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**Reading ability and visual perception:
Evidence from Lexilens glasses**

Supervisor

Professor Andrea Facoetti

Co-supervisor

Dr. Sandro Franceschini

Prof. Patrik Pluchino

Dr. Sara Bertoni

Dr. Giovanna Puccio

Candidate: Verena Gazzola

Student ID number: 2080576

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*A tutti i sacrifici, la bontà e il tifo di mio papà
A tutta la simpatia, la comprensione e gli abbracci di mia mamma
A tutte le risate, la compagnia e i consigli di mia sorella*

*A loro, e alla forza del loro amore,
dedico questo traguardo*

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Introduction

Developmental Dyslexia is a neurodevelopmental disorder that affects about 10% of the population causing impairment to read despite a normal intelligence. Many theories about Developmental Dyslexia have been formulated, from the classical visual deficit view of the disorder to the most influent phonological deficit hypothesis, and the debate is still open.

The present study aimed to investigate the placebo and nocebo effect of expectations on reading performance in university students. A pair of commercial polarized and backlit glasses (i.e. Lexilens) were used. They allow visual information to pass through with different speeds when tuned to specific temporal frequencies. These glasses are sold as a compensatory tool for dyslexic people since they have been proven to help them read more effortlessly.

We observed that of the entire sample of participants, only in poor readers flicker frequencies were correlated with their word reading skills, which could indicate that, when given the option to choose the speed at which visual information enters the brain, they select a slower rate to have enough time to process it adequately. This supports the hypothesis that Developmental Dyslexia may be due to a difficulty in processing visual information, specifically an impairment in the magnocellular pathway.

1. Developmental Dyslexia: definition and theories

1.1 Reading

Reading is a complex and acquired cognitive ability that aims to decode written symbols into corresponding linguistic sounds to understand a linguistic message. Reading can be viewed as the result of four distinct processes: phonological processing, which is the ability to break down words into their constituent sounds; orthographic processing, which involves recognizing written word forms; decoding, that is the translation of written words into sounds or phonemes; and comprehension, that involves the understanding of the information conveyed by the text (Perfetti, 2007). Reading is considered an acquired ability since it is a skill that humans developed recently in their evolutionary history, long after the brain's structure was formed. Unlike abilities like speaking or walking, which have deep evolutionary roots and are hardwired into specific brain regions, reading is a cultural and recent invention. When the human brain evolved, its primary functions centered on survival tasks like recognizing faces, processing sounds, and reacting to visual stimuli. Written language did not exist during most of our species' evolution, so there was no evolutionary pressure to dedicate brain areas specifically for reading. Hence, to read, the brain must repurpose or "recycle" existing regions originally evolved for other functions (Dehaene & Cohen, 2007). In particular, the Visual Word Form Area (VWFA), located in the left occipitotemporal cortex, is now fundamental to recognize letters and words. However, its primary role was recognizing objects, faces, or complex visual patterns. Broca's Area and Wernicke's Area are well-known for their critical role in language production and comprehension, but they also play an important role in

understanding the meaning of words while reading. Finally, parietal and temporal regions help linking the sounds of spoken language to the visual symbols of written language (grapheme-phoneme conversion), despite originally being dedicated to auditory processing. Since reading relies on this “neural recycling”, the process is not as effortless or automatic as other abilities like walking. It requires practice and not everyone acquires it at the same pace, in fact, some individuals struggle with reading (e.g., those with Developmental Dyslexia, DD).

1.2 Neural networks of reading

A written word that has to be read and understood has a long way to go across the eye and the brain. To ensure that the visual image falls on the central region of the retina, where visual acuity is at its highest and chromatic aberration does not occur, humans constantly perform a series of eye movements known as saccades. Saccades have an amplitude ranging from 1° to 4° and a duration between 20 ms and 40 ms. Between each saccade, there is a fixation period that typically lasts 200 to 300 ms, during which visual information is gathered. Following this, saccadic suppression occurs, during which the visual system temporarily stops the acquisition of new information to allow for the processing of previously collected data (Bossa, 2012). In 1975, George W. McConkie and Keith Rayner demonstrated that when we direct our gaze at any written text, we do not perceive the text in its entirety but only a portion of it, known as the span of visual perception of letters.

When a word is perceived, photons are projected onto the retina, where they are converted by the eye's photoreceptors (rods and cones) into chemical energy, and then into

electrochemical energy. Photoreceptors pass the information to ganglion cells, which, through two main pathways (the magnocellular and parvocellular pathways), send the information to three subcortical regions of the central nervous system: the superior colliculus (responsible for controlling saccadic eye movements), the pretectal area of the midbrain (involved in controlling pupillary reflexes), and the lateral geniculate nucleus (LGN), where 90% of visual information is processed. The LGN then transmits this information to the primary visual cortex, also known as the V1 visual area, that processes basic features of the stimulus. From here, the information moves to several other regions: V2, V3, V4 and V5 visual areas, inferotemporal cortex (ITC), inferior parietal lobule, medial superior temporal area. In these areas higher-order processes take place, such as object recognition and motion detection. Individuals with DD show brain differences across many of the regions involved in reading. Numerous studies have reported reduced activation in areas associated with phonological processing, including the left superior temporal gyrus (STG), temporo-parietal region, and inferior frontal gyrus (Nagy, 2006; Hoeft et al., 2007; Richlan, et al., 2012). Additionally, diminished activation in regions specialized for orthographic processing is well-documented, particularly in the left fusiform gyrus within the VWFA (Cohen et al., 2002; Van der Mark et al., 2009; Richlan et al., 2011; Olulade et al., 2015). Structural differences have also been observed in individuals with DD. Research has shown alterations in white matter tracts, such as the posterior segment of arcuate fasciculus, which connects language-related regions in the brain (Klingberg et al., 2000).

1.3 Developmental Dyslexia

The term “dyslexia” was first introduced in 1884 by the ophthalmologist Rudolph Berlin (Berlin, 1884), who used it to describe a reading difficulty caused by mild brain damage that affected the ability to decode written letters. Initially, however, this condition was referred to as "word blindness," a term coined by Adolf Kussmaul in 1877. He used this term to describe stroke patients who struggled with severe reading difficulties, despite having normal vision, language skills and intelligence. Later, William Pringle-Morgan suggested that this "word blindness" could be related to a developmental issue rather than an acquired condition. He described several cases of DD, including that of a young boy, and linked the reading deficit to the difficulty in memorizing visual impressions of words (Pringle-Morgan, 1896). Two decades later, American neurologist Samuel T. Orton published “Reading, Writing, and Speech Problems in Children”, where he affirmed that visual processing issues were at the root of DD (Orton, 1937). From the 1960s to the 1970s, a new theory emerged, proposing that DD stemmed from a phonological deficit, which impaired the representation, storage, and retrieval of spoken sounds, thereby hindering the association between graphemes and phonemes (Frith, 1985). Today, research on DD is divided. This field is highly complex, and there is still no definitive understanding of the mechanisms underlying it.

“Dyslexia is a learning difficulty that primarily affects the skills involved in accurate and fluent word reading and spelling. Characteristic features of dyslexia are difficulties in phonological awareness, verbal memory and verbal processing speed. Dyslexia occurs across the range of intellectual abilities. It is best thought of as a continuum, not a distinct

category, and there are no clear cut-off points. Co-occurring difficulties may be seen in aspects of language, motor co-ordination, mental calculation, concentration and personal organization, but these are not, by themselves, markers of dyslexia. A good indication of the severity and persistence of dyslexic difficulties can be gained by examining how the individual responds or has responded to well-founded intervention.”
(Rose, 2009)

When reading is impaired, we talk about DD. However, the term "dyslexia" in the DSM-5 is recommended for use only in clinical contexts, while the preferred terminology is “Specific Learning Disorder (SLD) with impairment in [a specific academic ability].” (Petretto & Masala, 2017). SLD refers to a single, broad category that includes various learning disorders. For reading disorders, specific abilities that may be partially or fully impaired (such as word reading accuracy, reading speed or accuracy, and/or reading comprehension) are identified. The diagnosis of SLD is based on four main criteria: a) the symptoms must persist for at least six months despite targeted interventions; b) one or more abilities are impaired, negatively affecting academic performance; c) the onset must occur during school age, even if the disorder fully emerges later; and in criterion d) are outlined several exclusion criteria, namely: 1) the absence of an intellectual disability (i.e., IQ of 70 ± 5); 2) learning difficulties can’t be explained by inadequate or incomplete instruction; 3) proficiency in the language used for academic instruction; 4) the absence of significant sensory issues (such as vision or hearing problems) that would account for the learning difficulties.

“Difficulties learning to map letters with the sounds of one’s language - to read printed words (often called dyslexia) - is one of the most common manifestations of specific learning disorder.” (Diagnostic and Statistical Manual of Mental Disorders, 5th ed.;

American Psychiatric Association [APA], 2013) In fact, despite prevalence estimates depend on the different criteria used to define DD, a common and shared definition of the cutoff for the reading performance is set at -1.5 standard deviations below the mean for age and estimates DD to affect around 7% of the population, with a prevalence in the male gender with a ratio of 1.5-3 males per one female.

As Rose (2009) claimed, DD is thought as a continuum, such as reading skills in general. DD is in fact conceived as the lower end of the gaussian normal curve of reading abilities. DD typically becomes apparent during elementary school when children are learning to read but may not fully manifest until later when learning demands increase. Early signs, such as language delays or difficulty with rhyming can emerge in preschool. Children who are predisposed to DD are slower and less accurate in recognizing individual letters before they learn to read compared to their peers. In fact, difficulties with letter recognition at ages four or five is the most reliable predictor of future reading difficulties (Lyytinen et al., 2015). This slower recognition extends to visual processing of letters within whole words, leading to problems with sequencing.

DD is lifelong but varies in its course, influenced by the individual's challenges, comorbidities, and support systems. Symptoms evolve with age: preschoolers may struggle with rhyming, language games or recognizing letters, kindergarteners can have challenges with letter recognition, writing, phoneme segmentation, and letter-sound association, elementary students often face difficulties with letter-sound correspondence, reading fluency, spelling, and math facts, while middle graders may have issues with multisyllabic words, word confusion, and comprehension. Adolescents and adults can experience slow, effortful reading, poor spelling, and trouble with comprehension. Avoidance of reading and writing activities is common, as are anxiety or panic attacks

(APA, 2015). Prematurity, very low birth weight and prenatal exposure to nicotine are risk factors for the development of DD. Also, children and adults with DD have been found to have low levels of omega-3 and omega-6 fatty acids in their blood, and the lower the quantity of docosahexaenoic acid, the bigger is the impairment in reading. What seems crucial is also the omega-3/omega-6 balance (Cyhlarova et al., 2007, Montgomery et al., 2013).

It is well known that SLD have an important genetic factor, in fact, the risk of having troubles reading is higher in children of parents with a history of DD, in every language context studied. DNA studies have been carried out and they evidenced several DD genes candidate: 1, 2, 3, 6, 15, 18 and X (Paracchini et al., 2007; Scerri & Schulte-Korne, 2010; Carrion-Castillo et al., 2013). A gene-by-environment influence has also been reported (Mascheretti et al., 2013).

SLD often coexist with other neurodevelopmental disorders (such as attention deficit and hyperactivity disorder, communication disorders, and autism spectrum disorder) as well as mental health issues (like anxiety and depression). Although these comorbidities do not rule out a diagnosis of a SLD, they can complicate the diagnostic process. Careful clinical judgment is necessary to identify the primary source of learning difficulties. Early diagnosis and intervention are essential to ensure the development of reading skills that are as fluent, accurate, and comprehensible as possible.

1.4 Phonological awareness deficit

As phonological skills are a prerequisite for good reading, an impairment in phonological awareness is largely attributed as the underlying problem of DD. According to the

phonological core deficit hypothesis (Frith, 1985) the main symptom of DD is an impairment in reading pseudo-words and the differences observed in individuals with DD are believed to result from a combination of compensatory factors and the severity of their phonological deficits. Non-linguistic factors, such as visual memory, perceptual speed, or exposure to written texts, as well as other linguistic abilities like syntactic and semantic skills, can play a compensatory role. Connectionist models of reading, often referenced by authors supporting this view, propose that children first learn to link spelling directly to phonology, and later to both meaning and sound. These models assume a single reading mechanism and do not classify dyslexic disorders into distinct subtypes.

Phonological awareness (Morais, 1991) refers to the ability to recognize and work with the sounds in spoken words. It involves not only distinguishing between different speech sounds but also actively manipulating them. It has also been suggested that the phonological awareness deficit compromises the ability to map speech sound onto homologous visual letters, thus making fluent reading difficult (Vellutino et al., 2004). To assess phonological awareness children are required to reflect on the phonological characteristics of language, but depending on the task, phonological awareness can be referred to as "global" or "analytic" (Morais, 1991). The former identifies a superficial understanding of the structure of a word and can be examined with tasks like rhyming or identifying the initial syllable. According to Morais (1991), this knowledge exists independently of literacy. The latter refers to a deeper understanding of the segmental structure of language and is assessed through tasks that involve manipulating phonemes (e.g., segmenting or blending them). This type of knowledge is thought to be linked to learning written language (and is absent in illiterate individuals). Until now, in all the languages studied, differences in phonological awareness are proven to predict future

phonological skills (Ziegler & Goswami, 2005). Notwithstanding this being the most widespread theory on DD's etiology it presents some fallacies. Coltheart and colleagues (2001) postulate there are two ways to read: the phonological route and the lexical route, in a model called the dual route cascaded model. The phonological route is the one used when people sound-out a word, using the grapheme-phoneme conversion strategy. It is the process used when a word is seen for the first time, or when the word doesn't exist (i.e., pseudo-word). New words and pseudo-words are read like that because they're not present in the person's mental dictionary (lexicon). With repeated exposure, a mental image of the word is formed, which enables the person to directly recognize and retrieve its meaning. This is the lexical route. Castles & Coltheart (1993) distinguished two different types of DD. Phonological dyslexia affects the phonological route and is characterized by difficulty reading non-words or unfamiliar words due to a deficit in applying grapheme-to-phoneme correspondence rules. Surface dyslexia, on the other hand, is marked by regularizing irregular words because of an over-reliance on the phonological route. Even if in the clinical practice most dyslexic readers show a mix of both phonological and surface dyslexia, the mere presence of patients with surface dyslexia indicates that not all types of DD are based on a deficit in phonological awareness (Vidyasagar & Pammer, 2010). Moreover, severe difficulties in meta phonological tasks do not always prevent efficient reading acquisition, as observed by Cossu and colleagues (1993), who documented a child with Down Syndrome who was fully able to read, despite completely failing meta phonological tasks.

Traditional treatment programs for DD were developed based on the phonological awareness deficit theory, so they focus on improving phonological skills and are generally quite successful, but they do not always lead to improvements in reading ability (Agnew

et al., 2004, Strong et al., 2011), thus arising the question if phonological skills are the main underlying cause of DD. Moreover, no studies have definitively shown a causal link between phonological awareness and the development of reading and spelling skills, as none have accounted for participants' pre-existing literacy abilities or the potential influence these skills may have on phonological awareness tasks (Castles & Coltheart, 2004; Brizzolara et al., 2006; Chilosi et al., 2009). Orsolini and colleagues (2009) demonstrated that phonological processing and phonological awareness deficits are not consistent in Italian children with DD examined, therefore, there is no clear evidence that reading disorders are systematically associated with a specific deficit in phonological processing and awareness. In fact, it is unclear whether phonological awareness precedes (and predicts) the development of reading skills or whether it is a byproduct of learning to read. That is, do children learn to segment and blend phonemes as they learn to read and write?

Another point of view (Stein, 2018) states that, since no differences in the phonological abilities of children with DD and children with impaired reading for other reasons have been found, whether everyone who struggles to read can be called dyslexic or nobody is. This is a provocative statement, but it can help to understand that the phonological theory cannot, at least not on its own, explain the complexity of the phenomenon of DD, and that other lines of research are necessary to clarify this issue.

1.5 The double-deficit hypothesis

The double-deficit hypothesis (DDH) of DD, introduced by Wolf and Bowers (1999), proposes that DD is not only caused by phonological processing deficits, as suggested by

the more traditional phonological deficit hypothesis, but also by impairments in another different cognitive skill: rapid automatized naming (RAN). This hypothesis has been influential because it allowed to identify subgroups of dyslexic individuals who struggle with either phonological processing, RAN, or both, and by explaining why some children with DD experience more severe reading difficulties than others. RAN refers to the ability to quickly name a series of visually presented stimuli, such as letters, digits, colors, or objects. The task to assess it is designed to measure the efficiency with which individuals can access and retrieve phonological information from long-term memory and articulate it quickly (Denckla & Rudel, 1976). Slower RAN speeds have consistently been found in individuals with DD, even in the absence of phonological deficits (Wolf et al., 2000). This suggests that RAN taps into cognitive processes that are distinct from those involved in phonological awareness, making it a critical component in understanding reading difficulties. The rapid access to phonological information is critical for fluent reading, as skilled readers must quickly recognize words and connect them to their phonological representations without consciously decoding each word letter by letter (Norton & Wolf, 2012). The DDH posits that individuals with DD can be divided into three distinct subgroups, each of which experiences a different combination of phonological and naming speed deficits: i) the group with phonological deficit only typically have difficulty with decoding and spelling but may read familiar words relatively fluently once learned; ii) individuals with naming speed deficit only can decode words accurately, but their reading tends to be slow and effortful, affecting overall fluency; iii) people with double-deficit struggle with both decoding accuracy and reading fluency, leading to pronounced reading difficulties. Studies have shown that children within the double-deficit group typically exhibit the most severe reading impairments (Compton et al., 2001).

This theory is supported by neurobiological studies that suggest disruptions in brain areas involved in visual processing and rapid serial naming (i.e., VWFA) (Richlan et al., 2011). Furthermore, individuals with combined phonological and RAN deficits (i.e., the double-deficit group) often show reduced connectivity between these brain regions, indicating that their impairments may stem from broader disruptions in the reading network (Pugh et al., 2000). These findings suggest that phonological and RAN deficits are not merely behavioral phenomena but reflect underlying differences in the brain systems that support reading.

Some researchers argue that the DDH does not fully account for all aspects of DD, particularly in non-alphabetic languages where phonological processing may play a lesser role (Ziegler & Goswami, 2005). Additionally, while RAN has been shown to be a strong predictor of reading fluency, its exact cognitive underpinnings remain unclear, and further research is needed to better understand how it interacts with other reading processes.

1.6 Auditory processing deficits

Auditory dysfunction has been proposed as a key developmental factor underlying the phonological deficits commonly seen in DD, given that speech is an acoustic signal. The Rapid Auditory Processing (RAP) deficit theory (Tallal, 1980) was one of the first to suggest that children with DD struggle to process rapid, sequential changes in auditory information, particularly the quick shifts in frequency that occur during speech, called formant transitions. These changes typically happen within a 40 ms window, which is crucial for differentiating linguistic units like consonants and vowels. Early studies on RAP deficits found that some children with DD had difficulty processing rapid sound

changes, suggesting this could contribute to their phonological challenges (Farmer & Klein, 1995). However, subsequent research produced mixed results. Some studies failed to find RAP deficits in DD, while others showed that children with DD could even outperform their peers in discriminating rapid frequency changes in speech sounds (Rosen, 2003). These conflicting results have led to ongoing debate about the relevance of RAP deficits in explaining DD.

A more recent theory (Goswami et al., 2011) focuses on impairments in processing slower temporal information, specifically the rise times in amplitude modulations, which are critical for detecting speech rhythm and prosodic features. Rise-time theory posits that children with DD have difficulty perceiving the slow-varying amplitude contours of speech, which affects their ability to detect speech rhythm, syllable structure, and stress patterns. Children with DD show significant impairments in rise-time discrimination compared to age-matched peers, and this difficulty is linked to deficits in phonological awareness and reading ability (Overy, 2003). Training programs that aimed to improve rhythm perception, such as activities involving music, drumming, or rhythmic language exercises, enhanced phonological awareness and reading skills in children with DD (Bhide et al., 2013). Furthermore, longitudinal studies (Huss et al., 2011) have found that rise-time sensitivity in pre-readers can predict later phonological awareness and reading success, reinforcing the idea that temporal processing deficits might play a causal role in DD.

These findings are encouraging, and coherent with the phonological deficit theory, nevertheless, cross-linguistic studies, particularly in languages with different prosodic structures, as well as more longitudinal studies, are required to fully understand the role of these auditory deficits in the etiology of DD.

1.7 Visual attention deficits

Reading is not only a phonological matter, for it implies sensory (e.g., visual) and attentional processes too. Visual attention is the cognitive process that consists in selectively focusing on specific visual information such as letters while ignoring other stimuli in the environment. It allows to prioritize certain stimuli and filter out irrelevant details. The relationship between impaired visual attention and DD has been well-documented, with numerous studies confirming that individuals with DD often struggle with visual attention shifting (Hari & Renvall, 2001; Valdois et al., 2004; Vidyasagar & Pammer, 2010; Facoetti, 2012). However, the precise direction of causality between visual attention deficits and reading difficulties remains unclear. One hypothesis suggests that a primary deficit in visual attention may hinder the ability to effectively process written text. Since reading requires selective focus on individual letters and words, impairments in the ability to shift and maintain attention across the text could significantly disrupt the reading process. According to this view, the visual attention deficit acts as a causal factor, hindering the development of reading skills from an early stage. On the other hand, it is also plausible that reading difficulties themselves contribute to the visual attention deficit. For instance, children who struggle to read may experience reduced exposure to text over time. This lack of practice with reading tasks could, in turn, weaken their visual attention mechanisms, as they are not regularly engaging in activities that would normally strengthen these skills. In this scenario, the reading difficulty would be the initial problem, with the visual attention deficit emerging as a consequence of limited exposure to reading tasks. Understanding this bidirectional relationship is key for developing effective interventions. If visual attention deficits are a primary cause,

targeted training aimed at improving attention-shifting abilities might benefit individuals with DD. Conversely, if the visual attention impairment is a byproduct of reading difficulties, interventions focusing on early literacy and reading exposure could potentially mitigate the effects on attention. Further research is needed to disentangle these possibilities and better understand how the two processes interact in the context of DD.

Another component of visual attention relevant for DD is the span of visual attention. It refers to the amount of visual information that can be maintained across brief interruptions, such as during blinks or eye movements. It plays a critical role in coherent visual experience and reading. Research suggests that the visual attention span may be reduced in DD, limiting the ability to process multiple-item arrays and impacting reading development (Bosse, et al., 2007; Bosse & Valdois, 2003, 2009). Typically, visual attention span is measured by presenting arrays of five elements (e.g., letters) briefly, with participants either naming all elements or specific ones. A common finding is an "M-shaped" reaction time and "W-shaped" accuracy curve, with crowding effects—interference from surrounding stimuli (see “Crowding” paragraph)—seen in reduced performance for elements in positions two and four. Children with DD, especially in Italian (Zoccolotti et al., 1999; Spinelli et al., 2002) and French studies (Bosse et al., 2007; Bosse & Valdois, 2003, 2009), exhibit larger crowding effects and reduced visual spans compared to controls, although again this might be influenced by reduced reading experience. One study found that children with DD had poorer visual spans for letters and digits but showed normal spans for unfamiliar symbols and colored dots, suggesting that the deficit may not extend to non-alphabetic stimuli (Ziegler et al., 2010). This supports

a non-causal interpretation of visual span deficits, implying that reading difficulties might result from, rather than cause, visual attention deficits.

1.8 Crowding

In the context of reading, crowding refers to the interference caused by surrounding letters or visual elements when trying to identify a target letter or word. This interference is more pronounced in the peripheral vision, making it harder to distinguish letters from one another when they are closely spaced. The crowding hypothesis suggests that dyslexic people have a wider "crowding zone," meaning that the distance over which surrounding visual stimuli interfere with letter identification is larger, making reading particularly challenging. Dyslexic readers experience greater crowding even in the foveal vision, where the crowding effect is typically less severe in typical readers (Pelli et al., 2007; Martelli et al., 2009). Studies found that dyslexic readers require more spacing between letters to read efficiently. According to Pelli and colleagues (2007), visual crowding limits the ability to process letters in groups and forces dyslexic readers to rely on a slower, letter-by-letter reading strategy. Based on the crowding hypothesis, one effective intervention strategy involves increasing the spacing between letters and words to reduce the crowding effect. Zorzi and colleagues (2012) demonstrated that increasing letter spacing significantly improves reading speed and accuracy in dyslexic children, alleviating some of the visual processing challenges linked to crowding.

While the crowding hypothesis provides a compelling explanation for the visual difficulties experienced by individuals with DD, it does not account for all aspects of the condition; however, Franceschini and colleagues (2012) highlight that the crowding

hypothesis complements phonological theories by addressing the additional visual processing challenges many dyslexic readers face.

1.9 Cerebellar deficit

The cerebellar theory of DD has gained attention in recent years. Nicolson, Fawcett and Dean (2001) found a correlation between DD and abnormal cerebellar functions in approximately 80% of the tested individuals. Traditionally, the cerebellum has been recognized for its role in motor coordination, but recent research has expanded this understanding, showing that the cerebellum also plays a crucial role in linguistic and cognitive skills. Nicolson & Fawcett published an article (2011) highlighting functional and anatomical abnormalities in the cerebellum of dyslexic individuals that are thought to impair the automatization of sensory-motor associations, such as the decoding of spoken language, which contributes to the reading difficulties dyslexic individuals face. The cerebellar dysfunction leads to a failure to develop automaticity in reading skills, resulting in poor fluency and slow decoding of text. Brain imaging studies support this by showing reduced activation in the right cerebellum during reading tasks in dyslexic individuals (Rae et al., 1998; Nicolson et al., 1999). Nicolson and colleagues (2001) further supports the cerebellar involvement by suggesting that the cerebellum is essential for the automatization of tasks like driving, typing, and reading. Based on this, researchers hypothesize that DD might result from difficulties in automating the process of associating graphemes with phonemes. This aligns with the broader magnocellular deficit theory, which also links reading problems to a more general temporal processing deficit affecting both motor and phonological skills. Despite these findings, the cerebellar theory

has faced criticism. Ramus (2003) noted that not all dyslexic individuals show sensory-motor deficits, in fact only around 30% of the dyslexic population exhibit such impairments. This selective manifestation has led to skepticism regarding the universality of the cerebellar theory.

Understanding the cognitive and neural underpinnings of DD is crucial for developing effective interventions. This brief review on DD theories leads to the observation that DD is likely to be a multifactorial and complex disorder that can result from a combination of phonological, visual, and attentional deficits. Understanding how these factors interact is fundamental for psychologist and clinicians to tailor their approaches to create better intervention programs to support individuals with DD.

2. The magnocellular deficit hypothesis

2.1 Magnocellular and parvocellular pathways

Vision is a complex process that begins with light detection by the eyes but is fundamentally a product of the brain. The eyes capture light and convert it into electrical signals that are then transmitted to the brain, where they are processed and interpreted. The LGN is a structure of the thalamus defined as the relay station between the eye and the visual cortex since it connects the optic tract to V1. It is composed of six layers of cells: two outer magnocellulars and four inner parvocellular that alternates with optic fibers. The magnocellular and parvocellular pathways are specialized in distinct aspects of visual perception. The magnocellular pathway is primarily responsible for processing motion and spatial awareness. It is characterized by large, rapidly conducting neurons known as magnocells (Goodale & Murphy, 1997). This pathway receives input from the magnocellular ganglion cells of the retina, which are specialized for detecting changes in contrast and motion (Maunsell & Van Essen, 1983). Magnocellular cells (M cells) constitute approximately 10% of the retinal ganglion cells (Enroth-Kugel & Robson, 1969; Shapley & Perry, 1986) and are characterized by their large size that stops them from resolving fine details (e.g.; they cannot distinguish between ‘a’ and ‘o’), but they can detect changes in the visual field rapidly (Maunsell et al., 1990; Merigan & Maunsell, 1993). M cells primarily receive input from long-wavelength (red and green) cones as well as from rods, which are sensitive to very low light levels. This makes them highly responsive to yellow light, especially under low-intensity conditions. In fact, some studies showed that a yellow filter can help children reading better since it improved their motion

sensitivity (Rey et al., 2005). M cells do not contribute to the conscious perception of color. Instead, they are more involved in the timing of light inputs and are particularly sensitive to movement. Due to this, they are often referred to as ‘blob’ detectors, signaling when motion occurs and providing a rough indication of spatial location. From the LGN, the visual information is forwarded to Layer 4C alpha of V1.

The remaining 90% of retinal ganglion cells are primarily parvocellular and koniocellular. These cells are essential for detecting fine detail and color, contributing to object recognition and identification. Their axons project to the parvocellular layers of the LGN, and subsequently to Layer 4C beta of the striate cortex.

2.2 Dorsal and ventral stream

After the magnocellular and parvocellular layers have interacted, the visual information is processed through two main pathways that extend from V1 in each hemisphere. These pathways are known as the dorsal and ventral streams. The dorsal stream, predominantly influenced by magnocellular inputs (with about 90% magnocellular and only 10% parvocellular), travels from V1 to the middle temporal (MT) area, often referred to as the ‘motion’ area, and then proceeds to the posterior parietal cortex and finally to the prefrontal cortex. This pathway plays a crucial role in mediating visual attention and guiding eye and body movements, and is commonly referred to as the ‘Where’ stream.

Conversely, the ventral stream projects to the ITC, it is primarily involved in object recognition, and is so usually called ‘What’ stream. This pathway includes the VWFA in the left ITC. Although the ventral stream is essential for object identification, it also

receives significant input from the dorsal stream, which helps direct visual attention to specific letters and facilitates their identification (see Vidyasagar & Pammer, 2010 for a review).

2.3 The magnocellular theory of DD

The magnocellular theory of DD (Stein, 2001) states that DD may be linked to dysfunctions in the magnocellular system. Research has shown that the magnocellular system, which is sensitive to motion and low spatial frequencies, can be assessed through psychophysical tests of spatial contrast and temporal flicker sensitivity. Lovegrove et al. (1980) demonstrated that dyslexic patients had impaired contrast sensitivity, especially at low spatial and high temporal frequencies, suggesting a deficit in the visual transient system, which is primarily magnocellular. Despite this, dyslexic individuals showed higher contrast sensitivity at high spatial frequencies, indicating that their visual deficits were not uniform across all types of visual tests. Further research by Martin & Lovegrove (1987) and Talcott et al. (1998) confirmed that dyslexic individuals generally exhibit lower flicker sensitivity compared to controls. These findings support the idea that DD may involve specific impairments in the magnocellular system. Substantial evidence linking DD to impairments in the visual magnocellular system was then repeatedly provided (Stein & Walsh, 1997). Through post-mortem examinations, researchers observed abnormal magnocellular layers in the LGN of the thalamus in dyslexic brains. These layers were found to have approximately 30% smaller neurons than those in control brains (Livingstone et al., 1991; Galaburda & Livingstone, 1993). Subsequent studies have confirmed these findings, revealing reduced magnocellular responses in both the

retina and LGN of dyslexic individuals (Pammer & Wheatley, 2001; Gori et al., 2014). Initial evidence from histological examinations of LGN tissue donated by dyslexic patients to the Orton Society highlighted these abnormalities (Livingstone et al. 1991) and modern neuroimaging techniques have further validated these findings, demonstrating similar LGN abnormalities in living individuals (Giraldo-Chica et al., 2015; Müller-Axt et al., 2017). A recent study (Müller-Axt et al., 2024) found aberrant responses specifically of the magnocellular LGN in young adults with DD.

Since magnocellular neurons are activated by moving stimuli, testing visual motion sensitivity has been proved more reliable in revealing magnocellular deficits in dyslexics because motion engages the entire magnocellular system, including central processing areas like V5/MT in the cortex. To assess motion sensitivity, Stein (2001) developed two panels that display randomly moving dots side by side. In one panel, a certain proportion of the dots move coherently. The participant must identify which panel shows the moving cloud. The proportion of coherent dots is gradually decreased until the participant can no longer distinguish the moving panel, establishing their threshold for detecting coherent motion. Studies with this test have found that individuals with significant reading impairment often showed poorer motion sensitivity compared to age- and IQ-matched controls (Cornelissen et al., 1995; Talcott et al., 1998; 2000). This result has been supported by various studies, including psychophysical, electrophysiological, and functional imaging research (Livingstone et al., 1991; Lehmkuhle et al., 1993; Eden et al., 1996; Demb et al., 1997, 1998). Also, Talcott et al. (2000) found that people's motion sensitivity correlates with their ability to spell irregular words.

A significant aspect of the magnocellular deficit theory is its correlation with the crowding hypothesis. The crowding hypothesis suggests that the ability to recognize

objects (such as letters) in the presence of surrounding visual stimuli is impaired in individuals with DD (see Gori & Facoetti, 2015 for a review; Bertoni et al., 2019). This difficulty is attributed to the magnocellular system's compromised performance, leading to challenges in distinguishing letters from their backgrounds when they are closely spaced or surrounded by other visual elements (Martelli et al., 2009). For instance, studies have shown that dyslexic individuals experience greater difficulties with letter recognition when they are flanked by other letters, which further supports the link between magnocellular dysfunction and visual crowding (Pelli et al., 2004). Moreover, empirical evidence suggests that interventions aimed at enhancing magnocellular function, such as using visual stimuli that emphasize motion or contrast, may improve reading performance in dyslexic individuals (Gori et al., 2016).

The magnocellular theory and the crowding hypothesis are also interconnected and supported by the noise theory of DD. This posits that individuals with DD have an increased sensitivity to visual noise, which can interfere with the processing of relevant visual stimuli (see Hancock et al., 2017 for a review). This theory highlights the role of background visual noise in hindering the clarity of letter recognition, making it challenging for dyslexic individuals to isolate characters from their background (Sperling et al., 2006). The interconnection between these theories settles on the fact that the magnocellular pathway is particularly vulnerable to noise. Impairments in this pathway may lead to an increased perception of noise, making even more difficult the visual processing required for reading. Studies have demonstrated that individuals with DD show greater difficulties in recognizing letters and words in visually noisy environments, which aligns with both the magnocellular and noise theories (Martelli et al., 2009). Interventions that enhance the signal-to-noise ratio in visual presentations, such as using

high-contrast or motion-based stimuli or extra-large spacing, may help mitigate these challenges by leveraging the strengths of the magnocellular system while minimizing the detrimental effects of noise (Van Der Kruk et al., 2017; Zorzi et al., 2012).

In conclusion, the magnocellular theory of DD provides valuable insights into the visual processing challenges faced by individuals with reading impairments. By highlighting the deficits in the magnocellular pathway, which is essential for processing rapid visual information, this theory underscores the difficulties dyslexic individuals encounter in recognizing letters and words. Moreover, the link between magnocellular dysfunction and reading difficulties emphasizes the need for targeted interventions that could enhance visual processing capabilities, thereby improving reading outcomes. Overall, this theory not only broadens our understanding of DD but also offers a framework for developing effective strategies to support individuals who struggle with reading (Gori et al., 2016; Franceschini et al., 2013).

3. Description of the research project

3.1. Goals and hypothesis

The present research was conducted with the double aim of investigating: (i) the presence of placebo and nocebo effects induced using glasses for the treatment of DD in university student's reading abilities; (ii) the possible psychobiological basis of placebo and nocebo effects by measuring three physiological indices as pupil dilation, blink rate and heart rate. Placebo and nocebo effects were induced using specific glasses (i.e., Lexilens), designed to improve reading skills in patients with DD, paired with precise verbal instruction and brief conditioning paradigms.

3.2 Method

The research was conducted in accordance with the ethical principles of the Declaration of Helsinki and was approved by the Ethics Committee of the Department of General Psychology at the University of Padua. Participation in the study was obtained following the signing of informed consent. The duration of the research was approximately 50 minutes. A diagnosis of epilepsy or not being a native Italian speaker were considered exclusion criteria.

3.2.1 Participants

One hundred and four University students attended the experiment. Two were excluded at the moment of the analysis because the data were incomplete, so 102 participants were included (20 males). All the participants were psychology students enrolled in the bachelor's degree program in Psychological Sciences of Development, Personality, and Interpersonal Relationships. The age ranged from 19 to 36 years, with the mean age being 20.68 and the standard deviation being 2.02. All the students received an extra point in an exam for participating in the experiment.

3.2.2 Materials, equipment

Word text reading evaluation

Reading skills were assessed by administering the passage "*Funghi in città*" (Judica & De Luca, 1993) to participants (see Appendix A), asking them to read aloud as quickly and accurately as possible. Reading time (in seconds) was measured using a stopwatch, number of errors were also recorded, then the parameter of syllables per second was calculated.

Glasses for calibration and reading evaluation

A pair of Lexilens glasses was used, connected through a cable to a device that allowed for the adjustment of "Vitesse" (i.e., the flicker rate of the lenses in hertz, Hz) and "Balance" (i.e., the luminance in candelas per square meter, cd/m²) through two

micrometric knobs. Another pair of Lexilens glasses, similar to the first but turned off, was used for the baseline and subsequent experimental conditions.

Glasses tuning concerned “Vitesse” (flickering frequency, range: 60-120 Hz, values -20; +40 in the box scale) and “Balance” (brightness, range -5; +5). As participants wore the glasses, the experimenter proceeded to explain how they worked: “These lenses change the way you perceive words. I will show you two extreme settings; focus on a word from the sheet that you find difficult to read and observe if you notice any differences.” So, the experimenter rapidly adjusted the speed of the flicker by turning the dial from one extreme to the other, and again asked participants if they noticed any differences. Then participants were asked to focus on the previously chosen word and say “stop” when it became easier to read: “Continue to focus on the word you find difficult to read, I will adjust the activation of the glasses more slowly; stop me when you find it easier to read.” This allowed participants to choose the initial flickering frequency. If participants did not select an initial value, the experimenter started from value 0. Once the initial value was selected, the flicker frequency was adjusted using a staircase procedure with sixteen steps (+/- 20; 15; 10; 8; 6; 4; 2; 1). At each step of the scale, participants were asked whether the new flicker frequency was better or worse compared to the previous one: “Does it seem better now (chosen point) or now (moving on the scale from the points indicated by the line)?” The frequency reported by participants as best was then used as the new starting point for the staircase adjustment.

After completing the scale for “Vitesse”, the experimenter proceeded to adjust the Brightness parameter that was controlled using a four-step staircase (+/- 2, -1) and participants were asked to choose between 0 or -3 as the initial value for the staircase

procedure. As with the previous adjustment, participants were asked to indicate which value was better between the previously chosen one and the subsequent one.

Pupillometry, blink rate and heart rate measurement (not part of this dissertation)

Pupil size and blink rate measurements were recorded using the Tobii PRO X3, with a sampling frequency of 120 Hz.

During the experiment, participants underwent a total of seven pupil measurements: one at the beginning of the entire experimental procedure and one at the end of each training phase for each of the three conditions, together with the cardiac measurements. Participants were required to fixate on a visual stimulus on a screen positioned 65 cm away for 60 seconds. Simultaneously, the experimenters monitored the average and maximum heart rate using the COOSPORIDE app. Average and maximum heart rates for each participant were recorded using the COOSPORIDE H6 heart rate monitor, paired with the corresponding COOSPORIDE app, which allows for easy visualization of the relevant values. At the end of each pupillometry, the relevant values were recorded on a designated paper form.

Computerized reading task

The software used to measure the speed and accuracy of reading words and pseudo-words was E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA), installed on a 13-inch laptop (1024x768). Reaction times (msec) during the reading of words and pseudo-words were recorded via an E-Prime response box, equipped with a microphone suitable for recording acoustic stimuli.

Each computerized evaluation consisted of three conditions: baseline, high frequency, and low frequency. These were in turn divided into two phases: training (15 trials) and evaluation (24 trials), with the whole process repeated for words and pseudo-words. Each trial in the training phase included a fixation cross (400-650 msec) followed by the stimulus (word or pseudo-word) that remained on the screen until the participant response on the microphone, that is, until they began reading the word or pseudo-word. A mask then remained on the screen until the experimenter entered the input via keyboard, coding as 1 if the response was correct, 0 if it was incorrect, and 2 if it was missed (e.g., due to a very low voice, a cough, etc.). Finally, the response time (RT) was presented on the screen for 1500 msec. In the baseline evaluation it was colored in blue for all the stimuli. In the conditions where a placebo effect was intended to be induced (words in the high frequency condition and pseudo-word in the low frequency condition) RT were arbitrarily colored 87% of the times in green (meaning that the RT was quicker than in the baseline evaluation) and 13% of the times in red (meaning that the RT was slower than in the baseline evaluation). On the contrary, when a nocebo effect was intended to be induced (words in the low frequency condition and pseudo-word in the high frequency condition) RT were arbitrarily colored 87% of the times in red and 13% of the times in green. At the end of the lists in the baseline condition, the glasses were handed to the experimenter who pretended to tune them to either high or low frequency, depending on the condition indicated by the PC. It is important to note that the glasses were turned off even during the conditions labeled as high frequency and low frequency.

For the computerized evaluation three lists of words and three lists of pseudo-word were created (X, A, B) (see Appendix B and C) balancing the stimuli for length and number of syllables and words for frequency of use too. 15 words and pseudo-words were test items

and were followed by a colored feedback on the screen and 24 were not. Words and pseudo-words were counterbalanced in the three conditions and participants were randomly assigned to one of them. The conditions were randomized with respect to the order of high and low frequency trials and the order of stimulus lists. Response time and number of errors were measured.

Final questionnaire

Subjective evaluations of the experiment were collected through a simple questionnaire, where participants were asked to assess and quantify the extent of the temporal influences (placebo and nocebo conditions) induced by the glasses on their reading abilities:

1. According to you, temporal frequencies influenced your reading abilities?
 - a) Yes
 - b) No
2. If yes, how much?
 - a) Not at all
 - b) A little
 - c) Very much

Additionally, information regarding personality traits was collected using a version of the “Big Five Inventory” questionnaire (Ubbiali et al. 2013) where participants were asked to evaluate certain personality traits using a Likert scale with values ranging from 1 to 5.

3.2.3 Procedure

Each student was evaluated by two or three experimenters: one was introduced as a French University collaborator for an external optics project. She wore a white lab coat and was responsible for calibrating the glasses and pretending to set them at the appropriate flickering frequency at the right time during the procedure. The other was responsible for administering the reading tests, performing pupillometry and explaining the experiment.

Upon arrival in the experiment room, participants were asked to read and sign the informed consent form. They were informed that they could leave the experiment at any time and that in this case their data would not be retained. Personal data were then collected. Then, participants were asked to put on the heart rate monitor band below their sternum, in direct contact with the skin. Subsequently, the first pupillometry and blink rate measurement was performed (see paragraph “Pupillometry, blink rate and heart rate measurements”) while some cardiac indices were being measured.

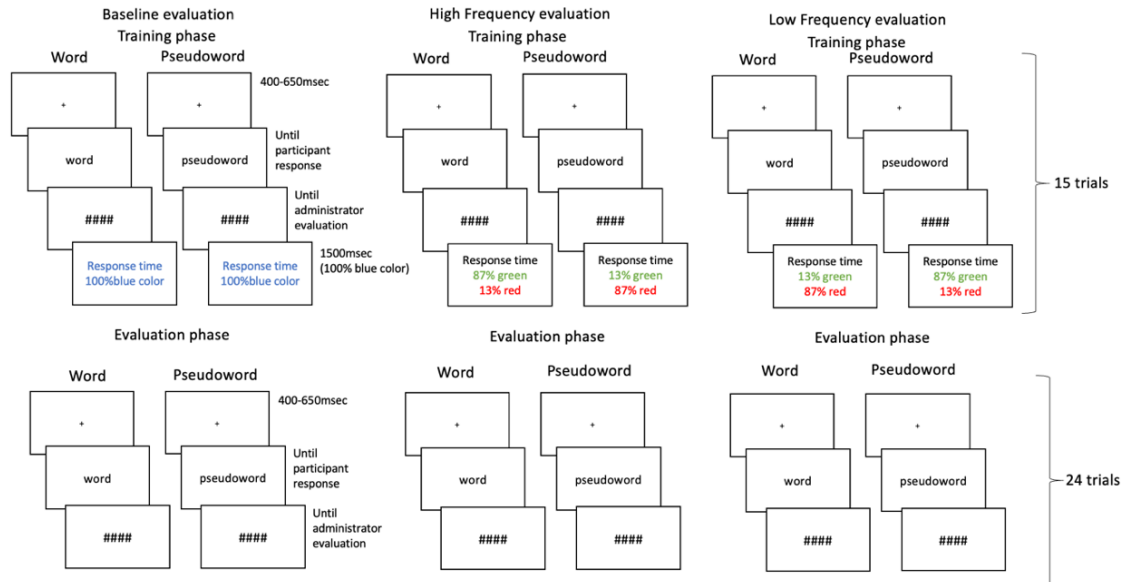
To test reading skills participants were asked to read the passage “*Funghi in città*” (Judica & De Luca, 1993). Afterwards, the procedure involved identifying the dominant eye. Participants were asked to close their right eye and cover the latch of the room door with their thumb placed in front of them, then to open the right eye and state whether they still perceived the latch as being covered by the thumb or not. If the latch was still visible the dominant eye was considered the right one, otherwise it would be the left one.

Then, the project was explained to the participants with these words: “The glasses you see on this desk were designed by a French company to improve reading abilities in both children and adults. They are special glasses equipped with polarized and backlit lenses

that allow visual information to pass through when tuned to specific temporal frequencies. It has been observed that the use of these lenses affects the reading skills of children and adults. Specifically, tuning these glasses to high temporal frequencies improves reading of meaningful words in both speed and accuracy, but worsens reading of pseudo-words. Conversely, tuning the glasses to low temporal frequencies improves reading of pseudo-words but worsens reading of meaningful words. Today, we will test your ability to read words and pseudo-words with three brief assessments and evaluate the effect of the glasses, calibrated for you, on certain physiological indices.” Next step was the glasses tuning (see paragraph “Glasses tuning”). Once the calibration was completed, the three administrations of words and pseudo-words followed in a counterbalanced order (Figure 1).

Figure 1

Schematic representation of the three conditions administered to each participant.



Each computerized evaluation included three conditions: baseline, high frequency, and low frequency. Response times (RT) were displayed for 1500 milliseconds. In the baseline condition, RTs were always shown in blue. To induce a placebo effect, RTs were colored in green 87% of the time (indicating faster responses) and in red 13% of the time (indicating slower responses) for words in the high-frequency condition and pseudo-words in the low-frequency condition. Conversely, to induce a nocebo effect, RTs were colored in red 87% of the time and in green 13% of the time for words in the low-frequency condition and pseudo-words in the high-frequency condition. The use of the heart rate monitor, dominant eye measurement, calibration procedures, colored feedback, and pupillometry were all designed to manipulate and induce specific expectations, that is, either a placebo or nocebo effect on reading abilities. The evaluation phase had the same structure of the training phase, meaning the fixation cross, the stimulus and the

mask, without the response time feedback instead. To assess reading abilities and correlate them with “Vitesse” and “Balance” values, only the Baseline condition data were used.

At the conclusion of the experimental session, participants were asked to complete a version of "The Big Five Inventory" (Ubbiali et al., 2013) (refer to Appendix D), along with two self-assessment questions.

3.3 Results

Since in a previous research Franceschini and colleagues (2024) had obtained unexpected evidence of a relationship between the “Vitesse” values chosen in the calibration of the lenses and the reading skills of children with DD, and that the glasses themselves were specifically designed to help people with reading difficulties, also in this case the entire sample was divided based on the reading skills of the passage “*Funghi in città*” and those who showed an average *Z* score in speed and accuracy below -1.5 standard deviations were selected as poor readers. Thus, two groups were formed: 75 typical readers (TR) and 27 poor readers (PR). Concerning speed, TR ($Z=.481$, $SD=.876$) were faster than PR ($Z=-1.144$, $SD=1.286$); and they were also more accurate ($Z=-.958$, $SD=1.131$) compared to PR ($Z=-5.501$, $SD=2.617$) (See Table 1).

Table 1

Descriptive statistics of TR and PR reading speed and accuracy

		N	Mean	Standard Deviation	Standard Error Mean
Z score text reading time	TR	75	.481611	.873144	.1011881

		PR	27	-1.144646	1.2859624	.2474836
Z score text reading errors		TR	75	-.9580	1.13119	.13062
		PR	27	-5.5011	2.61686	.50362
Mean Z score text reading		TR	75	-.237733	.7750808	.0894986
		PR	27	-3.322593	1.7729801	.3412102
Words mean reading time		TR	75	428.1637	43.81475	5.05927
		PR	27	453.9114	53.91794	10.37651
Pseudo-words mean reading time		TR	75	487.1372	66.28334	7.65374
		PR	27	533.2133	76.70864	14.76258
Words mean accuracy		TR	75	.9918	.01563	.00180
		PR	27	.9837	.02904	.00559
Pseudo-words mean accuracy		TR	75	.9407	.05352	.00618
		PR	27	.8820	.08283	.01594

First, the values of the variables “Vitesse” and “Balance” chosen by the group of TR and PR were compared. In the direction of the initial hypothesis, the mean value chosen by the PRs was significantly lower than that of the TRs ($t_{(100)}=1.864$, $p=.033$ one tail). No significant difference was observed in the “Balance” value (See Table 2 for descriptive statistics).

Table 2

Descriptive statistics of TR and PR “Vitesse” and “Balance” data

		N	Mean	Standard Deviation	Standard Error Mean
“Vitesse”	TR	75	-8.21	7.037	.813
	PR	27	-10.96	5.019	.966
“Balance”	TR	75	-.49	1.571	.181
	PR	27	-.96	1.698	.327

In order to verify whether there was any relationship between the choices of flicker and brightness parameters and reading skills, the averages of the reading performances in the Baseline and Evaluation phases were calculated exclusively in the Baseline condition (i.e., when no placebo/nocebo effects were expected). In this way, the parameters of word and pseudo-word reading speed and accuracy were obtained (see Table 3).

Table 3

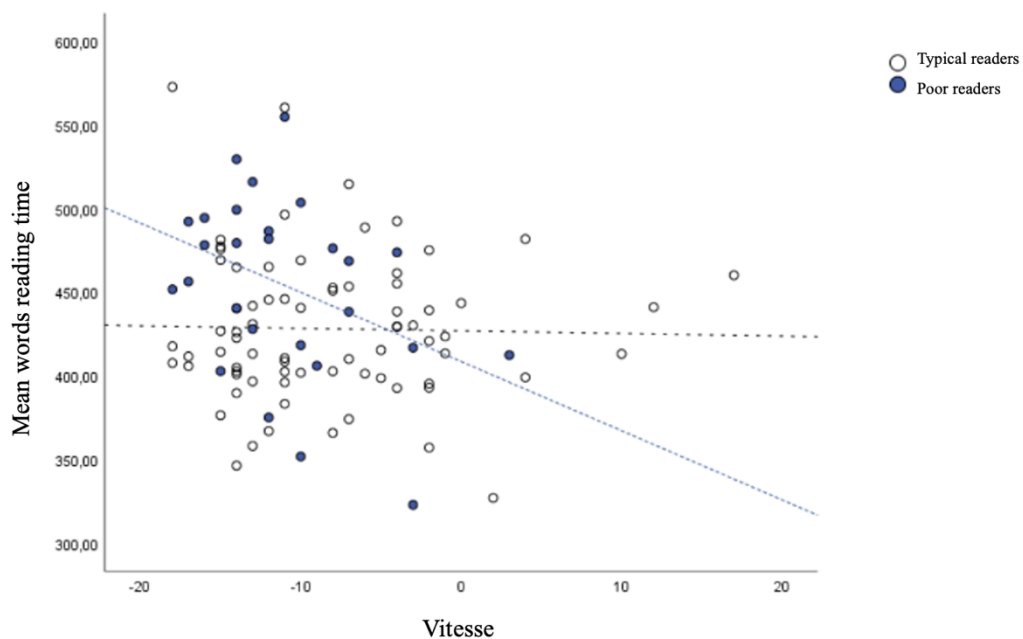
Descriptive statistics of whole sample reading speed and accuracy

	N	Minimum	Maximum	Mean	Standard Deviation
Words mean reading time	102	323.03	572.62	434.9793	47.80387
Pseudo-words mean reading time	102	366.08	664.55	499,3338	71.77074
Words mean accuracy	102	.90	1.00	.9897	.02022
Pseudo-words mean accuracy	102	.62	1.00	.9252	.06739

On the two samples, separately, it was verified whether there was a correlation (Pearson for response time and Spearman for accuracy rate) between the two variables and reading skills in the computerized tests. While no significant correlations were observed in the TR sample (all $p>.108$), in the PR group word reading speed were found to be correlated with the “Vitesse” value ($r=-.39$, $p=.048$) chosen by the participants (see Figure 1).

Figure 1

Graph of the correlation between “Vitesse” values and reading speed of words in poor readers and typical readers.



3.4 Discussion

The analysis of the data, aside from the placebo and nocebo effect and the psychophysiological measures (reported in other Master's thesis), revealed another interesting effect, for which the glasses tuning procedure was fundamental. In the experiment, “Vitesse” refers to the flickering frequency of the glasses which can alter how quickly or smoothly the eyes process text, ranging from 60 to 120 Hz, while “Balance” controls the brightness impacting visual contrast and clarity, with values between -5 and +5. These parameters were adjusted to influence how participants

perceived words while reading. By fine-tuning these settings, participants were able to modify their visual experience, selecting the values that made reading easier for them. The analysis highlighted that PR opted for a significantly lower level of “Vitesse” compared to TR. This finding is consistent with the work of Wolf & Bowers (1999), who noted that poor readers often exhibit slower processing speeds, which can affect their overall reading fluency. It is also consistent with theories that indicate how DD patients are more affected by noise in their reading performance (Van Der Kruk et al., 2017; Zorzi et al., 2012; see Gori & Facoetti, 2015 for a review), therefore they need a “slower” perception time of images. This allows them to process the image before it is presented again. This data can be considered one of the two core findings of the research together with the significant correlation between “Vitesse” and reading speed for words among PR, indicating that as the level of “Vitesse” decreases, reading speed for words also declines. This finding corroborates earlier research (McCloskey et al., 1995; McCloskey & Rapp, 2000; Vannuscorps et al., 2022) which found that single patients with reading impairment and mirrored vision were facilitated in reading by slow flickering frequencies. These insights are in turn in contrast with the literature on flicker contrast sensitivity, which shows that dyslexic individuals are not more sensitive to low- and high- frequency flickering compared to typical readers (Cornelissen et al., 1995; Williams et al., 2003). However, these studies primarily considered low-level visual perception and not reading implications. In fact, while dyslexic individuals might not show sensitivity to flicker contrast at a basic perceptual level, they could still experience challenges when processing rapid visual stimuli sequences in tasks that require higher-level cognitive functions, like reading. The research by Hari & Renvall (2001) supports this. Their study found that individuals with DD often struggle to process rapidly occurring stimuli, indicating that

these readers may have difficulty integrating visual information presented at high speeds, since their attention moves more slowly. This idea suggests that DD may arise from an impaired ability to handle rapid visual or auditory sequences. Since the magnocellular stream is the one accounting for rapid visual stimuli processing, we can take this as evidence supporting the magnocellular theory of DD. According to this hypothesis, presenting visual information at a slower rate could reduce the cognitive load involved in processing each stimulus in rapid succession, thereby enhancing reading performance. Later, Lallier et al. (2009) investigated whether the attentional sluggishness observed in dyslexic individuals by Hari & Renvall (2001) applies across different sensory modalities: auditory and visual. The findings indicate that dyslexic individuals, regardless of age, experience sluggish auditory attentional shifting associated with phonological disorders, and that adults but not children displayed a visual sluggish attentional shifting (SAS). A more recent research by Gori et al. (2023) found that children with DD demonstrate both distributed and focused visuo-spatial attention deficits instead. Since they assess that approximately 40% of children with reading difficulties exhibit dysfunction in visual attention, they propose that effective reading remediation programs should incorporate interventions that address both auditory-phonological skills and visual attention.

What has also been found is that neither “Balance” nor “Vitesse” correlated significantly with reading performance metrics in the whole sample. The lack of significant correlations between “Balance and reading performance (both speed and accuracy) cannot be compared with previous studies because there is a lack of significant research on the correlation between brightness and reading skills. In a recent study (Franceschini et al., 2024) it has been found that lower flickering frequencies enhanced the reading

performance of pseudo-words in children, but not in adults. In children with DD, the correlation was observed with pseudo-words, possibly because they still use the sub-lexical route to read, especially since they are younger. In contrast, university students that are poor readers may have already developed compensatory strategies, relying more on orthographic or visual memory rather than purely on phonological decoding. Additionally, their larger vocabulary and greater experience with written language allow them to unconsciously draw on familiar word patterns, reducing their dependence on the phonological route, even when reading pseudo-words.

Thus, why do adult PR, university students, when given the opportunity to choose the speed at which visual information enters the brain through flickering lens glasses, choose lower frequencies compared to typical readers? Why does “Vitesse” values correlate significantly with the speed of reading words? A possible explanation may be related to a mild impairment in the magnocellular-dorsal stream (Gori & Facoetti, 2014; Stein & Walsh, 1997). Stein (2001) suggested that individuals with DD often exhibit reduced magnocellular responsiveness, leading to difficulties in tracking rapidly presented visual information, which is critical for fluent reading. The presented findings align with this theory, as poor readers showed a significant relationship between their processing speed (i.e., “Vitesse” values chosen) and reading speed, supporting the notion that visual processing impairments in the magnocellular pathway may contribute to their reading difficulties.

4. Conclusions

University students who exhibited a reading performance one and a half standard deviations below the average, thus categorizing them as PR, requested lower flicker frequencies during the calibration of the “Vitesse” setting of the Lexilens glasses compared to TR. Furthermore, the lower was their reading performance, the lower were the frequencies they requested. The magnocellular pathway is primarily responsible for processing rapid visual information, such as reading text. Therefore, it can be hypothesized that these individuals have a deficit in this pathway, which may contribute to their reading difficulties. The significance of this result lies in its implication that the calibration preferences of poor readers reflect their unique processing needs. By favoring lower flicker frequencies, these students may be compensating for their slower information processing speeds, thus highlighting a potential adaptive strategy to enhance their reading experience. This adaptation could indicate that poor readers, in their efforts to optimize reading conditions, are seeking solutions that may help mitigate their reading challenges. This research provides valuable insight into the underlying cognitive and perceptual mechanisms associated with DD. By aligning the calibration preferences of these students with the magnocellular theory, the study adds empirical weight to the understanding of DD and suggests that targeted interventions could be beneficial in catering to the specific needs of individuals with reading difficulties.

This empirical evidence for the magnocellular theory of DD is quite significant, however, the study has several limitations that could be addressed in future research to enhance its robustness and applicability. Although the sample of 102 participants may seem adequate, it may not be representative of the entire population, moreover, the whole sample was

constituted of university students within a certain age range. A larger and more diverse sample could provide more generalizable results, also given the fact that participants may have been influenced by the instructions given prior to the experiment and their motivation to participate, especially considering they received an extra point for the exam. Also, the experimental conditions may not reflect an ecologic reading environment. The lack of a natural context could limit the applicability of the results to everyday life, also given the anxiety factor of reading out loud in front of the experimenters. Lastly, the experiment was not specifically designed to investigate the particular effects related to the magnocellular theory of DD, since it was designed to test the placebo and nocebo effects of expectations. This could limit the relevance of the findings to that specific theory, as the original focus was different. Future research should then focus on a larger and more generalized sample in experiments specifically designed to investigate the correlation between the magnocellular theory and visual processing abilities under more ecological and detailed reading conditions. Additionally, it is important to explore how this discovery can be utilized to assist in the development of reading skills for both children who are learning to read and adults who struggle with reading. Another line of research that this study opens is understanding why there is inconsistency in whether children and adults with DD or PR improve or struggle when reading words or pseudo-words under low flickering conditions. This discrepancy calls for further investigation into the differences in how dyslexic individuals of different ages process visual and phonological information when exposed to such stimuli. Future research should also try to understand how the magnocellular pathway develops and identify when and how it is possible to intervene to improve its functionality, in order to prevent reading difficulties in young children.

Despite all the limitations mentioned, the study has a significant strength: the participants' choice of flickering frequency was "unconscious," reducing the likelihood of cognitive or intentional biases influencing their decisions. This aspect strengthens the validity of the findings, as it suggests that the observed differences in “Vitesse” selection are not shaped by preconceived notions or deliberate strategies but rather reflect a genuine perceptual need. Furthermore, the fact that the correlation between “Vitesse” and reading speed emerged significantly only in PR makes the result even more robust. This specificity indicates that the slowed visual perception might be a distinctive feature of the cognitive profile of people who struggle with reading (PR and DD), with important implications for understanding how they process visual information and for designing targeted interventions. It reinforces the idea that they require extended visual perception time to compensate for difficulties related to visual noise and information processing, a point that deserves further investigation in future research.

Since I strongly support early prevention, I believe this research opens a valuable avenue for both prevention and early rehabilitation. By gaining a deeper understanding of the magnocellular system's role in reading and how it evolves, we can potentially design interventions that address these deficits before they lead to significant reading impairments. Also, in my view, any intervention should always be personalized, different interventions need to be tailored specifically to the individual's symptoms and the underlying causes of their reading difficulties. A personalized approach is essential for effectively addressing the different needs of those with reading impairment and maximizing their potential for improvement. So, this research opens directions for further exploration of customized educational strategies that consider the unique processing profiles of dyslexic readers.

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Appendix

Appendix A: passage used to assess reading skills in participant.

Funghi in città

Il vento, venendo in città da lontano, le porta doni inconsueti, di cui s'accorgono solo poche anime sensibili, come i raffreddati del fieno, che starnutano per pollini di fiori d'altre terre.

Un giorno, sulla striscia d'aiola d'un corso cittadino, capitò chissà donde una ventata di spore, e ci germinarono dei funghi. Nessuno se ne accorse tranne il manovale Marcovaldo che proprio lì prendeva ogni mattina il tram.

Aveva questo Marcovaldo un occhio poco adatto alla vita di città: cartelli, semafori, vetrine, insegne luminose, manifesti, per studiati che fossero a colpire l'attenzione, mai fermavano il suo sguardo che pareva scorrere sulle sabbie del deserto. Invece, una foglia che ingiallisse su un ramo, una piuma che si impigliasse ad una tegola, non gli sfuggivano mai: non c'era tafano sul dorso d'un cavallo, pertugio di tarlo in una tavola, buccia di fico spiacciata sul marciapiede che Marcovaldo non notasse e non facesse oggetto di ragionamento, scoprendo i mutamenti della stagione, i desideri del suo animo, e le miserie della sua esistenza.

Così un mattino, aspettando il tram che lo portava alla ditta dov'era uomo di fatica notò qualcosa d'insolito presso la fermata, nella striscia di terra sterile e incrostata che segue l'alberatura del viale: in certi punti, al ceppo degli alberi, sembrava si gonfiassero bernoccoli che qua e là s'aprivano e lasciavano affiorare tondeggianti corpi sotterranei.

Si chinò a legarsi le scarpe e guardò meglio: erano funghi, veri funghi, che stavano spuntando proprio nel cuore della città! A Marcovaldo parve che il mondo grigio e misero che lo circondava diventasse tutt'a un tratto generoso di ricchezze nascoste.

Appendix B: list of words used in the experiment.

	X		A		B	
1	uovo	topo	orto	palo	mela	seme
2	picco	nebbia	polpa	febbre	pacco	sabbia
3	fiume	anatra	colpa	bibita	lista	vipera
4	tregua	frase	bestia	folla	strato	ponte
5	cubo	nome	rata	mano	ruga	sera
6	mole	femmina	tuta	brivido	gita	margin
7	pugno	fata	tetto	rana	lusso	sugo
8	nuora	burro	zuppa	torre	globo	preda
9	staffa	codice	laccio	angolo	prugna	pagina
10	rito	pollice	nave	collera	pane	pillola
11		cervo		talpa		corvo
12		belva		fieno		trota
13		cane		lago		fame
14		nuvola		pugile		aquila
15		guerra		strada		gruppo
16		fetta		miele		furia
17		coro		lupo		toro
18		dose		tela		mago
19		lana		vela		orso
20		palma		ladro		litro
21		casa		anno		uomo
22		tana		cera		faro
23		aria		tipo		voce
24		rissa		razzo		targa

Appendix C: list of pseudo-words used in the experiment.

	X			A			B		
1	gunna	tiga		Vuzio	tala		frute	tode	
2	pice	fretto		Muda	giacco		gura	stago	
3	cepria	gettine		Squato	gussola		stalta	galvola	
4	banzo	midre		Tucca	ginte		tarza	nitte	
5	bramma	lata		Fietra	fasa		fabbia	vina	
6	scido	pintila		Vatta	riffica		ruaio	filmine	
7	tazio	vune		Tauna	voca		etrio	vufo	
8	tarbo	fiento		Piuta	fielo		panvo	focca	
9	blotta	inbubo		Spegna	medodo		crenio	ostite	
10	livro	ligaro		Luoto	ledovo		fuoto	lenere	
11		tabbia			tramma			tietra	
12		tepre			tospo			terla	
13		ruva			nuso			urba	
14		simbelo			fascene			diavelo	
15		stafua			foccia			fiombo	
16		burno			blima			cioia	
17		nete			neta			nama	
18		taso			voia			egio	
19		podo			pido			pite	
20		trena			rotmo			sonna	
21		mabe			arbe			zoba	
22		mulu			elmu			ormu	
23		nebe			auga			luba	
24		lomba			latto			lonno	

Appendix D: version of “The Big Five Inventory” used (Ubbiali et al., 2013).

Di seguito trova elencate delle caratteristiche che possono riguardarLa o meno.
Per esempio, è d'accordo di essere una persona a cui piace passare del tempo con gli altri?
Per favore scriva un numero a lato di ogni affermazione che indichi quanto Lei è d'accordo o in disaccordo con quell'affermazione.

1. In disaccordo fortemente
2. Un pò in disaccordo
3. Né d'accordo né in disaccordo
4. Un po' d'accordo
5. D'accordo fortemente

Io mi vedo come una persona che....

___	1.	È loquace	___	23.	Tende ad essere pigra
___	2.	Tende a trovare da ridire sugli altri	___	24.	È emotivamente stabile, non si turba facilmente
___	3.	Lavora in modo accurato	___	25.	È inventiva
___	4.	E' depressa, triste	___	26.	Ha una personalità energica
___	5.	È originale, propone idee nuove	___	27.	Può essere fredda ed emotivamente distaccata
___	6.	E' riservata	___	28.	Persevera finché il compito è terminato
___	7.	E' premurosa ed altruista con gli altri	___	29.	Può essere lunatica
___	8.	Può essere piuttosto sbadata	___	30.	Apprezza le esperienze artistiche, estetiche
___	9.	E' rilassata, gestisce bene lo stress	___	31.	È qualche volta timida, inibita
___	10.	Ha curiosità in molti ambiti diversi	___	32.	È premurosa e gentile pressoché con tutti
___	11.	È piena di energia	___	33.	Fa le cose efficientemente
___	12.	Attacca briga con gli altri	___	34.	Rimane calma nelle situazioni tese
___	13.	È un lavoratore affidabile	___	35.	Preferisce un lavoro che sia di routine
___	14.	Può essere tesa	___	36.	È estroversa, socievole
___	15.	È ingegnosa, un pensatore profondo	___	37.	È qualche volta scortese con gli altri
___	16.	Genera molto entusiasmo	___	38.	Fa dei piani e li porta a termine
___	17.	Per natura tende a perdonare	___	39.	Diventa facilmente apprensiva
___	18.	Tende ad essere disorganizzata	___	40.	Ama riflettere, giocare con le idee
___	19.	Si preoccupa molto	___	41.	Ha pochi interessi artistici
___	20.	Ha un'immaginazione attiva	___	42.	Ama cooperare con gli altri
___	21.	Tende ad essere taciturna	___	43.	È facilmente distratta
___	22.	Di solito si fida	___	44.	Ha una sensibilità raffinata per l'arte, la musica o la letteratura