, corresponding to various age levels or various experiments, we registered them separately (ex. *Bosse et al. 2009-1*, *Bosse et al. 2009-2*, and *Bosse et al. 2009-3*), as the samples analysed were related to different school levels, or different experimental data. As a result, 84 different effect sizes were included.

Seventy-five studies included in the analysis assessed attention skills and reading at the same time-point: these studies were based either on unselected samples of children or on group comparisons (impaired readers and typically developing readers). Nine studies assessed visual attention skills before the beginning of literacy training (based on unselected samples of kindergarten children) or compared children with family risk of dyslexia with children without family risk.

[INSERT Figure 1]

2.3 Data collection and coding procedure

A broad set of variables were collected for inclusion in subsequent analysis:

Type of effect size. Two types of effect sizes were included in the analysis: one based on group differences between good and poor readers and the other based on the correlation between visual attention and reading performance measured on unselected samples of children. This was used as a moderator variable in subsequent analysis.

Orthographic depth. The languages of participants were coded as *transparent* (Italian, German, Finnish, Spanish, Greek), or *opaque* (English, French, Dutch, Danish, Norwegian, Portuguese). The orthographic complexity of the language of reading instruction was evaluated as a moderator variable.

Sample characteristics

Age. The mean age of the samples (in years, using two decimals) was coded. The mean age range was 4 years (pre-literate samples) to 16.41 years. Due to the non-normal distribution of the variable, it was not considered as being continuous; rather, it was transformed into a categorical variable as follows: *preliterates* (≤6 years of age), *beginners* (7-9 years), *advanced readers* (> 9 years of age). Age group was considered a moderator variable that permitted evaluation of the role of level of reading development.

Attention task. We classified the tasks used to assess visual attention in the studies included in our analysis in four categories: visual search, line bisection task, Posner cueing task and visual attention span (VAS). Some of the studies that included measures of visual attention span provided not only a global report score (representing the number of strings or the number of letters correctly reported), but also a partial report task (based on accurately reporting a cued letter presented inside the string). Both scores were included in the analysis. For the studies that reported more than one outcome selected for the analysis (e.g., Franceschini et al., 2012; Tobia & Marzocchi, 2014), we calculated the effect size for each of them and then averaged them (Borenstein et al., 2021; Scammacca et al., 2014) . This allowed us to have only one effect size for each sample.

In the studies that included present / absent target accuracy, the results of the present target condition was used, as it demonstrates the gain in accuracy due to the cueing effect that seems to distinguish typical readers from dyslexic children (Facoetti, et al., 2010b). Furthermore, regarding reaction time, only the data for the left visual field were considered, because those values are used to quantified the extent of 'left mini-neglect’ (Facoetti & Turatto, 2000; Sireteanu et al., 2005).

The type of attention task was evaluated as a moderator variable with two levels, based on the type of visual processing required: *Visual-spatial orienting* that included 28 studies based on the Posner cueing task, the bisection task and studies based on a visual search task that explicitly required serial processing of the stimuli. The other category: *Visual attention span* (VAS), included 38 studies based on the visual attention span task (see Frey & Bosse, 2018, for a review) which is considered to index parallel visual processing in reading.

2.4 Statistical analysis

ProMeta 3 (Internovi, Cesena, Italy), was used to perform statistical analyses on the effect sizes of the studies included.

2.4.1. Evaluation of the mean relationship between reading and attention across all studies

Eighty-four effect sizes were included in the analysis. As 21 of the 84 effect sizes included were based on small samples, we considered Hedge’s *g* appropriate for estimating the overall effect size, because, for samples of fewer than 20 participants, it outperforms Cohen’s *d*, for preventing bias (Hedges, 1981). A meta-analytic approach was used to evaluate the relationship between study characteristics that corresponded to the independent variables (e.g., Harrison, 2011) and the outcomes (the relationship between reading and visual attentional measures) expressed in terms effect sizes, representing the dependent variable (Durlak, 1995).

Random-effects modeling was used as it assumes that that true effect is not identical for all studies; its goal is to estimate the mean of a distribution of effects (Borenstein et al., 2007). Thus, compared with fixed-effect modelling it permits incorporating variability from small studies (by assigning them proportional weighting), considering that each of them can be representative of a subset of the population. As consequence, when using random-effects modeling, the standard error and the confidence interval for the summary effects are larger. (Note that a 95% confidence interval is reported for each analysis that was performed.

As part of the meta-analytic approach, several analyses were performed to evaluate the basis of the variability across the studies that contributed to the mean effect size. Importantly, we wanted to determine if potential outliers or publication bias could influence the estimation of the mean effect size corresponding to the relationship between reading and visual-attentional performance. In order to evaluate the presence, and the contribution, of potential outliers to the estimation of the overall mean effect size, a forest plot was used to examine the distribution of the individual effect sizes and a sensitivity analysis was performed by comparing their effect sizes and confidence intervals with the estimated global effect size. On this basis, the suspected outliers were removed one by one, from each end of the distribution thus examining the impact both on the overall effect size and on the heterogeneity of the remaining studies (Bown & Sutton, 2010). The range of estimated effect sizes was reported after removing the outliers. Relatedly, given the possibility that smaller studies in a meta-analysis may show larger effect sizes (Sterne & Egger, 2005) we generated a funnel plot, which allowed us to visually assess the possibility of publication bias. In addition, the *trim-and-fill* procedure for the random-effects model was used to determine the possible impact of potentially missing studies (studies that were not published due to less significant results) (Duval & Tweedie, 2000). This procedure imputes effect sizes inside the funnel plot to obtain symmetry and also calculates an adjusted mean effect size.

Given that the studies involved different visual attention and reading tasks, and the samples varied in terms of age and language, we considered the magnitude of the ir influence of these variables on the overall result. The heterogeneity of the studies included was evaluated using the Q test (Hedges & Olkin, 2014) and the I^2 statistic (Higgins et al., 2003). If the homogeneity Q test is significant, it indicates a considerable variation among the effect sizes included in the analysis. The I^2 statistic was used to characterize the proportion of observed effect size variability due to differences in the real effect sizes rather than to sampling error (Borenstein et al., 2017); it offers the advantage that it is not influenced by the number of studies included in the analysis (Borenstein et al., 2009).

2.4.2. Moderator analyses

Four moderator variable analyses were performed to evaluate the relevance of the moderator variables to the relationship between visual attention and reading proficiency: type of effect size, orthographic depth, age group, and visual attention task. For these, the studies were grouped into subsets, based on the categories defined by the moderator variable. An overall estimation of the effect size and a 95 % confidence interval were provided for each level of the moderating variable. The homogeneity test values (as described just above) were reported for each moderator category. The ANOVA Q-test (based on the analysis of variance) was used to determine whether there was a significant difference in mean effect size between the categories when considered separately.

2.4.3. Analysis of the moderating effect of age on the effect sizes associated with orthographic depth, attention task, and type of effect size

In three additional analyses, we investigated the moderating effect of the age of participants on the relationship between attention and reading proficiency for different levels of orthographic depth, type of attention task and type of effect size. These analyses could provide information about the evolution of the association between attention and reading proficiency during reading development. The ANOVA Q-test was used for all the three analyses with age coded as a categorical variable.

3. Results

3.1. Mean effect size of the relationship between reading and attention

Eighty-four effect sizes were combined. Variability between studies was high: Q(83) = 291.83, p<.001, I^2 = 71.56 (Higgins et al., 2003), indicating that the variance in effect sizes was not due exclusively to sampling errors. Therefore, the random effects model was used to combine individual effect sizes. The overall mean estimate of effect size, was both large and significant: k=84, Hedge's *g* = -.98; 95% CI [-1.08; -.88], p<.001, favouring the typical reader group (Table 1).

[insert Table 1]

The funnel plot (Figure 2) indicated that no studies were missing on the right-hand side of the mean. A closer inspection of the plot indicates the presence of studies with high effect size and low statistical power. A sensitivity analysis, showed that, after removing the potential outliers, the overall effect size would vary from k=83, Hedge's *g* = -.95, 95%CI [-1.04; -.86] (for one study removed), to k=81, Hedge's *g* = -.93, 95%CI [-1.01; -.84] (for three studies removed), so the result of the analysis is robust, as it is not strongly influenced by the effect sizes coming from studies with high standard error. The data shows a strong and robust association between visual attention skills, as the estimated effect size does not change significantly when studies with high effect size and high standard error are removed.

[Insert Figure 2]

3.2. Moderator analyses

Considering the low homogeneity of the studies included in the analysis, further meta-analytic subdivisions of the overall sample was performed.

Type of effect size

The overall effect size was calculated by combining two types of data: correlational and, based on group differences (good vs. poor readers). When evaluating the differences between the two types of studies, we found that the effect size of the studies that evaluated differences between groups defined by reading performance was significantly higher ($Q_{between}(1) = 4.71$, $p=.042$) with respect to those obtained by summarising correlational data (Table 1).

Orthographic depth

We evaluated the moderator role of orthographic complexity by comparing studies based on the language of the participants. Forty-seven effect sizes relating to opaque languages and 37 effect sizes related to transparent languages were included in the analysis. As the results show (Table 1), the relationship between reading and visual attention skills is slightly but significantly stronger for deep orthographies when compared to transparent orthographies: $Q_{between}(1)$: 4.32, $p<.05$.

Age group.

We investigated whether the magnitude of effect sizes of individual studies varies in relation to the age group of the participants. As can be seen in Table 1**,** the strength of the association between visual attention and reading shows a clear trend of increasing with age, such that the mean effect size is larger for older readers when compared to pre-readers ANOVA $Q_{between}(2) = 21.30$, $p<.001$.

Attention task

The magnitude of the relationship of reading with each type of visual attention task is high and significant. When the subgroup of studies based on visual-spatial attention tasks were compared with studies based on the visual attention span task, we found an estimated mean effect size slightly, but significantly, higher for the latter $Q_{between}(1) = 6.90$, $p<.01$ (Table 1).

This indicates that the type of task used to evaluate visual attention is a moderator that partially explains the heterogeneity of the studies included in the overall analysis.

3.4. Age group analysis differentiated by orthographic depth

We analysed the effect of age on the relationship between reading and attention skills for studies aggregated on the basis of the orthographic depth. Interestingly, the mean effect sizes were similar at the preliteracy level in the two orthographic groups (transparent and opaque); after that, the mean effect size progressively increased among older children reading in a deep language ANOVA $Q_{between}$= 17.71, df = 2, $p<.001$, while, as shown in Table 2, the mean effect size across age groups for shallow languages did not change significantly ANOVA $Q_{between}(2)=5.27$, $p = .072$.

3.5. Age group analysis differentiated by the attention task used

When analysing the effect of age on the relationship between reading and attention depending on the type of attention task, we found a significant ($p<.05$) upward trend with age for the visual attention span and, also, non-significant differences between age groups for visual spatial attention orienting tasks (Table 2). This result suggests that the association between reading and multielement processing skills increases with age during the reading acquisition period. Interestingly, it does not support an association between visual spatial orienting tasks and any specific stage of reading development: the magnitude of the relationship between visual attentional processes involved in serial visual analysis seems to remain unchanged across age groups.

3.6. Age group analysis differentiated by the type of effect size

The moderator effect of age was confirmed regardless of the type of effect size, the estimated mean effect size revealing an upward trend, both in correlation and group difference studies. In particular, when only studies that evaluated the effect size of group differences were analysed, the mean effect size of the studies clustered by age groups showed a strong and significant upward trend Q between (2) = 13.10, p = 0.011 (see Table 2), showing that an initial visual skills gap between good and poor readers, quantified by a medium effect size at the preliteracy level, increases significantly until the end of compulsory schooling age.

4. Discussion

This study analysed the attentional processes involved in text decoding, during reading acquisition, by means of quantitative meta-analyses. The results confirm a strong and significant relationship between reading level and the visual attentional skills involved in efficient processing of the written word. The overall estimated effect size of this association is greater than g = -.90, in favour of typical readers, even after the exclusion of outliers.

The strength of the association between visual attention and reading skills is significantly higher in children who learn to read in languages with deep orthography. This is consistent with the existing evidence on language-related differences, in physiological responses, between English (deep orthography) and Italian (shallow orthography) university students while performing reading related tasks (Paulesu et al., 2001). This work reports that, despite the fact that various orthographies share a common reading system, there are differences in patterns of brain activation, with Italian readers showing stronger activation in areas related to phonological processing, probably indicating a higher proportion of phonological procedures within the decoding process. Our study suggests that differences between people reading different orthographies begin with their visual attentional processing of the written word.

4.1 Patterns of development in visual text processing

One goal of our study was to investigate specific patterns that describe how the relationship between visual processing performance and reading skills evolves during reading development . Our data show that when visual-spatial attention skills were evaluated in kindergarten children, the overall effect size (g =-.66) indicated that reading proficiency is moderately associated with visual-attention skills (Table 1). We estimated that a mean effect size of g = -.64 quantifies the gap between pre-reading attention skills in studies that compared children with dyslexia (or family risk of dyslexia) with typical readers (Table 2). This gap between the spatial attention skills of readers with different reading skill levels, which precedes the start of literacy training, supports the hypothesis of a delay in attention-orienting maturation in dyslexic children (White et al., 2019). After starting to learn to read, the strength of the association between visual attention and reading skills increases progressively, and it becomes significantly stronger in readers after 9 years of age (in the mature reader group g = -1.07). This upward trend could be explained by differences in attention maturation between good and poor readers during reading development. Further data would be needed to investigate the evolution of visual attention skills during literacy acquisition longitudinally.

One interesting aspect which emerged from this analysis, is the age-related diversity of the pattern of association between visual attention skills and reading development related to orthographic depth. Thus, while the magnitude of the association between visual skills at pre-literacy age and reading was similar regardless of the orthographic complexity, after the beginning of reading training, two different patterns of development emerged. While for readers in transparent languages, the change was not significant, in opaque languages, we found a significant increase with age in the strength of the association between attention skills and reading level (Table 2). This suggests that in relation to orthographic complexity, word visual analysis strategies evolve differently.

We investigated the potential moderating influence of the types of tasks used in assessing visual attention and their correspondence with theoretical models (Ans et al., 1998; Facoetti et al., 2006). The magnitude of the relationship between parallel processing capacity (VAS) and reading skills slightly increases with age (from moderate to high at pre-reader age to an estimated high overall effect size in the beginners and advanced readers). This trend indicates a strong influence of the visual attention span from the start to the later stages of reading development, when words are being decoded globally. The same upward trend (albeit not significant) was found for tasks that assessed focused visual spatial attention. This suggests that the association between decoding skills and efficient visual-spatial orienting may not confined to the early reading acquisition stage: on the contrary, it may continue to influence reading development even in more expert readers.

A separate analysis of the studies based on comparisons of good and poor readers showed that the gap between the two groups in terms of the relationship between reading proficiency and visual attentional processing increased significantly (Table 2). This suggests that the initial delay in the development of visual attention found in pre-literate children may not be ameliorated during the process of learning to read: on the contrary, it may increase.

4.2 Theoretical implications

Attentional processes support efficiency-driven visual processing, and our data showed a strong association of these processes with reading, which requires the visual analysis of an extremely cluttered environment: the written text. These processes require stimulus selection given the limited processing capacity of the brain (Carrasco, 2011). The results of our meta-analyses are consistent with a dual model of visual text processing, one that involves both types of processing, serial and parallel, during all stages of learning to read. Visual-spatial orienting has been presumed to be primarily required by the phonological route of word decoding (Facoetti et al., 2006). However, our data showed continuity in the association of visual-spatial attention with reading during all stages of reading development. This study offers further evidence for the models of attention involvement in serial and parallel processing in reading(Ans et al., 1998; Bosse et al., 2015; Bosse et al., 2007; Franceschini et al., 2012; Hari & Renvall, 2001), highlighting the complementarity of their roles in text decoding. Based on previous research, we can hypothesize that the contribution of attention processes associated with serial analysis of the letter string extends from the initial stage of learning to read, when the word is segmented into grapheme components (Facoetti et al., 2006; Perry et al., 2014), to the advanced stages of reading, when attentional processes facilitates both saccadic regulation and reading fluency (Hautala et al., 2020). Similarly, parallel processing of the letter sequence contributes both to the development of an orthographic lexicon during the early stages of reading training and also later in whole word recognition (Ans, et al., 1998). It has been shown that some words are skipped during reading, as saccadic planning is influenced by low-level information (such as word length and the proximity of the preceding fixation to the beginning of the word) and by holistic linguistic properties of the words, such as word frequency (Choi & Gordon, 2014; Reichle et al., 2012). This indicates that while the word in the foveal position is decoded by parallel processing, the parafoveal preview supplies the information necessary for a strategic adjustment of reading by skimming parts of a text or by skipping redundant parts of sentences (Hautala et al., 2020). Thus, a deficit in visual attention could explain the abnormal eye movements observed in dyslexic children during reading: a reduced visual attention window size could result in both shorter saccades and more frequent fixations when compared to typically developing children (De Luca et al., 1999; Seassau et al., 2014; Trauzettel-Klosinski et al., 2010). Dyslexic children showed similar patterns of eye movements regardless of the task performed (be it visual search or reading), while typically developing children showed a benefit from the linguistic content of the task, requiring less time for reading and showing a lower number of fixations (Seassau et al., 2014).

4.3 Causality considerations

The data gathered in this meta-analysis came from non-interventional studies, so a causal relationship between reading proficiency and visual attentional processing cannot be inferred directly. From a constructivist point of view, it is necessary to distinguish the influence that visual attention abilities can have on reading development from the influence that reading experience can have on the development of visual abilities, as is done by training sensory processes.

One source of relevant evidence that takes into account the methodological requirements suggested by (Goswami, 2015) are studies that evaluate attention skills prior to the beginning of literacy training, as these avoid the confounding effect of reading experience on the relationship between attention and reading skills. Several studies (Carroll et al., 2016; Franceschini et al., 2012; Gori et al., 2016; Plaza & Cohen, 2007; Shapiro et al., 2013) have reported data on the relationship between reading and attention measured at the pre-reading level using a visual search task, and have shown that future poor readers already had deficiencies in serial visual search abilities. Franceschini (2012) showed that pre-schoolers who would become future poor readers exhibited a delayed time-course in spatio-temporal orienting of attention and significantly lower accuracy in visual search tasks. Studies that evaluated attention based on unselected samples of pre-school children found a moderate (mean g = -.67) association between visual attention skills and future reading proficiency(Ferretti et al., 2008; Gori et al., 2016; Plaza & Cohen, 2007; Shapiro et al., 2013). Facoetti (2010a) compared samples of children at-risk of dyslexia to children without-risk. He found deficiencies in the automatic orienting of visual attention in the sample of children at-risk for dyslexia, seen in higher interference depending on the spatio-temporal proximity between stimuli.

Another type of evidence that supports the causal role of visual attention in reading development are findings that variability in visual attentional skills are not determined by differences in reading experience. Several studies have reported comparisons between dyslexic children and both age and reading level controls. However, the results obtained are contradictory: for the VAS task, Zoubrinetzky (2016) and Lobier (2012) found that the VAS skills of dyslexics are significantly lower than those of both the age control and the reading level control groups. This suggests that the differences were not determined by low reading experience in dyslexic children. Cuetos (2018) found the same type of difference when a visual search task was used to assess visual attention skills, while for the VAS task, the performance of children with dyslexia was similar to that of the reading level control group.

For drawing causal inferences, the effect of practice of attention skills on reading development provides an important source of evidence (Sireteanu & Rettenbach, 2000). A causal relationship between visual attention deficit and reading disorders was argued for on the basis of the reading progress obtained through a training program designed to develop visual attention skills. Several studies (Peters et al., 2019 for review) have investigated the efficacy of dynamic visual-attentional interventions (e.g. action video-games) or visual-perceptual training for reading development. Indeed, several studies (see, e.g., Franceschini et al., 2017; Franceschini & Bertoni, 2019; Lawton & Shelley-Tremblay, 2017) have reported improvements in reading level after a visual attention training program. It has been shown that an enhancement of visuo-spatial attention skills was followed by increased speed and accuracy of word and nonword decoding in both English children and Italian children (Franceschini et al., 2013, 2017). Action video game (AVG)-based training reduced perception and attention deficits in dyslexic children, and this significantly improved their reading abilities (Franceschini et al., 2015). Bertoni (Bertoni et al., 2021) showed that after AVG training, the capacity to shift rapidly between distributed and focused attention improved and resulted in an improvement in pseudo-word decoding greater than the mean improvement that would be expected in a dyslexic child after a year of reading development.

Werth tried to improve visual processing strategies by means of visual training (Werth, 2018). He showed that, by choosing the appropriate fixation point (to obtain a foveal projection) and controlling the saccade to the next word (or word segment) based on the number of letters that the reader can process in parallel, can be obtained an improvement in non-word decoding in children with dyslexia. He argued that most of the causes of developmental dyslexia are related to specifics deficits in visual processing: inadequate fixation points, excessive saccadic movements, low visual spans and, longer fixation times required to recognise the word. When controlling these aspects of visual perception strategies, the effect size related to the improvement in pseudoword decoding was Hedge's g = 1.72 (Werth, 2019).

To sum up, the data from this meta-analysis, together with the results of previous work including several training studies - targeted at improving parallel processing / serial processing or to facilitate the shift from one to the other - provide strong evidence that the visual attention involved in serial and parallel processing of letter strings could play a determining role at all stages of reading development.

4.4 Conclusion and limitations

This study has highlighted the importance of visual attention – despite various definitions and methodological differences found in the literature – throughout the reading acquisition period. It confirms that the gap in visual attention skills between typical readers and dyslexics evolves, from moderate to high, from the pre-literacy to mature reading. It has also demonstrates the importance of orthographic depth in the relationship between reading and attentional processes. One aspect that has not been considered here is the potential influence of the characteristics of the literacy training approaches: there are cases when children are taught to recognise words globally even when the language has a shallow orthography. Further research on how visual-spatial attention skills evolve during reading acquisition would be useful both when designing efficacious teaching methods as well as for developing approaches for diagnosis and for the treatment of children with reading disorders.

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