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Improve Reading-Related Skills Manipulating Attentional Control through Video Games, Parietal Neuromodulation, Caffeine and Positive Expectations

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Contents

Abstract

This dissertation investigates the multifaceted aspects of attention, exploring its definition, models, neural substrates, neurotransmitters, and interplay with emotions and expectations. The overarching objective is to unravel the intricate relationship between attentional control mechanisms and various interventions, encompassing action video game (AVG) training, emotional modulation through gaming, caffeine consumption, and the use of Lexilens® glasses, in the context of enhancing cognitive functions, particularly in individuals with developmental dyslexia (DD) and reading difficulties.

Specifically, Chapter 1 provides a comprehensive overview of attention, delineating its models and the neural substrates underpinning this fundamental cognitive process. It explores the intersection between attention, emotions, and expectations, laying the groundwork for subsequent investigations.

Chapter 2 delves into the long-term effects of AVG training on attention, utilizing studies focused on children and adults with DD. These studies, including a meta-analysis, examine how AVG training impacts this population's attentional control, phonological processing, and reading abilities. Additionally, the chapter investigates the synergistic effects of AVG coupled with transcranial random noise stimulation (tRNS) in adults with DD.

Chapter 3 focuses on the short-term effects of gaming and positive emotions on cognitive functioning across various age groups. Studies in this chapter probe into the immediate cognitive impacts of gaming and emotional states in school-age and preschool children, as well as young adults with and without reading difficulties. The research examines the role of action-like video games in salience processing and its implications for reading-related skills.

In Chapter 4, we investigate the effect of caffeine on attention modulation in a sample of healthy young adults. The study unveils the potential of this substance to enhance text reading abilities, executive control, and positive emotional engagement.

Finally, Chapter 5 explores the impact of Lexilens® glasses on reading enhancement. More interestingly, this section investigates the placebo effect driven by expectations and the influence of flickering glasses on reading skills in children with DD and young adults without a diagnosis of DD.

Collectively, this dissertation contributes to our understanding of attentional mechanisms and their modulation through diverse interventions. It elucidates the potential of AVGs, emotional modulation, caffeine, and innovative technologies like Lexilens® glasses in enhancing reading-related functions, particularly in populations with specific learning difficulties, while also outlining limitations and paving the way for future research in this domain.

The concluding evidence in this paper also highlights the role of expectations and the importance of predicting the placebo effect in training and in more general experimentation, especially when the research design involves children and/or susceptible populations.

Chapter 1. Focusing In: Understanding Attention

"Pay attention," "Stay focused," "Search for what you need." These commonplace directives underscore the ubiquitous importance of attention in our daily lives. From the mundane tasks of daily existence to the complex demands of cognitive processes, attention is the behavioural and cognitive process by which we are able to focus on a particular aspect present in our environment on the basis of its relevance, along with the ability to ignore irrelevant stimuli (Sarter et al., 2001). Giving a single definition that reflects all the processes involved when we talk about attention is complex, and the literature has tried to do so in several ways: from "the taking of possession by the mind, in clear and vivid form" (James, 1890), to the spotlight (Posner et al., 1980), zoom lens (Eriksen & St. James,1986) or "glue" that link features to objects (Treisman & Gelade,1980), until "a narrow focus of consciousness" (Cacioppo & Freberg, 2019). Also, in agreement with Narhi-Martinez and colleagues (2023), it is possible to define "Attention as a multi-level system of weights and balances". Indeed, the review proposed by the authors emphasises the top-down and bottom-up mechanisms involved in attentional processes, as well as the role determined by experience and other cognitive factors involved (e.g., working memory) and their dynamicity over time (Narhi-Martinez et al., 2023).

Rooted in the intricate neural networks of the brain, the concept of attention is not unitary (Baddley, 1990) but a dynamic and multifaceted cognitive mechanism. Some authors have proposed models of attention understood as multi-componential (Posner & Boies, 1971) and multidimensional (Sohlberg & Mateer, 1987) in an attempt to explain and understand how attention orchestrates the allocation of cognitive resources, shaping our perceptions, thoughts, and actions. Considering the complexity and breadth of the topic, this chapter will not propose all models and current knowledge on the topic but rather offer a background to introduce subsequent work and studies.

1.1 Attentional Models and Neural Substrates

The modern research on the concept of attention began in the 1950s and can be divided into three historical phases: the first phase (1950s - 1960s) focused on the study of abilities, performance, and limits of human capacities; the second phase (1970s - early 1980s) was characterised by the analysis of cognitive aspects, aiming to discover the processes and mechanisms that determine human performance; the third phase (1980s to the present) delves into the relationship between attentional processes and neural substrates, mind and brain. Most modern research on attention has developed within experimental psychology, with the information processing approach being the most widely adopted theoretical and empirical framework.

The initial exploration into the neural underpinnings of attention was conducted by Moran and Desimone (1985). The authors recorded individual cells in the visual cortex of trained monkeys tasked with identifying stimuli in one visual field while ignoring those in the opposite field. Their focus was on measuring the activity of cells in area V4, which selectively respond to colour. Remarkably, they observed that this activity was influenced by attention. The filtering of irrelevant information from the receptive fields of neurons in extrastriate areas may form the basis for the ability to identify and remember the properties of a particular object among the many that can be represented on the retina (Moran & Desimone, 1985; see Pasupathy et al., 2020 for a review on visual function of V4).

1.1.1 Dorsal and Ventral Attention Network

In a related vein, Corbetta and Schulman (2002) proposed a model exploring the activities of distinct brain networks associated with attention. Their investigation uncovered two underlying processes: “top-down" and "bottom-up." The former involves knowledge and expectations, directing attention either to objects ("what pathway") or space ("where pathway") and necessitating cognitive selection of stimuli and responses. The **Dorsal Attention Network** (DAN), anatomically comprising the posterior parietal and dorsal frontal cortex in both hemispheres, is implicated in top-down or goal-directed control. The functions associated with the DAN include overt or covert orientation of spatial attention, feature-based attention, biasing sensory information, top-down influence on bottom-up processing, and stimulus-driven attentional control (Vossel et al., 2012, 2014). Conversely, lateralised to the right hemisphere, the **Ventral Attention**

Network (VAN) involves the temporoparietal junction and the ventral frontal cortex. The VAN is engaged in bottom-up or stimulus-driven control (Corbetta & Schulman, 2002) and is typically activated during functions such as paying attention to relevant unexpected stimuli, attentional reorienting and shifting, distractor filtering, and paying attention to rare deviant stimuli (Vossel et al., 2012, 2014; See Figure 1). However, recent neuroimaging studies have revealed that DAN and VAN are not exclusively involved in their initially proposed functions, and their interactions through interfaces play a more crucial role in the dynamic and flexible attentional control (Cazzoli et al., 2021; Markett et al.,2022; Suo et al., 2021). Specifically, the influence of VAN on DAN led to decreased performance, manifested as lower speed and accuracy of responses. Conversely, better performance was associated with the influence of DAN on VAN, and it was shown that DAN filters information to the VAN (Vossel et al., 2014). It is essential to note that these brain regions were identified through visual tasks, although the VAN is believed to be shared between auditory and visual modalities (see Kim, 2014 for a meta-analysis).

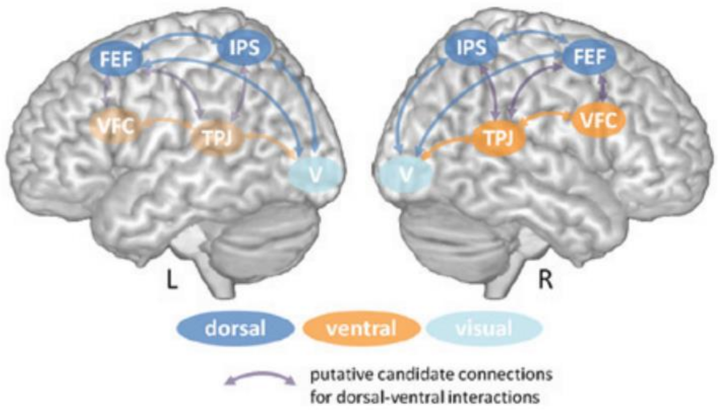

Figure 1. Schematic illustration of the components of the dorsal (blue) and ventral (orange) attention system in the human brain. Image from Vossel, S., Geng, J. J., & Fink, G. R. (2014). Dorsal and ventral attention systems: Distinct neural circuits but collaborative roles. Neuroscientist, 20(2), 150e159. https://doi.org/ 10.1177/1073858413494269.

1.1.2 Triple Network

Attention was also understood through a triadic approach, which contrasts processes of greater non-routine, goal-oriented cognitive control with those of perceptual salience, which are more driven by the characteristics of the stimulus itself and those of default and resting state (Menon, 2011). Specifically, the "Triple Network" include the Default Mode Network (DMN), responsible for self-representation (Buckner et al., 2008; Greicius et al., 2003), the Salience Network (SN) involved in encoding behaviour al relevance (Seeley et al., 2007), and the Central Executive Network (CEN) situated in the frontoparietal region and oriented toward goal-directed activities (Seeley et al., 2007; Vincent et al., 2008; see Ridder et al., 2023 for a review).

Without focused attention or engagement in attention-demanding tasks, the **DMN** is activated, representing a rest wakeful state and a phylogenetically ancient network controlling the parasympathetic nervous system (Hudak et al., 2018). Notably, this network is also implicated in various cognitive processes such as recalling the past, planning for the future, self-reflection, mind reading, and contemplating others (Andrews-Hanna, 2012). The DMN encompasses distributed regions, including the medial prefrontal cortex, precuneus, posterior cingulate cortex (PCC), superior prefrontal gyrus, parietal cortex, subgenual anterior cingulate cortex, middle temporal gyrus, inferior temporal cortex, hippocampus, and parahippocampus (see Baghdadi et al., 2020 for a review). The DMN serves bilateral but predominantly left-sided functions (Nielsen et al., 2013), with alterations in functional connectivity patterns during resting or other mental states (Andrews-Hanna et al., 2014; Hudak et al., 2018; Zhu et al., 2017). Upon initiating a task requiring attentional control, the brain transitions from the DMN to other networks discussed in subsequent sections. This transition has led to the DMN being referred to as the task-negative network (Fox et al., 2005). Dysregulation in the switching process between the DMN and other attention networks is associated with various brain diseases or disorders, including attention-deficit hyperactivity disorder (ADHD) (Hudak et al., 2018). The DMN, characterized by high energy consumption, is theorized to have evolved to continuously predict the environment through mental imagery, providing an evolutionary advantage (Suddendorf & Corballis, 2007; Suddendorf, 2006). Its fundamental function is proposed to support reinforcement learning by utilizing a Markov decision process (Dohmatob et al., 2020). Sensory predictions generated by the left temporoparietal junction (TPJ) are contextualised in the parahippocampus, and intentions are processed by the dorsomedial prefrontal cortex. The PCC/precuneus monitors the environment, while prediction errors are computed in the right TPJ, where the DMN and the SN overlap.

The **SN** is linked to the detection of salient stimuli (i.e. noticeable features from its surroundings), typically eliciting involuntary bottom-up attention and collaborates with the DMN and the CEN to modulate responses and behaviour (see Baghdadi et al., 2020 and Ridder et al., 2023 for reviews). Specifically, while SN and CEN guide behaviour in response to external stimuli, the DMN is implicated in internally directed actions (Uddin, 2016). The SN orchestrates the deactivation and activation of the DMN and CEN, with the insula in the SN sending signals to deactivate the former and activate the latter (Menon & Uddin, 2010; Nekovarova et al., 2014; Sridharan et al., 2008; Uddin, 2016), playing a crucial role in attention shifting (Menon & Uddin, 2010). Studies employing EEG and fMRI demonstrate the role and dynamics of the SN in attentional control, encompassing both bottom-up and top-down attention interactions. Specifically, this network involves key structures such as the dorsal anterior cingulate cortex and anterior insula, which crucially influences attention shifting by deactivating the DMN and activating the CEN, but also primary sensory areas and brain motor control areas but also structures like the rostral anterior ACC, mid anterior insula, habenula, PCC, and left inferior parietal area, that encodes behaviour al relevance and stimulus distinctiveness (Chand & Damala, 2016; Seeley, 2019; Uddin, 2016). Dysfunction in the interplay among these networks is implicated in brain disorders, such as major depression (Goldstein-Piekarski & Williams, 2019; see Schimmelpfennig et al., 2023 for a review).

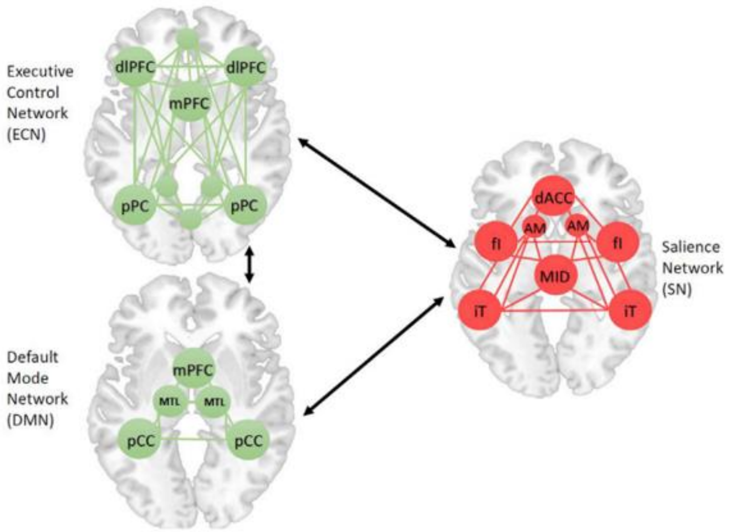

Figure 2. Representation of CEN, DMN and SN cerebral circuits. Image from Schwabe, L., Hermans, E. J., Joëls, M., & Roozendaal, B. (2022). Mechanisms of memory under stress. *Neuron*, *110*(9), 1450–1467. https://doi.org/10.1016/j.neuron.2022.02.020

Note: dlPFC: dorsolateral prefrontal cortex; mPFC: medial prefrontal cortex; pPC: posterior parietal cortex; MTL: medial-temporal lobe; pCC: posterior cingulate cortex; dACC: dorsal anterior cingulate cortex; AM: amygdala; fI: frontal insula; MID: midbrain; iT: inferior temporal cortex.

The **CEN** is considered an evolutionary extension of brain centers controlling the sympathetic nervous system. Indeed, a meta-analysis reveals that some of the brain areas associated with the central autonomic nervous system overlap with the CEN (Beissner et al., 2013). Specifically, the frontoparietal control network (FPCN), crucial in orchestrating the transition between resting and attentional states (Marek & Dosenbach, 2018), comprises two subnetworks, namely $FPCN_A$ and $FPCN_B$ (Kam et al., 2019). $FPCN_A$ is associated with internally directed attention, while $FPCN_B$ is involved in visuospatial attention (Kam et al., 2019). Each subnetwork encompasses various brain regions, like the rostrolateral prefrontal cortex, middle superior frontal gyrus, superior frontal gyrus in $FPCN_A$ and the inferior frontal sulcus, posterior part of the superior frontal sulcus in $FPCN_B$ (see Baghdadi et al., 2020 for a review). However, the brain areas engaged in FPCN may vary among individuals or be influenced by different brain diseases, including ADHD (Marek & Dosenbach, 2018; Tang et al., 2021). Left-lateralized and involved in goal-oriented behaviour, the CEN, also known as the FPCN (Vincent et al., 2008), exhibits protective functions related to the body's immune system against symptoms of mental disease (Cole et al., 2014; Miller et al., 2018; Padmanabhan et al., 2019).

In summary, while the SN and CEN contribute to cognitive functioning, they serve distinct roles in processing external stimuli and internal cognitive tasks, respectively. Indeed, the SN is primarily responsible for detecting and assigning importance to external stimuli and internal mental events and plays a crucial role in switching attention between different stimuli or tasks, integrating sensory information, and initiating appropriate behavioral responses. Instead, the CEN is involved in higher-order cognitive functions such as working memory, cognitive control, decision-making, and goal-directed behavior and plays a critical role in orchestrating and coordinating cognitive processes, allocating attentional resources, and maintaining task-relevant information in working memory.

Recent work by Schwabe and colleagues (2023) highlights the role and effects of the Triple Network on memory under stress. In particular, the authors propose a new integrative framework that connects cellular, systems, and cognitive mechanisms, providing insights into acute stress effects on memory processes and suggesting potential targets for treating abnormal memory in stress-related mental disorders (Schwabe et al., 2023; see Figure 3).

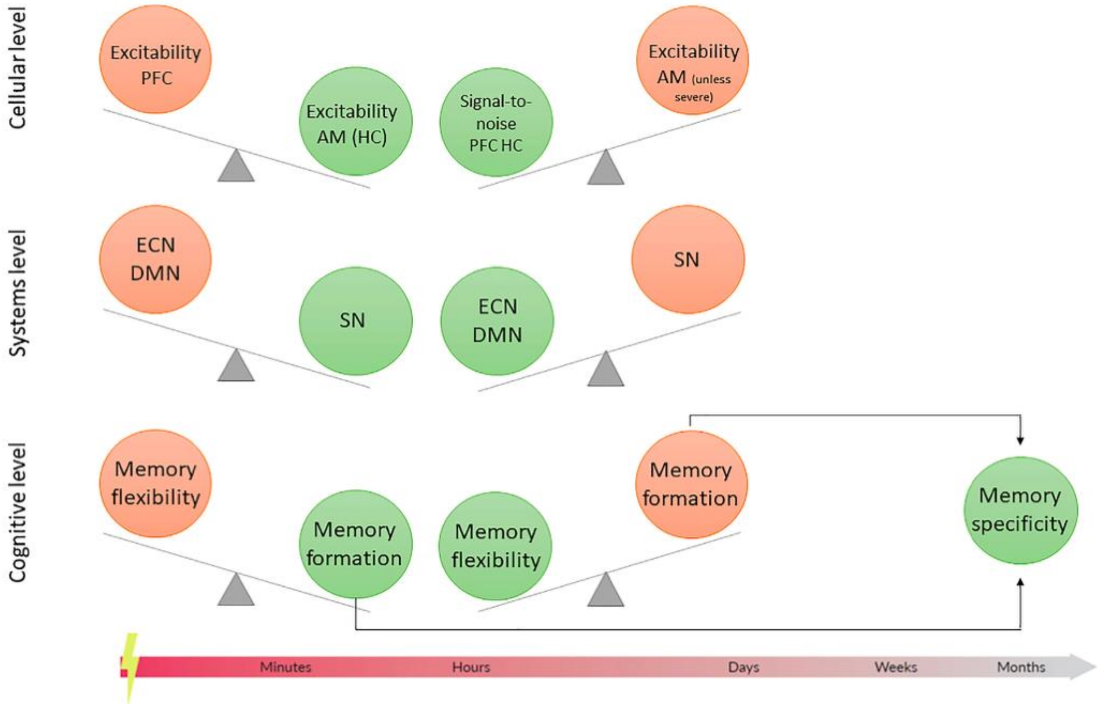

Figure 3. Integrative framework of how acute stress alters memory processes. Image from Schwabe, L., Hermans, E. J., Joëls, M., & Roozendaal, B. (2022). Mechanisms of memory under stress. *Neuron*, *110*(9), 1450–1467. https://doi.org/10.1016/j.neuron.2022.02.020.

Note: HC: hippocampus; AM: amygdala (AM); PFC: prefrontal cortex (PFC); SN: salience network; ECN: executive control network; DMN: default-mode network.

This model of large-scale brain networks is also the work of Hermans and colleagues (2014), which highlights the role of stress (i.e., a physical or psychological event that threatens an organism's homeostasis). Specifically, the authors' model proposes a framework describing global and dynamic shifts in network resource allocation in response to acute stressors, integrating analyses at the neuroendocrine, cellular, and brain systems, and behavioural levels. Cognitively, during the acute phase, neural resources are allocated to the SN while the CEN is actively suppressed. In the recovery phase, this pattern is reversed, with resources allocated to the CEN and the suppression of the SN. The roles of neurotransmitters and hormones, such as dopamine, serotonin, and neuropeptides, during these phases are not fully understood in human research, but future studies are expected to provide more details. Finally, the framework suggests that maladaptation to stress may result from an inability to contain sympathetic activation by subsequently released corticosteroids, potentially impairing cognitive control over the emotional aspects of stressful events (See Figure 4).

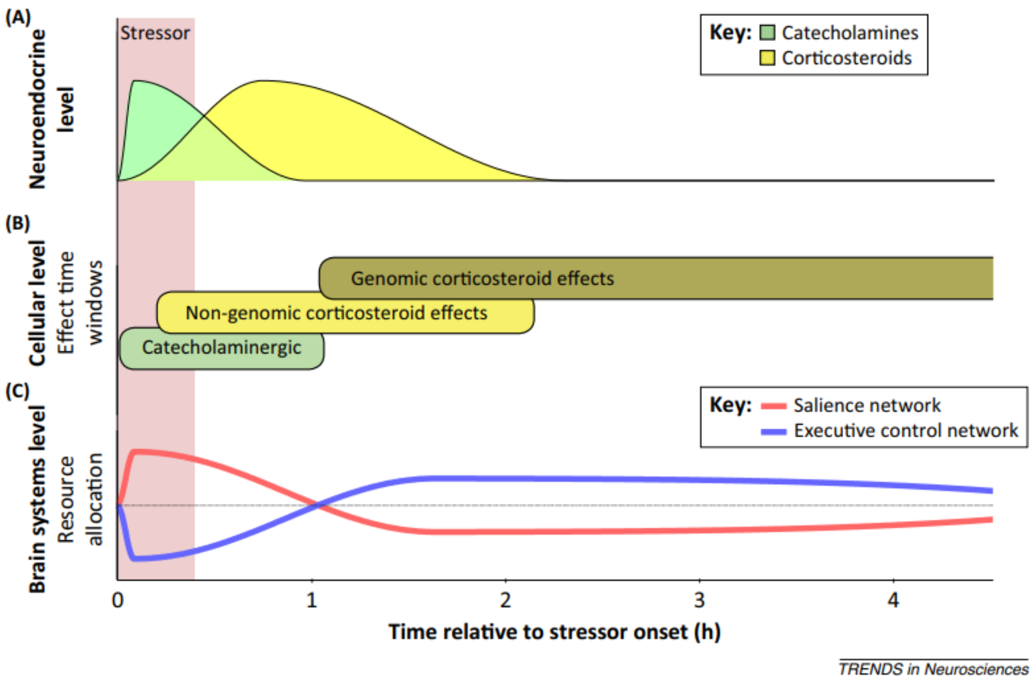

Figure 4. Biphasic-reciprocal model of reallocation of neural resources in response to stress. Image from Hermans, E. J., Henckens, M. J., Joëls, M., & Fernández, G. (2014). Dynamic adaptation of large-scale brain networks in response to acute stressors. *Trends in Neurosciences*, *37*(6), 304-314. https://doi.org/10.1016/j.tins.2014.03.006

1.2 Neuromodulation of Attention

Delving into the intricate realm of attention reveals a highly complex mechanism involving the concerted efforts of various brain areas and the influence of several neurotransmitters, and some are crucial to the operation of attentional networks. Examples of these include dopamine (DA), serotonin (5-HT), acetylcholine (Ach), and noradrenaline (NA, or norepinephrine) (Greene et al., 2009; Noudoost & Moore, 2011; Sarter et al., 2001; see Thiele & Bellgrove, 2018 and Baghdadi et al., 2020 for reviews). Notably, Ach emerges as the principal attention neuromodulator, exhibiting the capacity to diminish rate variability, thus augmenting population coding abilities (Furey et al., 2008; Kanamaru & Aihara, 2019; Thiele and Bellgrove, 2018). This reduction in variability translates into a decreased susceptibility to distractions and prolonged engagement with tasks (Deco & Thiele, 2009; Himmelheber et al., 2001; Thiele and Bellgrove, 2018). In the context of the orienting network of attention, Ach is indispensable for its functions, acting as both a neurotransmitter and neuromodulator in the central nervous system (CNS) and peripheral nervous system (PNS) (Furey et al., 2008; Thiele and Bellgrove, 2018). Cholinergic neurons, responsible for secreting Ach, are distributed in both the PNS and CNS. In the PNS, the release of Ach is vital for muscle activation and supports the autonomic nervous system's activity. Within the CNS, the pathway of Ach from the basal forebrain, including the medial septal, diagonal band nuclei, and nucleus basalis, to the cerebral cortex and hippocampus plays a pivotal role in various cognitive functions (see Baghdadi et al., 2020 for a review). These functions encompass arousal, attention, memory, and motivation (Furey et al., 2008; Thiele and Bellgrove, 2018). The intricate web of cholinergic activity within the CNS underscores its multifaceted contributions to cognitive processes (Kanamaru & Aihara, 2019). As a neurotransmitter, Ach aids in transmitting signals within neural circuits, while its role as a neuromodulator extends beyond immediate synaptic transmission, influencing the overall state and dynamics of neural networks (Deco & Thiele, 2009). In this dual capacity, Ach emerges as a linchpin in orchestrating cognitive functions and maintaining the delicate balance required for optimal attentional processes (Himmelheber et al., 2001).

Meanwhile, DA governs top-down attentional processes and regulates various cognitive functions (Noudoost and Moore, 2011; Thiele and Bellgrove, 2018). Specifically, evidence suggests that DA plays a crucial role in the integrity of attention-related networks, including the DAN, DMN, and FPCN (Dang et al., 2012).

Additionally, the pathway of DA from the SN to the striatum is involved in diverse aspects of motor control, highlighting the multifaceted roles of DA in neural processes (Miller et al., 2013). As a neurotransmitter, DA is synthesized in two midbrain centers, the substantia nigra and the ventral tegmental area (VTA), and subsequently transmitted to diverse brain regions, including the prefrontal cortex (PFC), striatum, and nucleus accumbens (NA) (Miller et al., 2013). The DA pathway originating from the VTA to the PFC is recognized as the emotion or reward circuit, implicated in responses to rewards and their anticipation (Miller et al., 2013).

Concurrently with other neurotransmitters, NA plays a crucial role in amplifying stimulus signals by releasing cellular sodium, thereby intensifying input-driven activity, particularly in response to behaviourally relevant stimuli and the alerting network (Sarter et al., 2001; Thiele and Bellgrove, 2018). Additionally, NA functions as a regulatory force, mitigating distractibility and promoting focused attention (Greene et al., 2009; Thiele & Bellgrove, 2018). Originating from the locus coeruleus (LC), NA is distributed to various brain regions (i.e. PFC, thalamus, hippocampus, hypothalamus, amygdala, and cerebellum; see Cherkasova & Hectman, 2013; Down & McElligott, 2022). Moreover, NA influences brain circuits involved in the emotional modulation of attention, highlighting its multifaceted role in cognitive processes (De Martino et al., 2008).

While 5-HT is widely recognized for its association with feelings of happiness, its influence extends beyond mood regulation. It plays a multifaceted role in various cognitive functions, including memory, learning, executive functions, and attention (Enge et al., 2011; Tsaltas & Boulougouris, 2011; Wingen et al., 2008). The role of 5-HT in attentional mechanisms adds a layer of complexity and ambivalence. Notably, its impact seems to enhance task focus when 5-HT levels are low, yet it contributes to disengagement as these levels rise (Thiele and Bellgrove, 2018). The 5-HT circuit includes brain structures such as the raphe nuclei, clusters of nuclei located in the brainstem, and projections extending to diverse areas, including the cerebral cortex, hippocampus, and amygdala (see Baghdadi et al., 2021 and Thiele and Bellgrove, 2018 for reviews). These structures are integral to the intricate modulation of 5-HT neurotransmission, influencing mood, cognitive functions, and emotional processing (see Bacqué-Cazenave et al., 2020 for a review).

Chapter 2. Long-Term Effect of Action Video Game Training on Attention

Introduction

For most people, reading is an automatic and almost involuntary process, but for children and adults with developmental dyslexia (DD) the reading process is slow and laborious. According to the American Psychiatric Association, DD is a specific learning disorder characterised by difficulty in reading acquisition (DSM-5, 2013). Despite adequate education and intelligence, individuals with DD manifest problems with word recognition, poor phonological decoding and spelling skills which interfere with school or work performance or with activities of daily living (DSM-5 TR, 2022).

The main neuropsychological deficits associated with DD seem to refer to auditory (e.g., Boets et al., 2007; see Tallal, 2004 for a review and Gu & Bi, 2020 for a meta-analysis) and phonological processing (see Peterson & Pennington, 2015; Vellutino et al., 2004; Ziegler & Goswami, 2005, for reviews and Melby-Lervåg et al., 2012, for a meta-analysis), rapid naming (see McWeeny et al., 2022 for a meta-analysis), sensorimotor coordination and implicit procedural deficit (see Nicolson et al., 2001 for a review and Lum et al., 2013 for a meta-analysis), executive functions (i.e., inhibition, switching attention and auditory working memory; see Lonergan et al., 2019 for a meta-analysis) as well as to visual attention mechanisms and magnocellular impairment (e.g., Franceschini et al., 2022b; Gori et al., 2016; Menghini et al., 2010; Stein & Walsh, 1997; Taran et al., 2022; Vidyasagar & Pammer, 2010; see Grainger et al., 2016, and Valdois, 2022, for reviews and Gavril et al., 2021 for a meta-analysis).

Although there are many longitudinal studies that have demonstrated the multiple cognitive deficits of DD (e.g., Bertoni et al., 2019; Carroll et al., 2016; Franceschini et al., 2012; Gori et al., 2016; O'Brien & Yeatman, 2021), most clinical training for reading enhancement in children with DD mainly involves phonologically-based reading instruction programs (Peterson & Pennington, 2012). In particular, phonemic awareness (e.g., Bowyer-Crane et al., 2008; Bradley & Bryant, 1983) and reading acceleration programs (Breznitz et al., 2013) are currently implemented for reading remediation in children with DD, even if the remediation based on explicit, systematic instruction on letter-to-speech integration (i.e., decoding strategies and "phonics training") appears to be the most efficient training (see Gabrieli, 2009, for a review; Galuschka et al., 2014, and McArthur et al., 2012 for meta-analyses). However, all the existing treatments for DD demand high levels of resources and are controversial (see McArthur et al., 2018 and Peters et al., 2019, for two systematic reviews). Indeed, the cognitive processes underlying these training-induced improvements in reading ability remain unclear (see Dehaene et al., 2015, for a review). Critically, as DSM-5 (2013, pp. 66) mentions, the exclusion criteria provide "despite the provision of intervention that targets those difficulties". In this way, if a child benefited from explicit and systematic reading instruction training, this child might not be diagnosed as DD.

The systematic review by Peters and colleagues (2019) highlights that visual attention training programs for children with DD (i.e., visual perceptual learning, visually-based reading acceleration programs and action video games, AVGs) can be an efficient alternative to traditional phonologically-based reading instruction programs. In particular, AVGs training is a visual attention training for children with DD because it involves no phonological and/or orthographic processing (Franceschini et al., 2013). According to the definition by Green and Bavelier (2012), AVGs are characterised by fast-paced events and objects that move unpredictably, even in the periphery of the screen. Moreover, these games involve a high degree of perceptual, cognitive and motor load. Indeed, the numerous visual stimuli must be followed or kept in working memory and may require the player to choose and execute different plans of action very quickly in order to achieve the goal. AVGs provide strong reward signals that stimulate and motivate behaviour and are the ideal gym for spatial and temporal attention, placing the brain in a more plastic state (Bavelier & Green, 2019). With reward systems, spatial and temporal attention leads to more efficient learning because they can attenuate the processing of goal-irrelevant information (Roelfsema et al., 2010). Importantly, the domain-general attentional advantage induced by AVGs experience extends beyond perceptual and cognitive processes. Indeed, a recent cross-sectional study indicates enhanced discrimination of facial emotions in AVG players arising from enhanced attentional processing of emotional information (Ciobanu et al., 2023). The dynamic stimuli of AVGs are mainly analysed by the magnocellular and dorsal pathways, whereas the FPCN, as well as the CEN, are crucial to efficiently playing AVGs (e.g., Dye et al., 2009; Gori et al., 2016; Green & Bavelier, 2015; Nava et al., 2020; Oei & Patterson, 2013; see Bavelier & Green, 2019 for a review).

Accordingly, evidence from neuroimaging and electrophysiological studies shows that the experience of playing with AVGs is associated with a structural and functional change in the prefrontal regions (e.g., Gong et al., 2017; Richlan et al., 2018) and the posterior parietal cortex (Cui et al., 2021; Föcker et al., 2019; Foerster et al., 2023; Tanaka et al., 2013). These neural changes could underlie the cognitive improvements induced by this gaming experience (see Bediou et al., 2018; 2023; Ren et al., 2023 and Wang et al., 2016, for meta-analyses). In particular, several studies have shown that AVGs training could improve perceptual, attentional and visuo-spatial mechanisms (Alsaad et al., 2022; Bavelier & Green, 2019; Bediou et al., 2018, Wu et al., 2021), but also reading and phonological abilities in children and adults with and without DD (e.g., Antzaka et al., 2017; Bertoni et al., 2019; 2021; Cancer et al., 2020; Franceschini & Bertoni, 2019; Franceschini et al., 2017a; Pasqualotto et al., 2022; Mancarella et al., 2022; see Peters et al., 2019 for a review).

Overall Aim and Studies

The literature underscores the multifaceted benefits of AVGs on different cognitive tasks, suggesting their potential to cultivate a broad skill set rather than imparting specific abilities (Bavelier et al., 2012; Zhang et al., 2021). So, in this chapter, AVGs are also proposed as tools fostering the capacity for "learning to learn," indicating the rapid acquisition of proficiency in novel tasks (Green et al., 2010). Specifically, the main of the first proposed study ("Study 1. Action Video Games Enhance Attentional Control and Phonological Decoding in Children with Developmental Dyslexia") was to compare the effects of training with AVG toward training with Non-Action Video Games (NAVG) in children diagnosed with DD. The effectiveness of the proposed training was deepened through a meta-analysis ("Study 2. Action Video Games Training in Children with Developmental Dyslexia: A Meta-Analysis") by comparing it directly with an active control treatment, that is the more stringent control condition. The preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines (Moher et al., 2009; Page et al., 2021) are followed to answer doubts about the real efficacy of this unconventional training for reading difficulties in children with DD.

Finally, considering that the AVG induce plasticity in the frontoparietal attentional networks (Bavelier et al., 2012; Bertoni et al., 2021; Jordan & Dhamala, 2023; see Bavelier & Green, 2019 for a review) and that transcranial random noise stimulation (tRNS) works on the modulation of large-scale neural networks (Reed & Cohen Kadosh, 2018), in the third study ("Study 3. Action Video Game Training and Parietal Neuromodulation to Improve Attention and Reading Abilities in Adults with Developmental Dyslexia") we test the effect of the combination of an intensive but brief AVG training with bilateral tRNS on the posterior parietal cortex in adults with DD. In particular, we chose to combine AVG with high-frequency tRNS (hf-tRNS), which is capable of inducing excitatory effects (Campana et al., 2016; Terney et al., 2008), hypothesizing a boost of the AVG training effect during the gameplay, and expecting better reading and temporal attention performance measured at the end of this innovative combined training.

Study 1. Video Games Enhance Attentional Control and Phonological Decoding in Children with Developmental Dyslexia

Bertoni, S., Franceschini, S., Puccio, G., Mancarella, M., Gori, S., & Facoetti, A. (2021). Action Video Games Enhance Attentional Control and Phonological Decoding in Children with Developmental Dyslexia. Brain sciences, 11(2), 171. https://doi.org/10.3390/brainsci11020171

Abstract

Reading acquisition is extremely difficult for about 5% of children because they are affected by a heritable neurobiological disorder called developmental dyslexia (DD). Intervention studies can be used to investigate the causal role of neurocognitive deficits in DD. Recently, it has been proposed that action video games (AVGs) - enhancing attentional control - could improve perception and working memory as well as reading skills. In a partial crossover intervention study, we investigated the effect of AVG and non-AVG training on attentional control using a conjunction visual search task in children with DD. We also measured the non-alphanumeric rapid automatized naming (RAN), phonological decoding and word reading before and after AVG and non-AVG training. After both video game training sessions, no effect was found in non-alphanumeric RAN and word reading performance. However, after only 12 h of AVG training the attentional control was improved (i.e., the set-size slopes were flatter in visual search) and phonological decoding speed was accelerated. Crucially, attentional control and phonological decoding speed were increased only in DD children whose video game scores were highly efficient after the AVG training. We demonstrated that only efficient AVG training induces a plasticity of the fronto-parietal attentional control linked to a selective phonological decoding improvement in children with DD.

2.1.1 Material and Method

Participants

Participants were 14 native Italian-speaking children (four females and 10 males; mean age=8.93 years SD=0.99) with DD. DD was diagnosed based on National Health Service criteria: typical intelligence quotient, no hearing difficulties or neurological deficits, normal or corrected to normal vision (DSM-5; APA, 2013). A child was diagnosed with DD if their speed and/or accuracy in word and pseudoword standardized reading tasks were below − 2 standard deviations. The information about video game experience was collected through interviews with parents during a pre-informative briefing about the experimental training. Children with DD did not know the aim of the training and in the previous 6 months did not play AVGs for more than 1 h per week. A crossover intervention study, in which each participant was treated both with AVGs and NAVGs (but two children; n=12) in counterbalanced order, was executed. Specifically, 2 children were not avaible to concude the entire design. The study was approved by the Ethics Committee of Psychological Research, University of Padua (Protocol number: 1452; Code: D32B2B803B68E2600F95F0CF66DC42D8).

Training Procedure

Participants were individually trained in a dimly lit and quiet room. Participants were tested between 2 to 3 days before the start of treatment and re-tested between 2 and 3 days after the end of training. Training consisted of 9 days of AVG sessions and 9 days of NAVG sessions of 80 min each and vice versa, for a total of 12 hours of training with AVG and 12 hours of training with NAVG. Between T2 and the start of the other training session about 10 days passed. Video games were played standing about 200 cm from a 27-inch TV screen. The commercial Wii^{TM} video game ("Rayman ® Raving Rabbids", PEGI: 7 years old) and the mini-games list for AVG and NAVG training were the same used in previous research (Bertoni et al., 2019; Franceschini et al., 2013; 2017; Gori et al., 2016). Similarly to Franceschini and Bertoni (2019), the final video game scores of the individual players were recorded after the two training sessions. The timeline of the present study is reported in Figure 5.

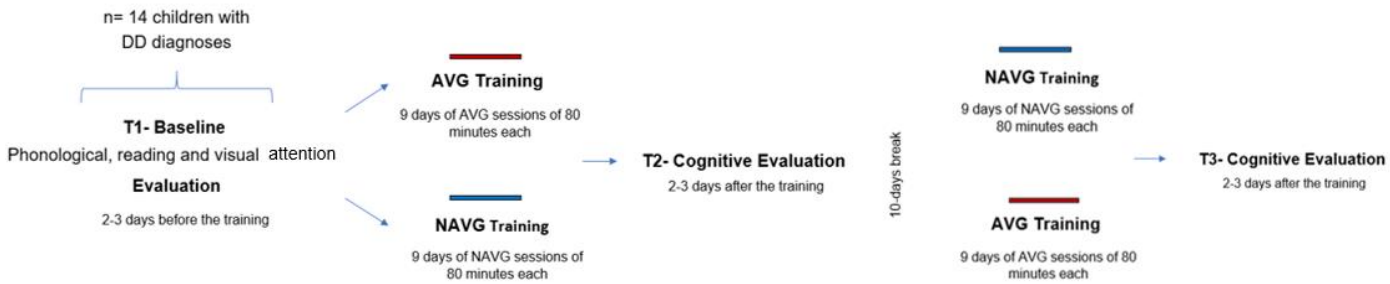

Figure 5. Schematic representation of the timeline of Study 1.

Neuropsychological Battery

Reading Tasks

Pseudoword and word texts and lists order administration were counterbalanced between children before and after AVG and NAVG trainings.

1. Word List Reading

Reading abilities (speed and number of errors) were measured using three-word texts (based on "Marcovaldo", Calvino, 1966), and three lists, of 27 words each, composed of 2–4 syllables (Franceschini et al., 2016).

2. Pseudoword List Reading

Phonological decoding abilities (speed and number of errors) were measured using three pseudoword texts (Franceschini et al., 2016), and three lists of 15 pseudowords each, composed of 2–4 syllables (the same syllables in different order for the three lists; Franceschini et al., 2016).

Visual Search Task

The experimental procedure and data acquisition were controlled with E-prime 2.0 (Psychology Software, Inc., Sharpsburg, PA, USA). Participants were seated 60 cm away from the screen. The children' task was to indicate the presence or absence of the target ignoring the distractors with a key press (Y or B on a keyboard, respectively). The stimuli (little puppets) were shown at two eccentricities: at 4.30 deg and 9.07 deg around the center of the screen. The children were asked to keep their eyes on the center of the screen for the duration of each trial. To control that children were fixing at the center of the screen, in eight fixation control trials, a stimulus (target or distractor) was shown at the center of the screen. The target and distractors were similar in color, but they differed in shape. After a small cross (0.1° and 0.6 cd/m2) appeared at the center of the screen for 500 msec, the target and distractors (both of 2.86° × 3.82°) were shown for 2000 msec. The task was composed of four different set-size conditions (3, 5, 9 and 13 stimuli with or without the target; Figure 6). A total amount of 208 trials were presented (eight fixation control trials; 50 trials for each set-size, 25 trials with target and 25 trials without target).

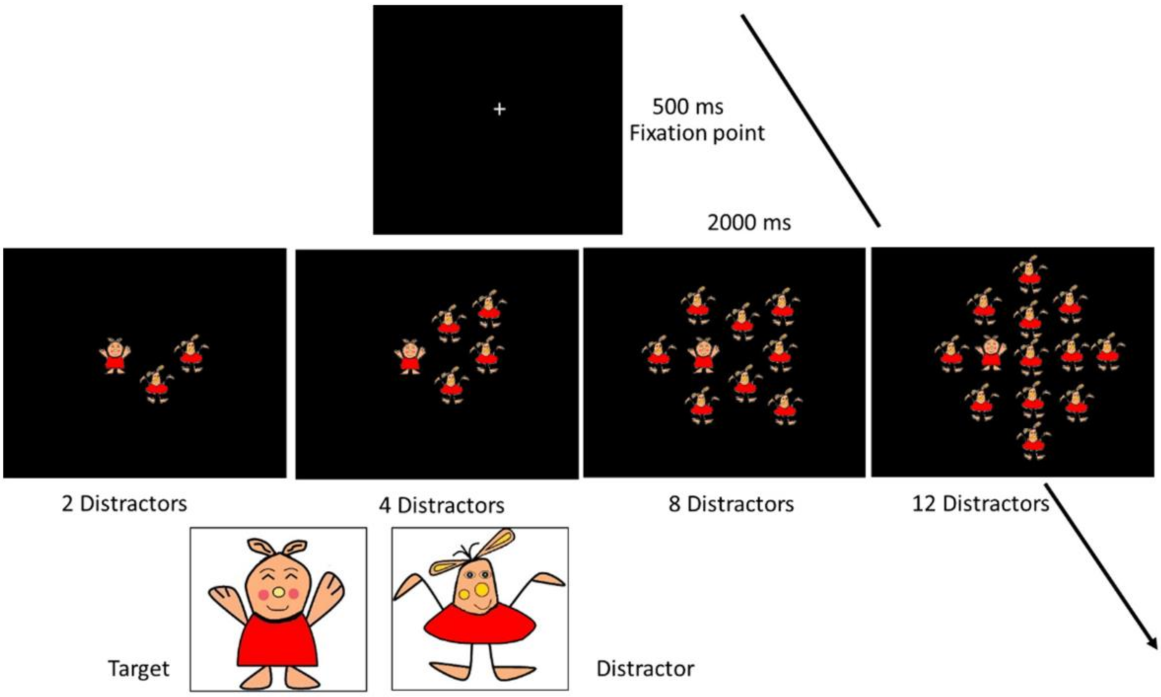

Figure 6. Schematic representation of the serial visual search task with the four possible distractor set-sizes (target present condition is reported). Target and distractor stimuli are also reported. Image from Bertoni, S., Franceschini, S., Puccio, G., Mancarella, M., Gori, S., & Facoetti, A. (2021). Action Video Games Enhance Attentional Control and Phonological Decoding in Children with Developmental Dyslexia. Brain sciences, 11(2), 171, p. 5. https://doi.org/10.3390/brainsci11020171

Non-Alphanumeric RAN Task

The experimental procedure and data acquisition were controlled with E-prime 2.0 (Psychology Software, Inc., Sharpsburg, PA, USA). Cross-modal mapping from visual stimuli to the correspondent spoken words was measured by using a computerized single-item RAN task (Mascheretti et al., 2018), in which a single-filled colored circle was presented (i.e., red, blue, white and Green). Since previous studies showed that alphanumeric RAN tasks are biased by reading experience (Rakhlin et al., 2013), we used a non-alphanumeric RAN task. Previous studies showed that non-alphanumeric RAN tasks predict later reading performance (Lervåg & Hulme, 2009; Bertoni et al., 2019). Participants were seated 60 cm away from the screen. After a fixation point (500 msec), and a blank screen of 50 msec, a colored circle (diameter=4.3 deg) appeared at the center of the screen remaining until the children responded. The children' task was to name the colors of the circles as fast as possible in a microphone connected to a response box (E-prime 2.0 Psychology Software, Inc., Sharpsburg, PA, USA), which recorded the onset of vocal response. Response's accuracy was entered by the experimenter, by pressing the corresponding key on the computer keyboard. The inter-trial interval was 1550 msec. A total amount of 32 trials were presented, divided into two blocks of 16 trials each (four trials for each color).

2.1.2 Results

Within-Subject Analysis: Pre vs. Post-AVG and Pre vs. Post-NAVG

Reading Task

Phonological Decoding Tasks

Pseudoword reading speed (syllables per second, syll/sec) improvement was evaluated in AVG and NAVG training sessions by two separate ANOVAs with a 2 x 2 design. Specifically, the within variables were the Time (pre- and post-training) and the Tasks (pseudowords lists and pseudowords texts). Results showed a significant main effect of Time in the AVG training ($F_{(1,13)}$=8.982, p=0.010, η^2=0.409; pre-AVG M=0.95, SD=0.23, post-AVG M=1.06, SD=0.31; mean improvement=0.11 syll/sec).

In contrast, the main effect of time in the NAVG training was not significant ($F_{(1,11)}$=1.558, p=0.238, η^2=0.124; pre-NAVG M=1.07, SD=0.31; post-NAVG M=1.11, SD=0.34; mean improvement=0.04 syll/sec). Individual data analysis showed that after the AVG training session, 8 out of 14 players (about 60%) improved their pseudoword reading speed more than the mean improvement after the NAVG training session.

The same ANOVAs considering the number of errors as dependent variable were not significant neither after AVG nor after NAVG training session (AVG: $F_{(1,13)}$=0.188, p=0.67, η^2=0.014; pre-AVG M=7.57 SD=5.16, post-AVG M=7.93 SD=3.85; mean improvement=− 0.36 errors; NAVG: $F_{(1,11)}$=0.059, p=0.813, η^2=0.005; pre-NAVG M=8.50 SD=3.86, post-NAVG M=8.71 SD=5.36; mean improvement=− 0.21 errors).

Thus, the reading improvements after the AVG training were characterized by increased phonological decoding speed without any cost in accuracy, confirming the previous experimental evidence (Bertoni et al., 2019; Franceschini & Bertoni, 2019; Franceschini et al., 2013; 2017).

Word Reading Tasks

Word reading speed (syll/sec) improvement was evaluated in AVG and NAVG training by two separate ANOVAs with a 2 x 2 design. Specifically, the within subject factors were the Time (pre and post-training) and the Tasks (word lists and word texts). Results did not show any significant effect neither after AVG nor after NAVG training session (AVG: $F_{(1,13)}$=0.084, p=0.776, η2=0.006; pre-AVG M=1.25, SD=0.40, post-AVG M=1.27, SD=0.49; mean improvement=0.02 syll/sec; NAVG: $F_{(1,11)}$=0.062, p=0.807, η^2=0.006; pre-NAVG M=1.30 SD=0.44, post-NAVG M=1.27, SD=0.41; mean improvement=− 0.03 syll/sec). The same ANOVAs considering the number of errors as dependent variable, did not show any significant effect either after AVG nor after NAVG training session (AVG: $F_{(1,13)}$=0.006, p=0.941, η^2=0.001; pre-AVG M=12.14, SD=8.14, post-AVG M=12.2,5 SD=6.39; mean improvement=− 0.11, errors; NAVG: $F_{(1,11)}$=0.989, p=0.341, η^2=0.082; pre- NAVG M=11.75 SD=6.08, post-NAVG M=13.38, SD=8.99; mean improvement=− 1.63 errors).

Visual Search Task

The RTs (in msec) and accuracy (in rate) in the visual search task were analyzed by using two ANOVAs with a 2 x 2 x 4 x 2 design. Specifically, the within-subject factors were the Time (pre and post-training), the Task Conditions (target present and target absent), the Set-Sizes (2, 4, 8 and 12 distractors) and the Training (AVG and NAVG).

RTs

In the ANOVA for the AVG training, the main effects of task condition ($F_{(1,13)}$=27.16, p<0.001, η^2=0.676), and set-size ($F_{(1,13)}$=138.11, p<0.001, η^2=0.914) were significant. In addition, the task condition × set-size interaction ($F_{(1,13)}$=45.36, p<0.001, η2=0.777) was significant. Crucially for our hypothesis, time × set-size interaction was also significant ($F_{(1,13)}$=5.56, p=0.035, η^2=0.30). Planned comparisons showed that the RTs reduction was present in the more difficult set-size condition (12 distractors: $t_{(13)}$=2.192, p=0.047; pre-AVG M=1222 SD=170; post-AVG M=1106 SD=157; see Figure 7, Panel A) and not in the other set-size conditions (eight distractors: $t_{(13)}$=2.066, p=0.059; pre-AVG M=1138 SD=168; post-AVG M=1049, SD=130; four distractors: $t_{(13)}$=1.705, p=0.112; pre-AVG M=1066, SD=164; post-AVG M=979, SD=118; two distractors: $t_{(13)}$=1.158, p=0.268; pre-AVG M=940, SD=134; post-AVG M=894, SD=106). Planned comparison showed that the AVG training reduced the slope of the set-size effect measured as the RTs difference between the smaller (i.e., two distractors) and the larger (i.e., 12 distractors) set-size conditions ($t_{(13)}$=2.307, p=0.038; pre-AVG slope: M=281, SD=89; post-AVG slope: M=212 SD=91).

In the ANOVA for the NAVG training, the main effects of task condition ($F_{(1,11)}$=25.62, p<0.001, η^2=0.70) and set-size ($F_{(1,11)}$=118.99, p<0.001, η^2=0.915) were significant. In addition, the task condition × display size interaction ($F_{(1,11)}$=27.65, p<0.001, η^2=0.715) was significant. Importantly, time × set-size interaction was not significant ($F_{(1,11)}$=0.254, p=0.62, η^2=0.023).

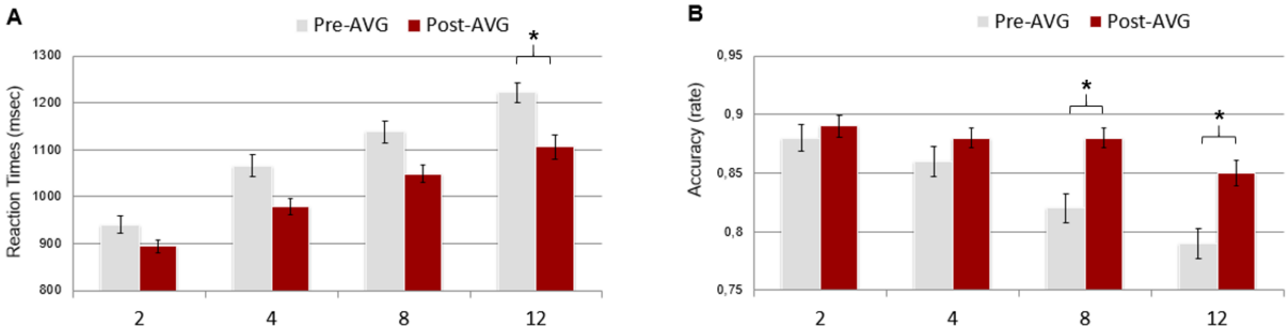

Figure 7. Panel (A): reaction times (in msec) in visual search before (pre-AVG) and after (post-AVG) action video game training. Panel (B): accuracy (in rate) in visual search before (pre-AVG) and after (post-AVG) action video game training. Error bars report the mean standard error. The asterisks indicate the significant differences.

Accuracy

In the ANOVA for the AVG training main effects of time ($F_{(1,13)}$=7.25, p=0.018, η^2=0.358) and set-size were significant ($F_{(1,13)}$=9.75, p=0.008, η^2=0.429). In addition, the task condition × set-size interaction was significant ($F_{(1,13)}$=11.07, p=0.005, η^2=0.460). Crucially for our hypothesis, time × set-size interaction was also significant ($F_{(1,13)}$=4.68, p=0.048, η^2=0.265). Planned comparisons showed that the accuracy improvement was present in the more difficult set-size conditions (12 distractors: $t_{(13)}$=2.877, p=0.013; pre-AVG M=0.79, SD=0.09; post-AVG M=0.85, SD=0.08; eight distractors: $t_{(13)}$=3.312, p=0.006; pre-AVG M=0.82, SD=0.09; post-AVG M=0.88, SD=0.07; see Figure 7, Panel B), but not in the other set-size conditions (four distractors: $t_{(13)}$=1.006, p=0.33; pre-AVG M=0.86, SD=0.09; post-AVG M=0.88, SD=0.06; two distractors: $t_{(13)}$=0.762, p=0.46; pre-AVG M=0.88, SD=0.08; post-AVG M=0.89, SD=0.07). Moreover, planned comparison showed that the AVG training nullified the slope of the set-size effect measured as the accuracy difference between the smaller (i.e., two distractors) and the larger (i.e., 12 distractors) set-size conditions (pre-AVG: $t_{(13)}$=3.941, p=0.002; two distractors: M=0.87, SD=0.08; 12 distractors: M=0.79, SD=0.09; post-AVG: $t_{(13)}$=1.418, p=0.18; two distractors: M=0.89 SD=0.07; 12 distractors: M=0.85

SD=0.08; one-tail t-test pre- vs. post-AVG slope: ($t_{(13)}$=1.879, p=0.04; pre-AVG slope: M=0.08, SD=0.08; post-AVG slope: M=0.04, SD=0.11).

In the ANOVA of accuracy in the NAVG training only the main effect of the set-size was significant ($F_{(1,11)}$=13.99, p=0.003, η^2=0.56). Importantly, time × set-size interaction was not significant ($F_{(1,11)}$=3.07, p=0.11, η^2=0.218).

Non-Alphanumeric RAN Task

The vocal RTs (in msec) in the RAN task were analyzed by two ANOVAs with a 2 x 2 design. In particular, the within-subject factors were the Time (pre- and post-training) and the Training (AVG and NAVG). Neither ANOVA on AVG nor NAVG training showed any significant effect (AVG: $F_{(1,13)}$=0.10, p=0.757, η^2=0.008; pre-AVG M=876, SD=245, post-AVG M=848, SD=232; mean improvement=28 msec; NAVG: $F_{(1,11)}$=1.364, p=0.267, η^2=0.11; pre-NAVG M=870, SD=234, board game M=796, SD=172; mean improvement=74 msec).

Action Video Game Ability after Training

Similarly to Franceschini and Bertoni (2019), we recorded the video game scores of participants in order to control the players' game efficiency after AVG training. The median game score was calculated after AVG training. We divided the sample in two sub-groups: the children with a game score greater than the median score (high score players, HSPs, n=7; three females and four males) and those who showed a game score lower than the median score (low score players, LSPs, n=7: one female and six males).

The change of pseudoword reading speed (syll/sec) between pre- and post-AVG training was analyzed with two non-parametric Wilcoxon tests for HSP and LSP sub-groups. The results show an improvement in pseudoword reading speed only in HSP sub-group (Z=− 2.20, p=0.028; pre-AVG M=1.06, SD=0.23, post-AVG M=1.23, SD=0.34; phonological decoding speed improvement=0.17 syll/sec SD=0.14), but not in LSP sub-group (Z=− 1.37, p=0.17; pre-AVG M=0.85, SD=0.19, post-AVG M=0.89, SD=0.15; phonological decoding speed improvement=0.04, SD=0.07).

The non-parametric Wilcoxon tests in HSP and LSP sub-groups were also conducted to test the possible difference in RTs and accuracy of the set-size slope, indexed as the difference between the smaller (i.e., two distractors) and the larger (i.e., 12 distractors) set- size conditions. The RTs and accuracy set-size slopes were reduced only in HSP sub-groups (RTs: $Z=-2.20$, $p=0.028$, pre-AVG M=278, SD=79, post-AVG M=175, SD=57; accuracy: $Z=-2.20$, $p=0.028$, pre-AVG M=0.08, SD=0.08, post-AVG M=− 0.2, SD=0.08), showing an attentional control enhancement only after an efficient AVG training indexed by higher video game score.

Between-Subjects Analysis

These findings demonstrate specific improvements in phonological decoding speed and attentional control selectively induced through efficient AVG training.

However, direct comparisons between the two training and between HSP and LSP after AVG training are necessary to stringently demonstrate the selective effects of AVG and HSPs after AVG training on phonological decoding speed and attentional control indexed by RTs and accuracy of the set-size slope. The ideal ANOVA with two groups (AVG and NAVG) by three times (T1, T2 and T3) design cannot be carried out because 2 out of 14 (about 15%) of participants were trained only with AVGs between T1 and T2.

T1 vs. T2

Similarly to the typical between-subjects intervention studies e.g., (Bertoni et al., 2019; Franceschini et al., 2013; 2017a; 2017b), in this first between-subjects analysis, we directly compared the improvements (i.e., post- training–pre-training performance) induced by the AVG and NAVG training in our two groups of children with DD (n=8 and n=6, respectively). This first analysis allows us a partial comparison between AVG and NAVG training in children with DD without any previous AVG experience.

To investigate the selective clinical effect of the AVG treatment on reading skills, we also compared the improvements induced by the AVG and NAVG training vs. one-year (8760 h) of spontaneous development of the phonological decoding speed (Tressoldi et al., 2001). If the AVG training actually has a robust clinical effect on phonological decoding speed, then we should find a significant difference in the NAVG control group, but not in the AVG group, indicating that 12 h of AVGs accelerate pseudoword reading similarly to 1 year of spontaneous development.

Phonological Decoding Tasks

Independent-samples t-test (one-tail) showed that the pseudoword reading speed improvement (syll/sec) was significantly different between AVG and NAVG groups ($t_{(12)}$=1.92, p=0.04; mean AVG improvement between T1 and T2=0.12 syll/sec, SD=0.15 vs. mean NAVG improvement between T1 and T2=− 0.005 syll/sec, SD=0.07).

In addition, a one-sampled t-test showed that the reading speed improvement in the AVG group was not significantly different ($t_{(7)}$=− 0.59, p=0.29) from the spontaneous reading development (i.e., 0.15 syll/sec; Tressoldi et al., 2001).

Independent-samples t-test (one-tail) showed that the pseudoword reading errors improvement was not significantly different between AVG and NAVG group ($t_{(12)}$=− 0.24, p=0.40; mean AVG improvement between T1 and T2=− 0.31, SD=2.99 vs. mean NAVG improvement between T1 and T2=0.08, SD=3.02).

Visual Search Task

Independent-samples t-test (one-tail) on RTs slope (RTs difference between 12 and 2 set-size in msec) reduction between AVG and NAVG group was marginally significant ($t_{(12)}$=1.47, p=0.08; mean AVG slope improvement between T1 and T2=80 msec, SD=143 vs. mean NAVG slope improvement between T1 and T2=− 33 msec, SD=140).

Independent-samples t-test (one-tail) on accuracy slope (RTs difference between 2 and 12 set-size in rate) reduction between AVG and NAVG group was not significant ($t_{(12)}$=1.07, p=0.15; mean AVG slope improvement between T1 and T2=− 0.01, SD=0.09, mean NAVG slope improvement between T1 and T2=− 0.06, SD=0.06).

T2 vs. T3

In the second between-subjects analysis, we compared the improvements induced by the AVG and NAVG training between T2 and T3 in our two groups (now n=6 for both groups). This type of comparison is not the typical analysis of between-subjects intervention studies (Franceschini & Bertoni, 2019; Bavelier & Green, 2019), because in this case the NAVG control group now had previous AVG experience. Indeed, it cannot be excluded that the effect of the previous AVG training is “carried over” to the following NAVG training. Thus, this comparison should be considered with caution.

Phonological Decoding Tasks

Independent-samples t-test (one-tail) on reading speed (syll/sec) showed no significant difference between AVG and NAVG ($t_{(10)}$=0.39, p=0.35; mean AVG improvement between T2 and T3=0.07, SD=0.09, mean NAVG improvement between T2 and T3=0.11, SD=0.17).

The one-sample t-test (one-tail) showed that the reading speed improvement in the AVG group was marginally different to the spontaneous reading development ($t_{(5)}$=− 2.003, p=0.051; mean AVG improvement between T2 and T3=0.07, SD=0.09).

Independent-samples t-test (one-tail) on reading errors showed no significant difference between AVG and NAVG ($t_{(10)}$=− 0.04, p=0.48; mean AVG improvement between T2 and T3=− 0.42, SD=3.50, mean NAVG improvement between T2 and T3=− 0.50, SD=3.18).

Visual Search Task

Independent-samples t-test (one-tail) on RTs showed no significant difference in the reduction of the slope between AVG and NAVG ($t_{(10)}$=0.44, p=0.33; mean AVG improvement between T2 and T3=55, SD=59, mean NAVG improvement between T2 and T3=78, SD=114).

Independent-samples t-test (one-tail) on accuracy showed no significant difference in the reduction of the slope between AVG and NAVG ($t_{(10)}$=1.23, p=0.13; mean AVG improvement between T2 and T3=− 0.09, SD=0.07, mean NAVG improvement between T2 and T3=− 0.03, SD=0.11).

Comparison between First NAVG Group vs. Second NAVG Group

In the third between-group analysis, we tested the effect of previous AVG training on the next NAVG training directly comparing the improvements in the first NAVG group (between T1 and T2; n=6, without previous AVG experience) and the second NAVG group (between T2 and T3; n=6, with previous AVG training experience).

To investigate the clinical effect of the previous AVG training on reading skills, we also compared the improvements induced by the first and second NAVG group vs. one year of spontaneous development of the phonological decoding speed. If the previous AVG training actually has a robust clinical effect on the subsequent NAVG training, then we should find a difference only in the first NAVG control group.

Reading Task: Phonological Decoding Tasks

Independent-samples t-test (one-tail) on reading speed (syll/sec) showed a marginal difference between NAVG groups ($t_{(10)}=1.44$, $p=0.09$; mean NAVG improvement between T1 and T2=− 0.005, SD=0.07, mean NAVG improvement between T2 and T3=0.11, SD=0.17).

One-sample t-test (one-tail) showed that the first NAVG group is significantly different to the spontaneous reading development ($t_{(5)}=-5.62$, $p=0.001$; mean NAVG improvement between T1 and T2=− 0.005, SD=0.07), whereas the second NAVG group was not significantly different to 0.15 syll/sec ($t_{(5)}=-0.63$, $p=0.28$; mean NAVG improvement between T2 and T3=0.11, SD=0.17).

Independent-samples t-test (one-tail) on reading errors showed no significant difference between NAVG groups ($t_{(10)}=-0.33$, $p=0.38$; mean NAVG improvement between T1 and T2=0.08, SD=3.02, mean NAVG improvement between T2 and T3=− 0.5, SD=3.18).

Visual Search Task

Independent-samples t-test (one-tail) on RTs showed a marginal difference in the reduction of the slope between two NAVG groups ($t_{(10)}=1.50$, $p=0.08$; mean NAVG improvement between T1 and T2=− 33, SD=140, mean NAVG improvement between T2 and T3=78, SD=114).

Independent-samples t-test (one-tail) on accuracy showed no significant difference in the reduction of the slope between two NAVG groups ($t_{(10)}$=0.62, p=0.28; mean NAVG improvement between T1 and T2=− 0.06, SD=0.06), mean NAVG improvement between T2 and T3=− 0.03, SD=0.11).

Comparison between HSP and LSP Groups

Finally, to stringently test the effects of AVG training efficiency, in our fifth between-subjects analysis, we directly compared HSPs and LSPs after the AVG training.

Reading Task: Phonological Decoding Tasks

Independent-samples t-test (one-tail) on reading speed (syll/sec) showed a significant difference between HSP and LSP AVG group ($t_{(12)}$=1.99, p=0.035; mean HSP improvement between pre and post-training=0.17, SD=0.14, mean LSP pre and post-training=0.04, SD=0.07).

Visual Search Task

Independent-samples t-test (one-tail) on RTs showed no significant difference in the reduction of the slope between HSP and LSP AVG group ($t_{(12)}$=1.13, p=0.14; mean HSP improvement between pre and post-training=103, SD=89, mean LSP improvement between pre and post-training=36, SD=129).

Independent-samples t-test (one-tail) on accuracy showed a significant difference in the reduction of the slope between HSP and LSP AVG group ($t_{(12)}$=2.13, p=0.028; mean HSP improvement between pre and post-training=0.09, SD=0.07, mean LSP improvement between pre and post-training=− 0.001, SD=0.09).

2.1.3 Discussions

In this partial crossover intervention study, we investigated the effects of visuo-attentional training based on AVGs in children with DD. The results show that 12 h of AVG training improves pseudoword reading speed and attentional control in a serial visual search task. These results are confirmed not only using two independent comparisons within each training session (i.e., pre vs. post-training within-subject analysis), but also when more stringent between-group comparisons (i.e., AVG vs. NAVG between-subject analysis) on improvements were executed. In contrast, there are no beneficial effects of AVGs in word reading performance and in cross-modal mapping measured through non-alphanumeric RAN.

The improvement in pseudoword phonological decoding speed is in line with the literature (Bertoni et al., 2019; Franceschini et al., 2013; 2017; 2019). The pseudoword reading skills are based on sub-lexical mechanisms that are driven not only by the bottom-up MD pathway (Franceschini et al., 2018), but also by prefrontal top-down attention (Bavelier & Green, 2019).

It is demonstrated that the intrinsic characteristics of AVGs, such as the speed in terms of transient events and moving objects, the high degree of perceptual and motor load, and the emphasis on peripheral processing, enhance the “action” stream that include both the MD pathway (Gori et al., 2016) and prefrontal top-down attention (Bavelier & Green, 2019).

AVG play enhances various aspects of attentional control now better understood as changes in the capacity to rapidly shift between a distributed versus a focused attentional state in the spatial resolution (Bavelier & Green, 2019), necessary in both pseudoword reading (Franceschini et al., 2013) and visual search (Eimer, 2014).

Study 2. Action Video Games Training in Children with Developmental Dyslexia: A Meta-analysis

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Abstract

Longitudinal studies and meta-analyses have shown a causal link between attentional dysfunctions and developmental dyslexia (DD). We carried out a meta-analysis to test the effectiveness of action video games (AVGs) training on visual attention in children with DD. Pubmed, Cochrane, Science Report, EBSCO Database, Scopus, ProQuest Dissertation and Theses, and IEEE Explore were consulted. Only quantitative studies with measures of pre- and post-treatment reading skills, written in English, and with an active control group were considered. The risk of bias was evaluated according to RoB2 and ROBINS-I assessment tools. Out of 2073 records, nine experiments using AVGs in 238 children (aged 5-15) with DD were selected. The Hedge’s g results indicate that AVGs training affects visual attention as well as reading-related functions. Studies with a larger sample including follow-up assessments and neurobiological studies are needed to verify AVGs long-lasting effects in DD.

2.2.1 Material and Method

Search Strategy

This meta-analysis was conducted according to the PRISMA checklist (see Figure 1).

Only articles published in English were considered, with no limitation on the year of publication. Pubmed, Cochrane, Science Report, EBSCO Database, Scopus, ProQuest Dissertation and Theses, and IEEE Explore were used to search for the studies contained in this meta-analysis.

The search terms used were:

1. Dyslexia (or “Developmental Dyslexia”);
2. Action Video Games;
3. 1 and 2;
4. AVG;
5. 1 and 4
6. Reading (or “Reading Abilities” or “Reading Skills”);
7. 3 and 6;
8. 5 and 6.

In addition to the search terms reported above, we also referred to bibliographic references from the systematic review by Peters and colleagues (2019).

Study Selection

The studies in this meta-analysis use visual attentional training with AVGs to improve reading skills in children and adolescents (5 to 15 years old). The experimental group sample necessarily had to involve children diagnosed with DD. The authors had to provide sufficient information to show that they met the criteria for the diagnosis, regardless of the diagnostic system used (e.g., DSM-5 or ICD-10). Other diagnoses had to be excluded, including attention deficit or neurological disorders. In addition, these studies had to have a sample with at least one active control group requiring children with DD. Single case studies and qualitative studies were excluded. Only quantitative studies that reported one or more measures of reading skills, including word and pseudoword reading speed (RS), accuracy (RA) and comprehension (RC), and provided sufficient data regarding participants' performance in pre- and post-training were included. The selection of studies considered the information in the paper or the supplementary materials. If the data contained in the text of the article were insufficient, the corresponding authors were contacted. The eligibility process was executed by two independent reviewers , with a screening of the title, abstract, and method used in each record for preliminary identification. In case of doubts and disagreements, a third co-authorwas involved. The studies included in this meta-analysis were discussed and approved by all the authors.

Table 1. Summarizes the described criteria used to select the studies covered in this meta-analysis.

Eligibility Criteria:
1. Use of action video games (AVGs) Training
2. Age of participants between 5 and 15 years old
3. Scientific articles published in English Language
4. Presence of an active control group
5. Experimental group with developmental dyslexia (DD) diagnosis
6. No neurological or neurodevelopmental disorders diagnosis within the sample (other than DD)
7. Quantitative study with measurement of pre- and post-treatment reading skills

Table 1. Inclusion criteria used to select the studies covered by this meta-analysis.

Data Collection Process

Data were extracted and collected from the information in the paper and/or the respective supplementary materials. When the data contained in the text of the article were insufficient or missing, the corresponding authors were contacted. If the authors did not respond to this request, missing data were extracted from the graphs in the paper using GetData Graph Digitizer. This program allows to extract means and standard deviations of participants' performance in the tasks directly from the figures in the original articles. This process was performed by two reviewers . Before analysing the data, the transcripts were checked by all the authors.

The following information was recorded for each study:

- Sample information (country, language, chronological age and sample size);
- Training information (intervention groups, duration, description and game used);
- Study information (design, number of experimental and control group participants and cognitive skills assessed);
- Results (means, SD or standard errors and p-value);
- Outcome (unit of measurement, performance changes and cognitive effects of AVGs training).

Extracted data were tabulated in a data file and attributed to different outcome categories uniformly and consistently with what was reported in the original article. The following labels were specifically considered: word and pseudoword reading performance (RP; the mean between RS and RA), reading comprehension (RC, accuracy), phonological processing (PP, accuracy), visual attention (VA, speed and accuracy) and multisensory attention (MA, speed and accuracy). Both lists and/or texts of word and pseudoword were considered in RP.

Risk of Bias in Individual Studies

The risk of bias in individual studies was evaluated according to Revised Cochrane risk-of-bias for Randomized Trials tool (RoB2; Sterne et al., 2019) and Risk of Bias in Non-randomised Studies of Interventions (ROBINS-I) assessment tool (Sterne et al., 2016). The assessment process was conducted independently by three reviewers and discussed with a fourth co-author . Missing information was collected by contacting the corresponding authors of the studies. The final level of risk, as well as the choice of including the studies or not, was approved by all authors.

The choice of very strict eligibility criteria made it possible to select studies with a low level of risk. None of the studies showed high-risk levels. The main critical points refer to the domain of "bias arising from the randomisation process" and "bias due to deviations from intended interventions". In particular, in some cases (Bertoni et al., 2019; Bertoni et al., 2021; Franceschini et al., 2017b), the allocation of participants in the respective groups was not completely random, and the study was not conducted in a double-blind manner. Furthermore, according to the authors, the participants were always blind to the allocation in the various groups and had no expectations with regard to the effectiveness of the training offered. The experimenters, on the other hand, knew the aims of the study and the research objectives. Therefore, blindness was considered to be of medium level of risk. There are no critical points in "bias due to missing outcome data", "bias in measurement of the outcome" and "bias in selection of the reported results" domains: the possibility of access to the raw datasets provided all the necessary data for the goals of this meta-analysis (see Tables 2 and 3 for details).

Authors	Randomization Process	Deviation from Intervention	Missing Data	Measure of the Outcome	Selection of Reported Results	Overall
Bertoni et al., 2019	Yellow	Yellow	Green	Green	Green	Green
Bertoni et al., 2021	Yellow	Yellow	Green	Green	Green	Green
Franceschini et al., 2013	Green	Yellow	Green	Green	Green	Green
Franceschini et al., 2017a	Green	Yellow	Green	Green	Green	Green
Franceschini et al., 2017b	Yellow	Yellow	Green	Green	Green	Green
Luniewska et al., 2018	Green	Green	Green	Green	Green	Green
Peters et al., 2021a	Green	Green	Green	Green	Green	Green
Peters et al., 2021b	Green	Green	Green	Green	Green	Green

Table 2. Assessment of the risk of bias in the included studies using RoB2 for Randomised Controlled Trials studies. Green: low risk; Yellow: medium risk; Red: critical risk.

Authors	Confounding	Selection of Participants	Classification of Intervention	Deviation from Intended Intervention	Missing Data	Measure of Outcome	Reported Results	Overall
Gori et al., 2016	Green	Green	Green	Green	Green	Green	Green	Green

Table 3. Assessment of the risk of bias in the included studies using ROBINS-I for Non- Randomised Controlled Trials studies. Green: low risk; Yellow: medium risk; Red: critical risk.

2.2.2 Results

Study selection

A total of 2073 records from the 7 databases were selected (Pubmed: 16 records; Cochrane: 5 reports; Science Report: 13 reports; EBSCO: 231 reports; Scopus: 23 reports; Proquest: 1784 reports; IEEE Explore: 1 record); 2047 were unique citations (26 duplicate records). The review process of titles and abstracts identified 46 records, while 2001 records were removed because they did not meet eligibility criteria (see Table 1). Three records were excluded because they were not written in English; 28 were removed because they did not use AVGs training according to Green and Bavelier's definition (2012); 3 records used a study design that did not meet the criteria; the reading outcomes in 3 records were not measured; one study was excluded for the absence of the control group. At the end of the process, 8 articles including 9 independent studies were considered in this meta-analysis.

The review process is summarized in Figure 8.

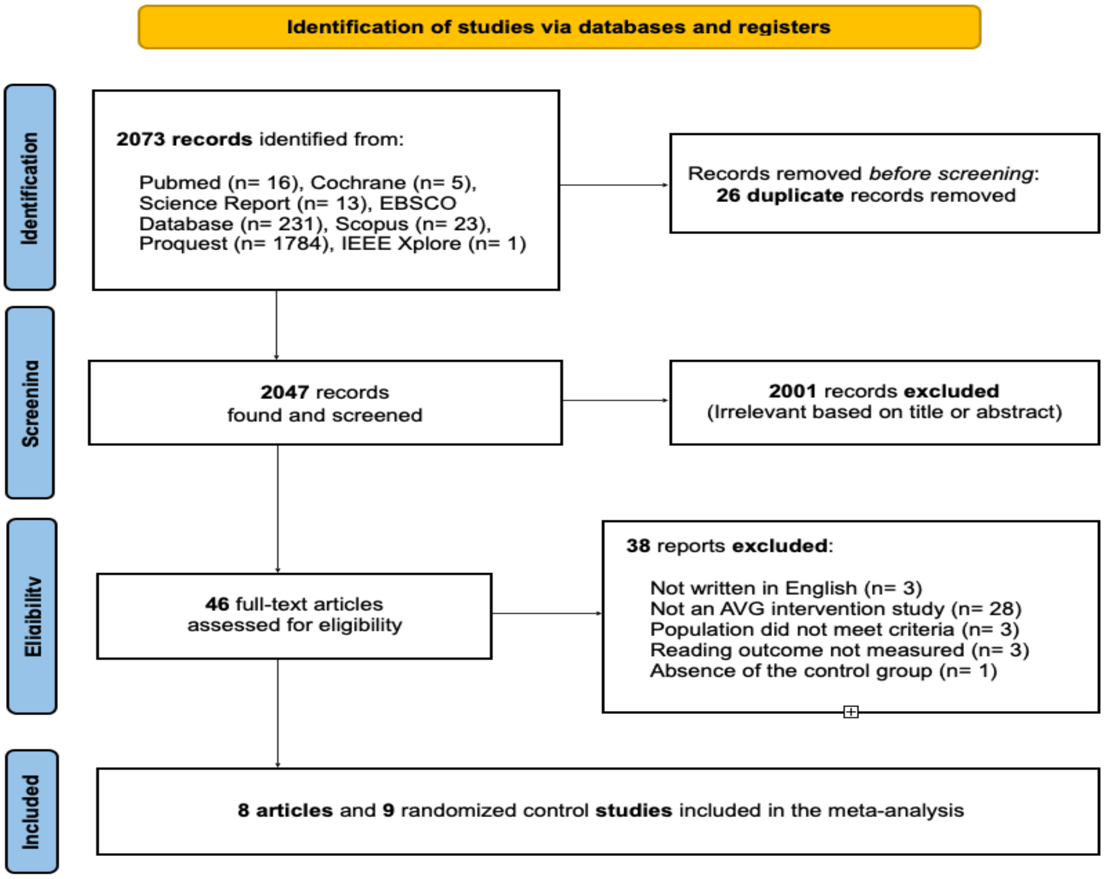

Figure 8. PRISMA diagram of included studies

Study Characteristics

According to the eligibility criteria (see Table 1), all the studies included in this meta-analysis used AVGs training to measure its effects in the experimental group. The present meta-analysis includes eight scientific papers and nine randomised controlled studies. Peters and colleagues' study (2021) included two experimental groups: AVG+Increased Attention Action Video Game Group (AVG+) and Action Video Game-Regular Group (AVG-R) hereafter referred to, respectively, as Peters et al., 2021a and Peters et al., 2021b. All studies used a between-subject experimental design except one (Gori et al., 2016), which used a within-subject design. The duration of the AVGs training ranged from 5 (Peters et al., 2021) to

13,3 hours (Luniewska et al., 2018) (mean duration=10.58 hours; SD=3.19 hours), and the length of each session was either 30 (Peters et al., 2021a; 2021b), 50 (Luniewska et al., 2018), or 80 minutes (Bertoni et al., 2019; 2021; Franceschini et al., 2013; 2017a; 2017b; Gori et al., 2016). All the control groups used NAVGs training, except for Luniewska and colleagues (2019), which used a phonological NAVG, and Peters and colleagues (2021), which used a "treatment-as-usual school-based reading intervention" (phonics remediation). The AVGs training lasted approximately 2 weeks each using single-player models and commercial games (i.e., "Fruit Ninja®" and "Rayman Raving Rabbids™") via computer (Luniewska et al., 2018; Peters et al., 2021a; 2021b) or Wii™ (Bertoni et al., 2019; 2021; Franceschini et al., 2013; 2017a; 2017b; Gori et al., 2016). This meta-analysis involves a total of 238 children (mean age=10.28 years old; SD=0.68) with a diagnosis of DD and 57 total observations. In particular, 6 studies included VA tasks (67% of total), 8 studies measured RS and RA (89%), and 5 studies assessed PP (56%). Only 3 studies evaluated RC (33%), and 2 measured MA skills (22%). Table 4 summarises and includes additional information about the studies considered.

Results of Individual Studies

Table 4 summarises the main information about the sample (group size, native language and mean age), the training used for the experimental group and the control group, the duration of the training, the design's studies and the outcomes measured. Analyses were carried out using the package Metafor (version 3.8, 2022) in the R environment (version 4.2.2; R Core Team, 2022).

The following cognitive outcome measures were considered: VA, RP and PP. In contrast, MA and RC, given the scarcity of measures, were only considered in the GCO.

Table 4. Studies included in the meta-analysis

#	Author (Year)	Language	Design	Sample Size (n); Control group (C), Treatment group (T)	Age (SD)	Treatment duration (hours)	training	Skills Assessed (Task/measure type)
1	Bertoni et al (2019) experiment 3	Italian	Between subject	n=14 C=7; T=7	10.1 (1.6)	12 (80 min x 9 sessions)	AVG vs NAVG	VA (visual attention accuracy)
2	Bertoni et al (2021)	Italian	Between subject	n=14 C=6; T=8	8.93 (0.99)	12 (80 min x 9 sessions)	AVG vs NAVG	WR (speed, accuracy); PR (speed, accuracy); VA (visual search speed, visual search accuracy)
3	Franceschini et al (2013)	Italian	Between subject	n=20 C=10; T=10	9.84 (1.4)	12 (80 min x 9 sessions)	AVG vs NAVG	WR (speed, accuracy); PR (speed, accuracy); MA (cross modal temporal attention speed, cross modal temporal attention accuracy), VA (distributed and focused attention accuracy)
4	Franceschini et al (2017a) experiment 4	Italian	Between subject	n=14 C=7; T=7	10.41 (1.71)	12 (80 min x 9 sessions)	AVG vs NAVG	RM (speed, accuracy); VA (global Navon incongruent condition speed)
5	Franceschini et al (2017b)	English	Between subject	n=28 C=12; T=16	10.27 (1.61)	12 (80 min x 9 sessions)	AVG vs NAVG	WR (speed, accuracy); PR (speed, accuracy); VA (accuracy focused visuo-spatial attention); MA (auditory costs speed, visual costs speed); PP (phonological short-term memory and phoneme blending accuracy)
6	Gori et al (2016) experiment 3	Italian	Within subject	n=11 C=11; T=11	11.02 (1.26)	12 (80 min x 9 sessions)	AVG vs NAVG	WR (speed, accuracy); PR (speed, accuracy); VA (CDM accuracy); PP (pseudoword repetition accuracy)
7	Luniewska et al (2018)	Polish	Between subject	n=54 C=27; T=27	11.00 (1.00)	13.3 (50 min x 16 sessions)	AVG vs phonological NAVG	WR (speed); PR (speed, accuracy); MR (accuracy); RC (accuracy); PP (RAN speed, phoneme deletion accuracy, pseudoword repetition accuracy)
8	Peters et al (2021a)	English	Between subject	n=42 C=19; T=23	10.53 (0.95)	5 (30 min x 10 sessions)	AVG+ vs as-usual Training	WR (speed, accuracy); RC (accuracy); PP (CTOPP speed)
9	Peters et al (2021b)	English	Between subject	n=42 C=19; T=23	10.60 (1.01)	5 (30 min x 10 sessions)	AVG-R vs as-usual Training	WR (speed, accuracy); RC (accuracy); PP (CTOPP speed)

Note. WR=Word Reading; PR=Pseudoword Reading; MR=Mixed Reading word and pseudoword; RC=Reading Comprehension; PP=Phonological Processing; VA=Visual Attention; MA=Multisensory Attention. AVG+=Increased Attention Action Video Game Group; AVG-R=Action Video Game-Regular Group

Synthesis of Results

Global Cognitive Outcome (GCO)

The overall analysis of all considered studies (Bertoni et al., 2019; 2021; Franceschini et al. 2013; 2017a; 2017b; Gori et al. 2016; Luniewska et al., 2018; Peters et al; 2021a; 2021b), using the performance at 57 measures (GCO) in 238 children with DD, indicated a general cognitive improvement in the training group compared to the active control group (Z=2.40; p=0.02) with a small to medium effect size (g=0.38). The forest plot of these effects is reported in Figure 9. The measures considered in this meta-analysis were not characterised by significant statistical heterogeneity (Q=2.36; p=0.97).

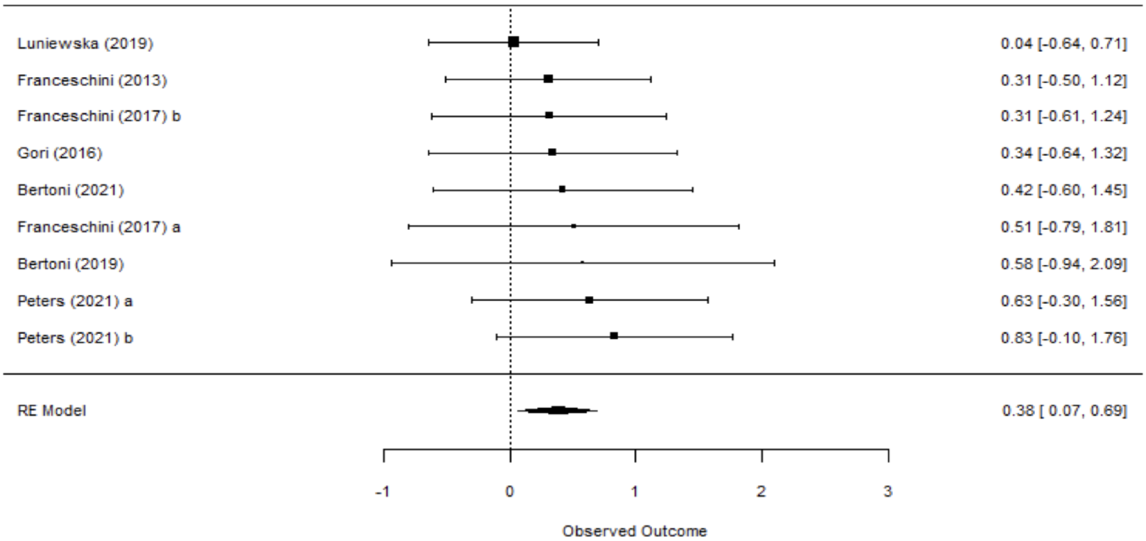

Figure 9. Forest plot of Hedges's g (95% CI) in the GCO.

Visual Attention (VA)

Six studies (Bertoni et al. 2019; 2021; Franceschini et al. 2013; 2017a; 2017b; Gori et al. 2016) used the performances of 8 measures of the visual task as the outcome of VA abilities in 101 children with DD. The results of the meta-analysis, which considered the accuracy and the speed in terms of reaction times, indicated that VA efficiency significantly improved in the training group (Z=2.67; p=0.01) with a medium to large effect size (g=0.72) compared to the active control group. The forest plot of these effects is reported in Figure 10. The measures considered in this meta-analysis were not characterised by significant statistical heterogeneity (Q=0.41; p>0.99).

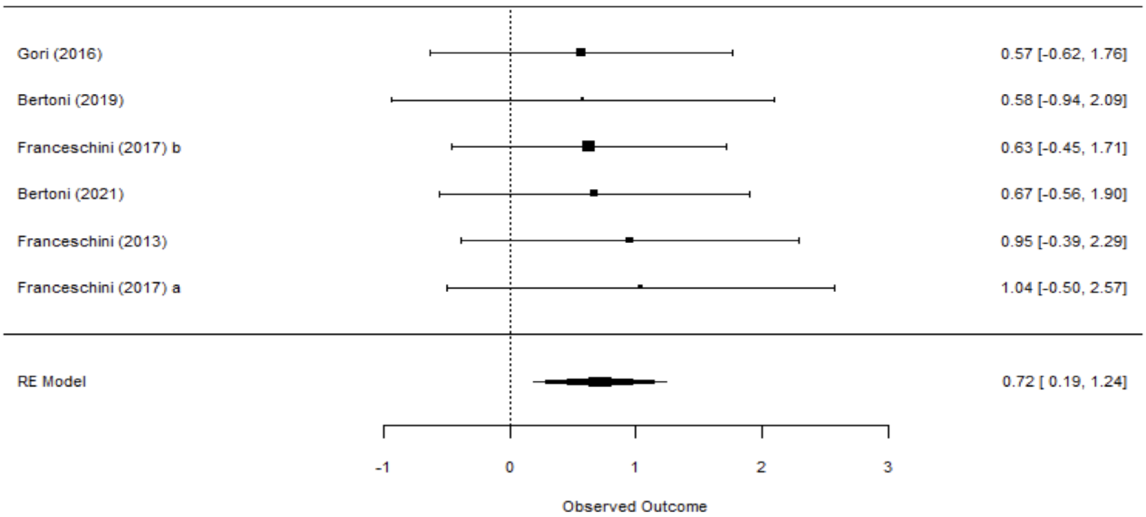

Figure 10. Forest plot of Hedges's g (95% CI) in VA.

Reading Performance (RP)

Eight studies (Bertoni et al., 2021; Franceschini et al., 2013; 2017a; 2017b; Gori et al., 2016; Luniewska et al., 2018; Peters et al; 2021a; 2021b) used the performances of 33 measures as the outcome of RP in 224 children with DD. The results of the meta-analysis, which considered the accuracy and the speed in terms of reading time, indicated that there was a marginally significant improvement in RP efficiency in the training group (Z=1.95; p=0.05 with a small to medium effect size (g=0.36) compared to the active control group. The forest plot of these effects is reported in Figure 11. The measures considered in this meta-analysis were not characterised by significant statistical heterogeneity (Q=2.27; p=0.94). Since AVGs training mainly works on speed of processing (i.e., the sampling rate of sensory events; Green et al., 2010), we carried out two different meta-analyses, the first on RS and the second on RA.

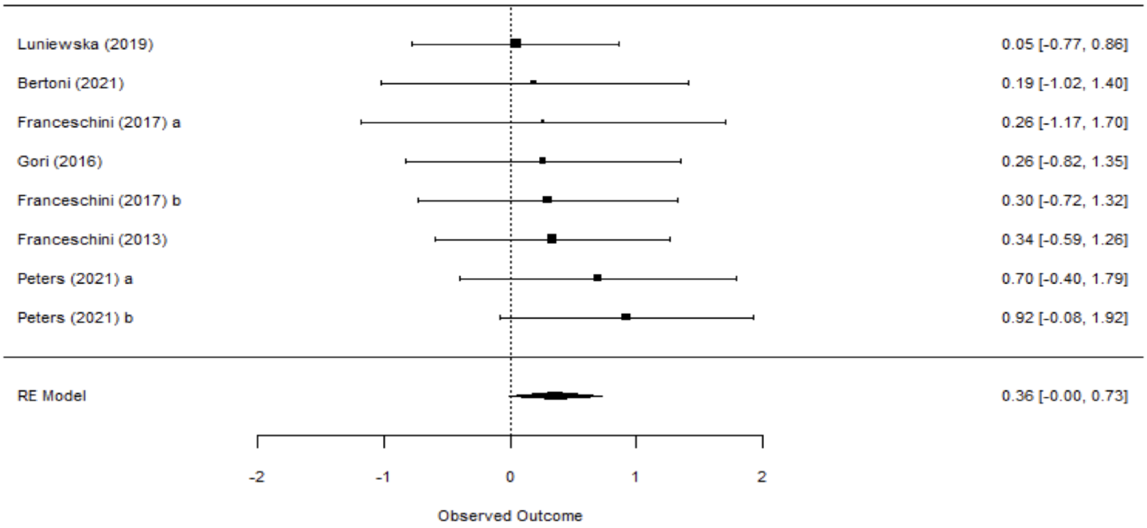

Figure 11. Forest plot of Hedges's g (95% CI) in RP.

Reading Speed (RS)

Eight studies (Bertoni et al., 2021; Franceschini et al., 2013; 2017a; 2017b; Gori et al., 2016; Luniewska et al., 2018; Peters et al; 2021a; 2021b) used the performances at 15 measures as the outcome of RS abilities in 224 children with DD. The results of the meta-analysis, considering the speed in terms of reading time, indicated that RS improved significantly in the training group (Z=2.21; p=0.03) with a small to medium effect size (g=0.44) compared to the active control group. The forest plot of these effects is reported in Figure 12. The measures considered in this meta-analysis were not characterised by significant statistical heterogeneity (Q=0.82; p>0.99).

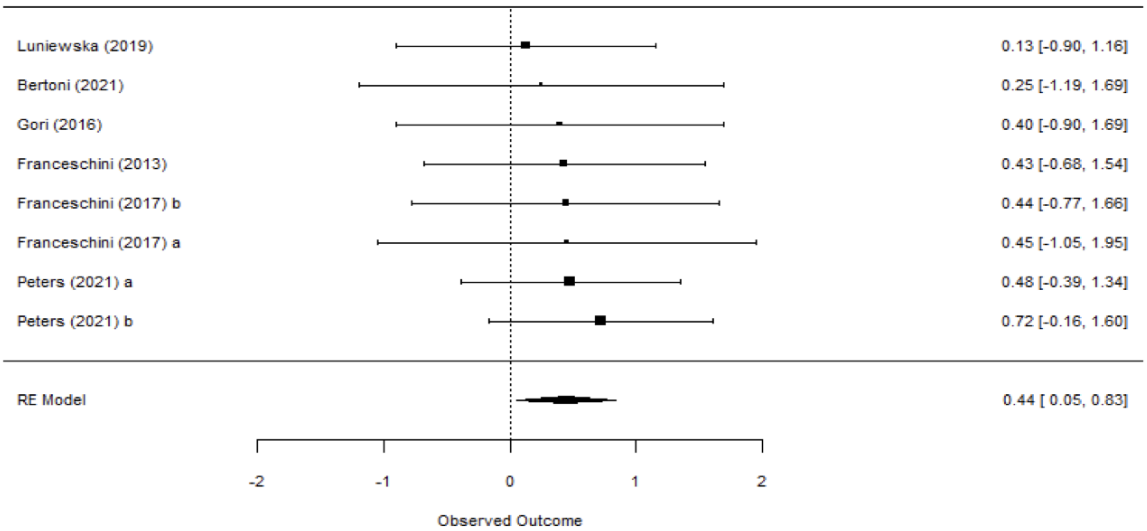

Figure 12. Forest plot of Hedges's g (95% CI) in RS.

Reading Accuracy (RA)

Eight studies (Bertoni et al., 2021; Franceschini et al., 2013; 2017a; 2017b; Gori et al., 2016; Luniewska et al., 2018; Peters et al; 2021a; 2021b) used the performances in 18 measures as the outcome of RA abilities in 224 children with DD. The results of the meta-analysis, which considered the accuracy in terms of misspelt syllables or wrong-read words, indicate that accuracy did not improve significantly in the training group (Z=1.35; p=0.18) compared to the active control group (g=0.30). The forest plot of these effects is reported in Figure 13. The measures considered in this meta-analysis were not characterised by significant statistical heterogeneity (Q=2.62; p=0.92).

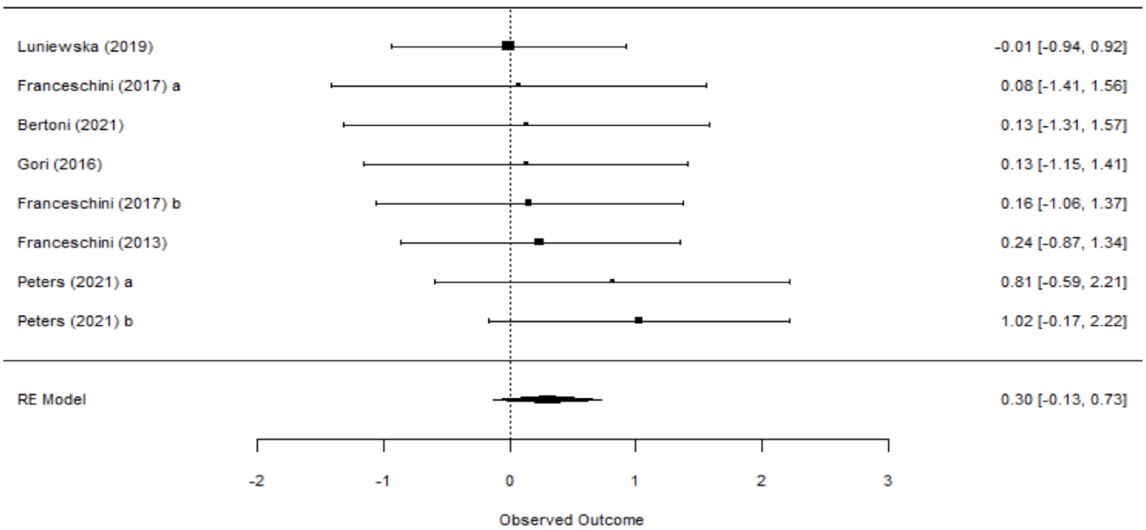

Figure 13. Forest plot of Hedges's g (95% CI) in RA.

Phonological Processing (PP)

Five studies (Franceschini et al., 2017b; Gori et al., 2016; Luniewska et al., 2018; Peters et al., 2021a; 2021b) used the performances in 10 measures of PP as the outcome in 176 children with DD. The meta-analysis results, which considered the accuracy and the speed, indicated that PP efficiency was significantly improved in the training group (Z=2.14; p=0.03) with a small to medium effect size (g=0.45) compared to the active control group. The forest plot of these effects is reported in Figure 14. The measures considered in this meta-analysis were not characterised by significant statistical heterogeneity (Q=2.70; p=0.61).

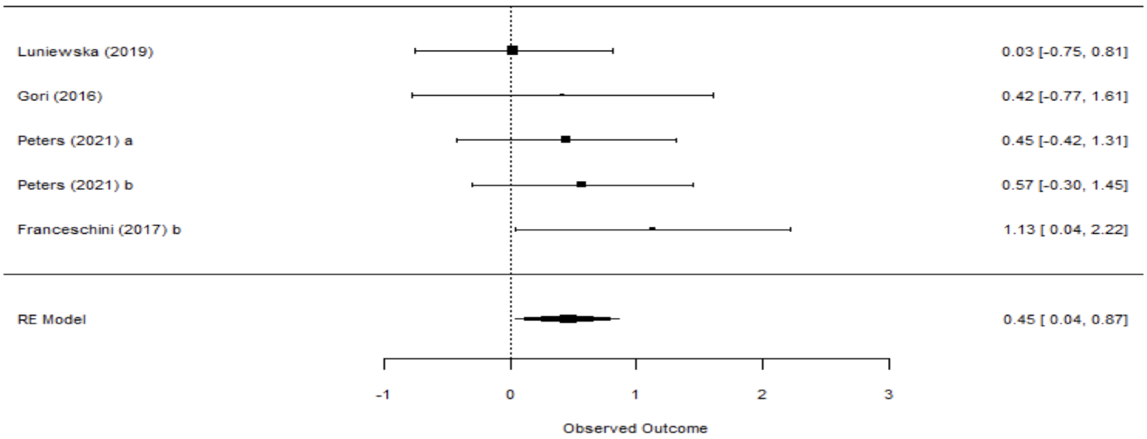

Figure 14. Forest plot of Hedges's g (95% CI) in PP.

Risk of Bias Across Studies

The Egger's regression asymmetry test indicates that there is no evidence of publication bias (p=0.37), and the funnel plot suggests that the included studies are distributed symmetrically (see Figure 15).

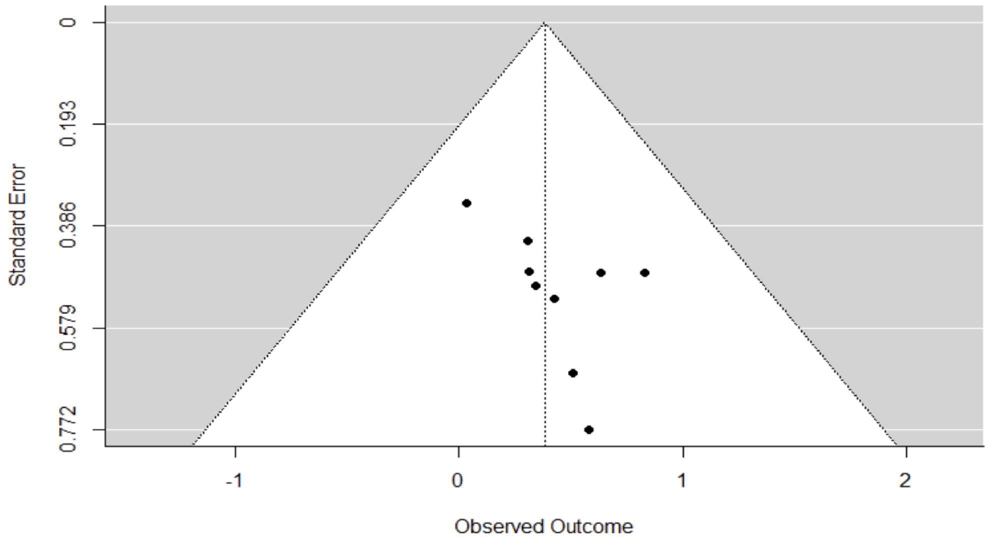

Figure 15. Funnel plot for risk of bias across selected studies.

Additional Analysis

Given the wide chronological age range (from 5 to 15 years old) and the difference in the number of hours provided by each training (from 5 to 13.3 hours), other analyses were conducted to assess possible differences in the studies considered. The results in the GCO show no significant differences in the chronological age of children with DD (Z=-0.52; p=0.60) or in the number of training hours (Z=-1.32; p=0.19).

See Table 5 for details about the analysis of chronological age and training hours in the different cognitive domains considered in this meta-analysis.

Cognitive Domain	Estimate	Standard Error	P-Value
VA Age Training hours *	-0.08	0.4	0.84
PP Age Training hours	-1.33 0.04	0.88 0.07	0.13 0.54
RP Age Training hours	-0.03 -0.08	0.29 0.06	0.91 0.15
RS Age Training hours	-0.04 -0.04	0.34 0.06	0.90 0.48
RA Age Training hours	-0.01 -0.11	0.33 0.07	0.97 0.11

*There were no differences in training hours, so the analysis was not conducted.

Table 5. Additional analysis about chronological age and training hours in the different cognitive domains was considered.

Some studies also considered the RC abilities (Luniewska et al., 2018; Peters et al., 2021a; 2021b) and MA abilities in terms of speed and accuracy (Franceschini et al., 2013; Franceschini et al., 2017b). However, the measured results were not enough to be analysed and were therefore only considered in the GCO. Based on the results of the different studies, we can suppose that there is a benefit of AVGs training on these abilities (but see Luniewska et al., 2018). Further analyses should be done when more studies will be conducted.

2.2.3 Summary of Evidence

This meta-analysis considered eight scientific publications and nine randomized controlled studies. All children involved in the studies (n=238) met the diagnostic criteria for DD. The studies, written in English, investigated attentional, reading and phonological outcomes across 3 languages (i.e., Italian, English and Polish), and were not significantly different in intervention intensity and chronological age of children with DD.

The meta-analysis results show a significantly larger improvement in the AVGs training compared to the active control group in GCO, VA, RS and PP. In contrast, there are no differences in RA between AVGs training and active control group (see Figure 16 for a summary of the results).

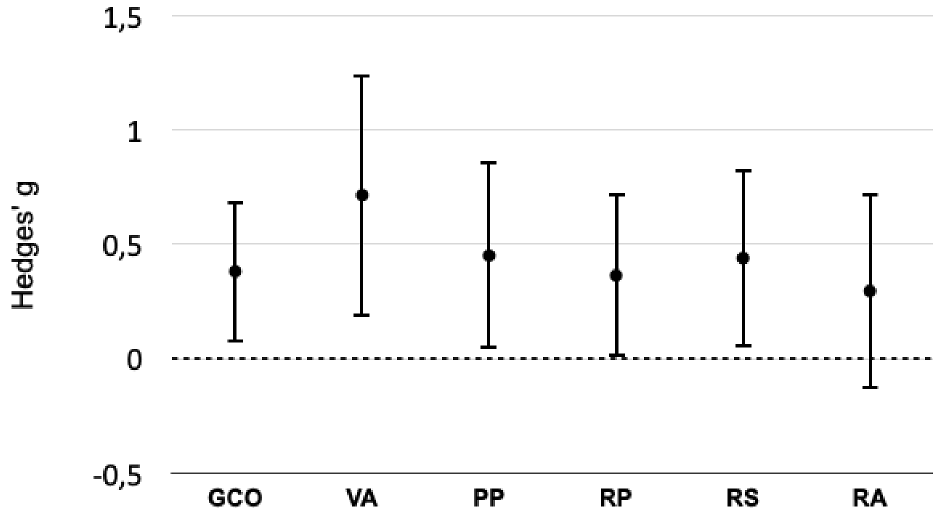

Figure 16. Summary of results. Effect sizes of AVGs training in global cognitive outcome (GCO), visual attention (VA), phonological processing (PP), reading performance (RP), reading speed (RS) and reading accuracy (RA) in children with DD. Error bars represent the 95% CI.

2.2.4 Discussion

The aim of this meta-analysis is to evaluate and measure the possible effects of AVGs training on cognitive functions, such as VA and RP, in children with DD. In agreement with the systematic review of Peters and colleagues (2019), the results demonstrate that AVGs training is able to induce both near transfer effects on VA abilities, and far transfer effects on RS and PP, that are cognitive skills not directly stimulated during AVGs training (see Figure 16). Considering the relationship between attention and reading abilities (see Perry & Long, 2021 for a critical review), it is possible to assume that AVGs training produces a direct effect on domain-general skills, such as spatial and temporal deployment of attention. Then, cascade effects on domain-specific skills are generated, such as on reading and PP also in an atypically developing brain (see Bediou et al., 2018 and Ren et al., 2023 for meta-analyses, Sampalo et al., 2023 for a systematic review on young-adults).

According to Bavelier and colleagues (2012), this attentional and perceptual training produces clear near transfer effects on directly stimulated skills, but also far transfer effects by producing improved efficiency in learning process (see von Bastian et al., 2022 for a review on cognitive training-induced changes).

Study 3. Action Video Game Training and Parietal Neuromodulation to Improve Attention and Reading Abilities in Adults with Developmental Dyslexia

Abstract

Action video games (AVG) have been shown to improve attention and reading performance in developing brains. However, transcranial random noise stimulation (tRNS) could amplify these effects, removing barriers to adult brain plasticity. A double-blind randomized controlled trial showed that combining 15-hour AVG training with parietal tRNS could be more effective in improving attention and reading skills in 20 adults non-AVG players with developmental dyslexia (DD). Specifically, the AVG+tRNS group showed behavioural enhancements in word text reading, pseudoword decoding, and temporal attention compared to the placebo (i.e. AVG+ sham) condition. Moreover, only the AVG+tRNS group had a lower P300 amplitude elicited by stimulus-driven attentional engagement at the first salient target and a higher P300 amplitude elicited by goal-directed attentional disengagement at the second target. This study also confirmed a causal relationship between attentional control and phonological decoding, indicating that the combination of AVG training with parietal neuromodulation increases the efficiency of visual attention deployment based on phonological decoding. This suggests that the combination of AVG training and parietal stimulation may reshape DAN and VAN.

2.3.1 Materials and Method

Participants

The study involved 20 young adults (9 males and 11 females; M=22.85y.o., SD=6.53) native Italian speakers with DD diagnosis by the Italian National Health Service according to APA's inclusion and exclusion criteria (i.e. DSM-5; 2013) or reading difficulties assessed. Participants were chosen from a sample of approximately 700 adults based on their AVG experience (no use of AVGs for more than 5 hours per week in the previous six months) and their score on the Adult Reading History Questionnaire (ARHQ; Lefly & Pennington, 2000), in order to pre-select potential participants with reading difficulties. During the initial assessment, students were tested on their reading skills using clinical reading assessments (Sartori et al., 2007; Judica & De Luca, 2005). The project was proposed to participants who performed at least one of the tests, in accuracy and/or reading speed, at or below -1.5 SD under the average (DSM-5, 2013). There were no reports of sensory deficits (auditory, visual, or motor) or cognitive impairments (such as language disorders, neurological disability, ADHD, or autism spectrum disorders).

Participation in the study was voluntary. The procedure and the goals for data collection were made explicit on the form that was given to participants.

The study was written in compliance with the European Union Standards of Good Clinical Practice, and it was authorized by the University of Padua's Ethics Committee (Protocol number: 1551, Code: BE9FF4D8B5D9A48C1FC4E286332F3932).

Procedure

Participants were individually tested and trained in a dimly lit and quiet room. Participants were tested between 3 to 5 days before the start of treatment and re-tested between 2 and 3 days after the end of training. Training consisted of 12 days of AVG sessions of 75 min each, for a total of 15 hours. The AVG was played standing about 150 cm from a 27-inch TV screen. A commercial Play Station™ 3 ("Call of Duty: Modern Warfare 2", PEGI: 18+ years old) was used; this is one of the most prevalent and successful first-person shooter games (e.g., Nguyem and Bavelier, 2023).

In addition, during the first six sessions of training the sample was randomly divided into two sub-groups: a sub-group received active high-frequency tRNS stimulation (hf-tRNS group) and the other one received sham stimulation (sham group) during the same first 6 sessions of AVG training. The hf-tRNS stimulation was generated by a Brain Stimstimulator by E.M.S. (Bologna, Italy) and was delivered via a pair of identical rubber scalp electrodes (4×4cm), covered with saline-soaked synthetic sponges. The hf-tRNS (frequency=101–640Hz; intensity=1.5mA) was delivered over bilateral posterior parietal areas (P3 and P4 according to the 10-20 EEG system; Herwig et al., 2003; Okamoto et al., 2004). Elastic bandages were used to maintain the electrodes in place during the training. The duration of the stimulation was about 20 min. A ramp-up of 30 sec was used before the beginning of the training. In the sham stimulation, a ramp-up of 30sec was immediately followed by a ramp-down of 30s. The study was conducted in double-blind: the experimenter who trained and manipulated the tRNS conditions was not the same one who then evaluated the cognitive effects of the AVG training. Moreover, the participant did not know the random assignment group in which he or she was participating and, therefore, the experimental condition.

The reading skills of the hf-tRNS group were re-tested four months after the end of the training (follow-up).

EEG Data Acquisition and Preprocessing

During the execution of the AB task in both the hf-tRNS (10 participants) and sham (8 participants) groups, EEG was recorded with 32 active Ag/AgCl electrodes (Micromed System Plus analysis system, Micromed®) distributed over the scalp according to the International 10-20 EEG System, both before and after the assigned treatment. Data was sampled in real-time at 512Hz. All electrodes were referred to the right mastoid online. Electro-oculograms were recorded vertically and horizontally from electrodes placed under each eye and on the two external canthi. Offline, data were downsampled to 256 Hz, recomputed to an average reference, bandpass filtered using Butterworth filters between 0.5 and 30Hz, and notch filtered to remove 50-Hz line noise.

Data were baseline corrected in both analyses by subtracting the mean over a 200msec pre-stimulus window, and all epochs with inappropriate behaviour al responses (e.g., L1 correct and L2 incorrect) were excluded. This process was implemented individually for the lag 3 and lag 8 circumstances. To identify and remove artefacts associated with eye blinks and muscular movements, we used EEGLAB's runica function to perform the Independent Component Analysis (ICA) for each participant. Following that, we calculated the absolute amplitude in each trial and rejected any trials that were above ±80 □V. If necessary, spherical interpolation was performed on individual faulty electrodes (average number of interpolated electrodes: M=2.7, SD=1.42).

The timeline of the present study is reported in Figure 17.

EEG Data Analysis

Based on previous research into the neuroelectric correlates of AB (e.g., Babiloni et al., 2020; Dell'acqua et al., 2003; Kranczioch et al., 2003; 2005, Mishra et al., 2011) we focused our EEG data analysis on a neural hallmark of AB phenomena, the P300 ERP component elicited by L1 and L2 presentation, separately for lag 3 and lag 8. This method allowed us to track the alteration of the P300 component after treatment in both the hf-tRNS and sham groups. In particular, the P300 component was estimated using time frames of 200-350 ms and 350-550 ms for L1 and L2 presentation, respectively, for lag 3 and lag 8 conditions.

Following previous research (e.g., Babiloni et al., 2020; Dell'acqua et al., 2003) and scalp map distribution, electrodes for P300 studies were chosen to include and average the brain activity of the following centro-parietal electrodes: P3, Pz, P4, Cp3, Cpz, Cp4. We used repeated measures ANOVA to investigate whether ERPs modulations were influenced by the times (within-subjects factor, two levels: pre- and post-training) and the target (within-subjects factor, two levels: L1 and L2), with the Group (hf-tRNS and sham) as the between-subjects factor. In circumstances where the sphericity assumption was violated, the Greenhouse-Geisser adjustment was used.

To evaluate P300 modulations following AVG+hf-tRNS and AVG+sham training, all post-hoc comparisons were performed using paired-sample t-tests, separately for L1 and L2 targets.

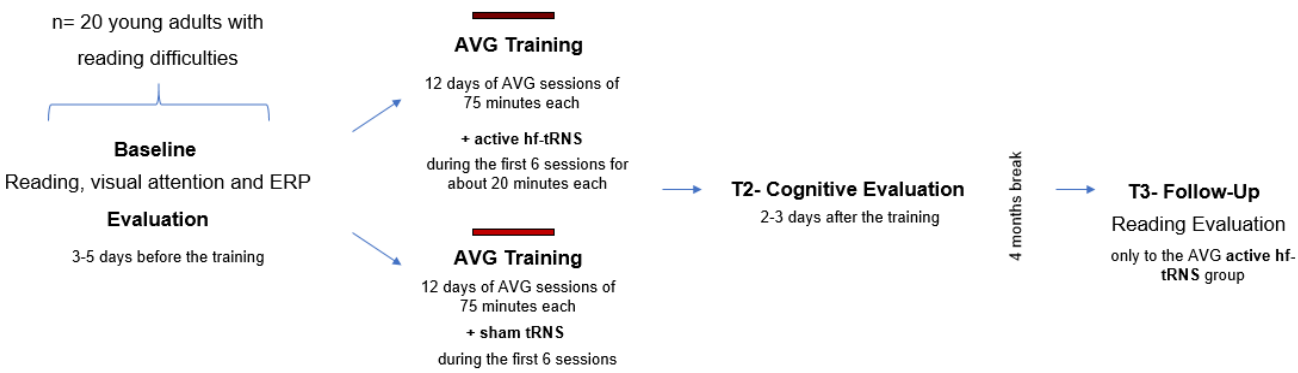

Figure 17. Schematic representation of the timeline of Study 3.

Neuropsychological Battery

Reading Tasks

Pseudoword and word texts and lists order administration were counterbalanced between participants before and after AVG training.

1. Text Reading (Judica & De Luca, 1993)

The passage reading test requires lexical, sub-lexical, semantic and comprehension skills and is considered a representative test of every day reading difficulties.

In the two sessions between the different individuals, the two texts were administered in counterbalanced order.

Participants were asked to read aloud each text as rapidly and accurately as possible. Two texts with 218 syllables each and paired for reading difficulty were used to assess text reading abilities (Judica & De Luca, 1993). The reading speed (syll/sec) and the number of errors were also recorded. A misread word was counted as one error regardless of the number of incorrect letters or syllables pronounced; spontaneous self-correction did not constitute an error.

2. Pseudoword List Reading (Sartori et al., 2007)

Phonological decoding abilities (speed and accuracy) were measured using three lists of 48 pseudowords each, for a total amount of 127 syllables each (Sartori et al., 2007). Reading time (in seconds) and accuracy (number of errors) were measured. Participants were invited to read each text aloud as quickly and as accurately as possible. The reading time was measured from the moment the experimenter turned the sheet until the participant pronounced the last letter of the last pseudoword of the list. A wrongly read pseudoword was counted as one error, independently from the number of wrong letters or syllables pronounced. Self-correction was not counted as an error.

Temporal Attention Task

Temporal attention abilities were evaluated through a Rapid Serial Visual Presentation (RSVP) task to measure the attentional blink (AB) effect (see Ronconi et al., 2016 for details). The experiment was presented on an HP CRT monitor, refreshing at 100 Hz. Stimuli presentation and data acquisition were performed using Presentation (Neurobehavioural Systems, version 14).

The participant was positioned at a distance of 60 cm from the monitor in a quiet, dimly lit room in the presence of the experimenter. The participant was asked to keep his or her gaze on the central fixation point (a cross shape subtending 2°×2° for 2000msec), at which a sequence of 22 stimuli (2 targets and 20 distractors) appeared in rapid temporal succession, one after the other, in the center of the screen.

With no interstimulus delay, black distractors were shown for 100 ms. The target letters were displayed for 60 milliseconds before being followed by a 40 millisecond hash (#) mask. The target-mask duration was thus equal to the distractor duration. To avoid the expected appearance of the first red target letter (L1), it was randomly placed as the fourth, fifth, or sixth item in the stream. The second black target letter (L2) occurred with similar frequency at delays 3 or 8.

Participants were given an unlimited amount of time at the end of each stream to report the target letters in the correct order and were obliged to guess if they were unsure. The target letters could be any of the twenty-one letters of the alphabet (chance level=5%), and both target letters and digit distractors were allocated at random on each trial, with the restriction that consecutive items could not be the same. The experiment included 230 trials (split into 5 mini-blocks of 46 trials), with 205 L2-present trials, 20 L2-absent trials (catch trials), and 5 initial practice trials (see Figure 18).

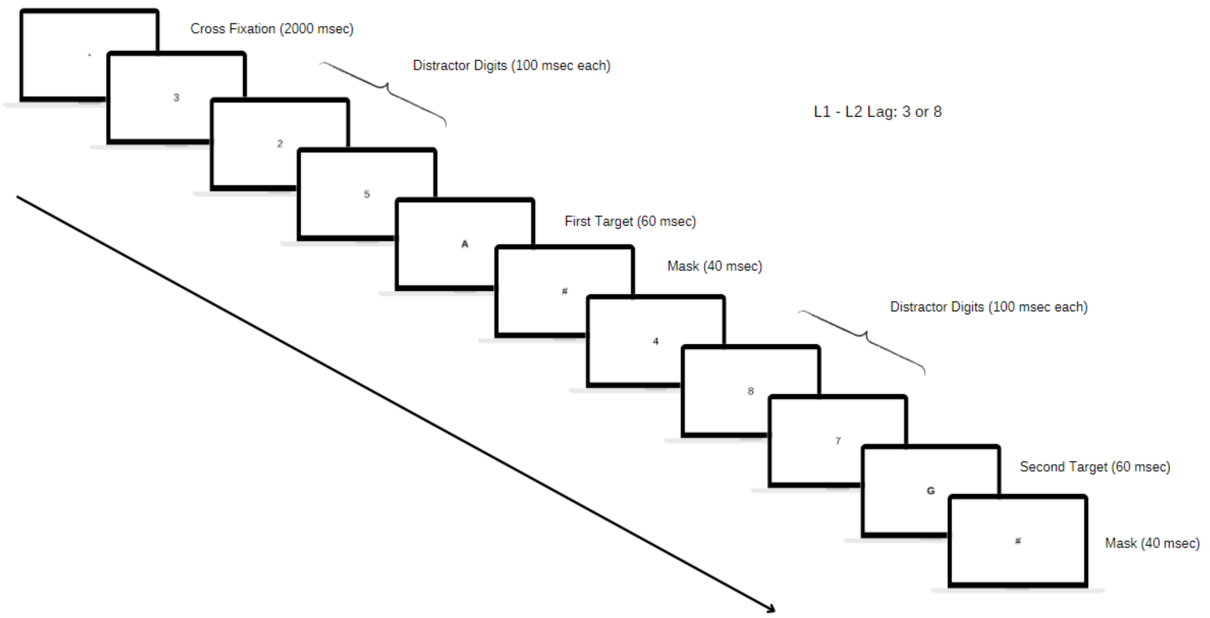

Figure 18. Representation of the temporal attentional task (AB) used. Targets, covered immediately followed by a mask, were randomly alternated by distractor digits with a lag of 3 or 8 stimuli.

2.3.2 Results

Performance at the Baseline

The hf-tRNS and sham groups did not differ in age and in pseudoword reading skills, both in speed and errors (p>0.621 and p>0.111, respectively), in the pre-training condition. In contrast, the two groups differ in word reading speed (hf-tRNS M=-1.98, SD=0.97; sham M=-5.66, SD=3.75; $t_{(18)}=3$, p=0.008), but not in word reading errors (p>0.472). Moreover, the two groups did not differ in the attentional performance at both lag conditions (all ps>0.320).

Between-Group Differences in the Reading Performance and Temporal Attention Enhancements

A multivariate analysis of variance with the word text reading speed as covariate (MANCOVA) with a 4 x 2 design was run. The within-subject factors were the enhancement obtained in pseudoword lists and word texts reading efficacy and the enhancement obtained in the AB task at the two lag conditions, while the between-subject factor was the group (hf-tRNS vs. sham). The effect of the group ($F_{(14)}=3.73$, $p=0.029$) was significant. For this reason, we have run a within-subject analysis to test if the gain obtained in the two training sessions was different from an absence of improvement (no gain=0) through one-sample t-tests for the variables analyzed in the MANCOVA.

Reading Abilities

In order to have a variable that considers the accuracy and reading speed simultaneously and to avoid the trade-off speed accuracy effect, a ratio was calculated between the accuracy (number of pseudowords or words read correctly) and the speed (time in seconds).

Text Reading

The t-test analyses on text reading abilities reveal that the enhancement in word reading efficacy of the hf-tRNS group was significantly different from 0 ($t_{(9)}=2.52$, $p=0.033$). On the contrary, the sham group did not show a difference in word reading performance ($t_{(9)}=1.36$, $p>.21$; see Figure 37).

Pseudoword List Reading

The t-test analyses reveal that the enhancement in phonological decoding efficiency of the hf-tRNS group was significantly different from 0 ($t_{(9)}=8.65$, $p<0.0001$). On the contrary, the sham group did not show an improvement in phonological decoding abilities ($t_{(9)}=1.63$, $p>0.14$; see Figure 37, panel B).

Follow-Up Analyses on Reading Abilities

To verify the maintenance of the effects on reading skills, a t-test analysis was carried out on the participants' performance by comparing the performance post-AVG training and that obtained 4 months after the end of the training (follow-up).

The results show that the hf-tRNS group maintained the enhancement in pseudoword reading efficiency (post-training vs follow-up: $t_{(8)}$=1.01, p>0.34), and the word reading efficiency continued to enhance (post-training vs follow-up: $t_{(8)}$=4.85, p=0.001).

See Figure 19, panels A and B.

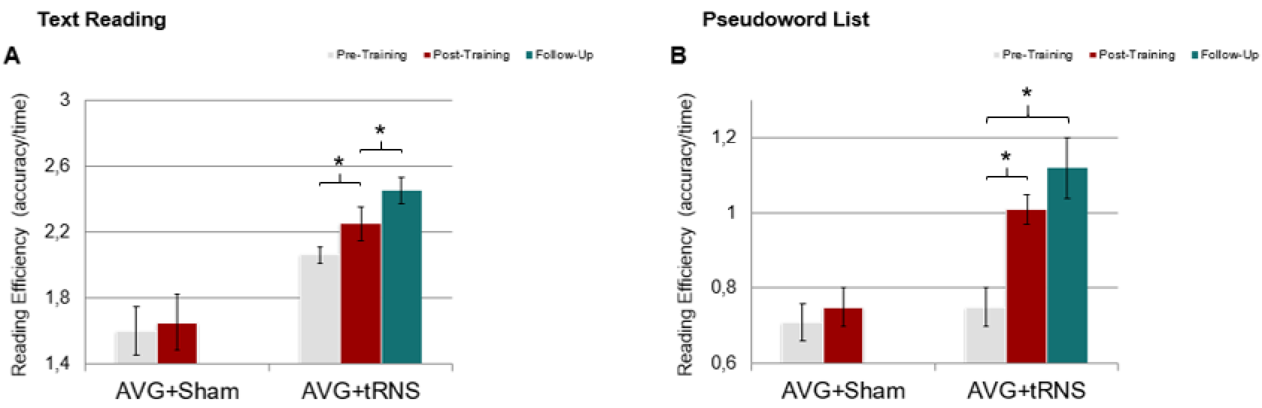

Figure 19. Reading efficiency (accuracy/time) of participants in the text (A) and pseudoword list (B) at three different times (pre-training, post-training and after 4 months). Data are reported as means ± standard errors. The asterisk indicates a significant difference.

Temporal Attention Task (AB)

The t-test analyses show that the hf-tRNS group's improvement in attentional abilities was substantially different from 0 in lag3 and lag8 ($t_{(9)}$=4.88, p=0.001 and $t_{(9)}$=4.35, p=0.002, respectively). On the other hand, the sham group did not show any gain in attentional skills in lag3 as well as in lag8 ($t_{(9)}$=0.61, p>0.56 and $t_{(9)}$=1.69, p>0.13, respectively; see Figure 20).

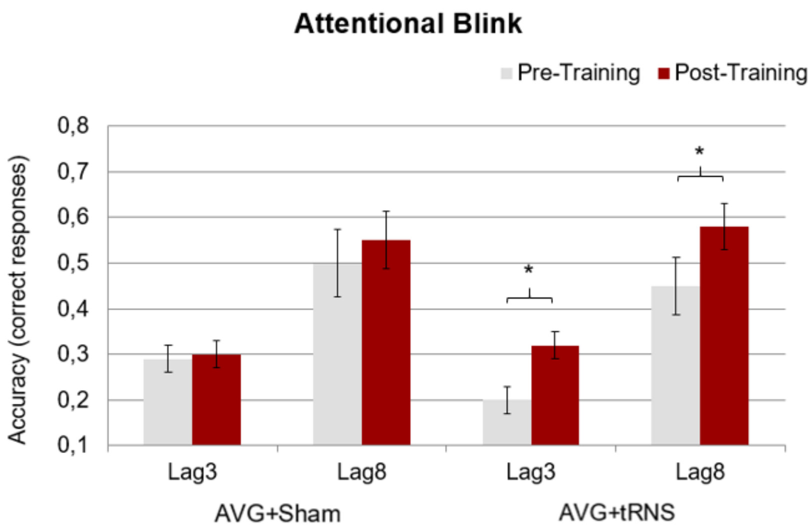

Figure 20. Accuracy (correct responses in L1 and L2 targets) of participants in the temporal attention task (Attentional Blink, AB) text (A) at two different times (pre- and post-training) in two different conditions (Lag3 and Lag8). Data are reported as means ± standard errors. The asterisk indicates a significant difference.

Correlation Analysis between Attentional and Reading Skills

Correlation analysis was performed on the gains in pseudoword and word reading efficiency, as well as attentional abilities (considering the mean between the two lag conditions) while controlling for pre-training word reading speed. The improvements in attentional abilities and pseudoword reading efficiency were found to be positively correlated (r=0.60, p=0.007; see Figure 21).

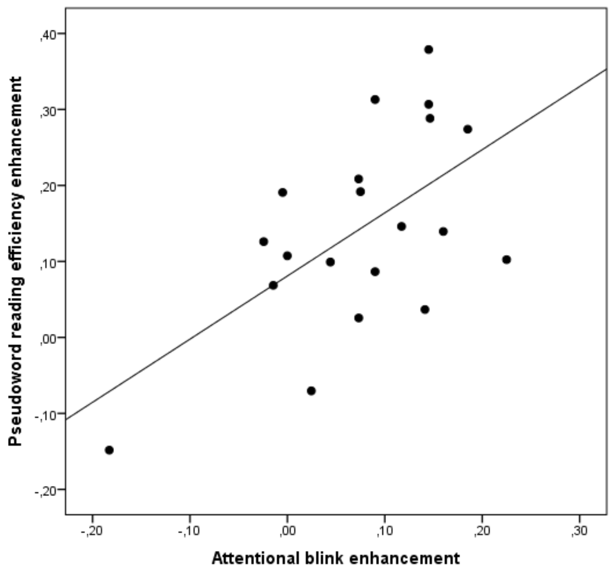

Figure 21. Partial correlation analysis: scatterplot of residuals of pseudoword reading efficiency (accuracy/speed) and attentional abilities (considering the mean between the two lag conditions) after controlling for pre-training word reading speed.

Individual results of behavioural enhancements in the hf-tRNS group

The aim of this analysis is to better estimate the individual advantage of hf-tRNS in the temporal attention and reading performance enhancements for each participant. The gain obtained in word, pseudoword reading and AB task in each hf-tRNS participant was compared to the mean of the gain obtained in the sham group. The results indicate that the gain in pseudoword reading of 10 hf-tRNS participants (100%) was higher than the mean of the gain of the control group. The gain in word text reading efficiency of 7 hf-tRNS participants (70%) was higher than the mean of the gain of the control group. The gain in AB performance of 9 hf-tRNS participants (90%) was higher than the mean of the gain of the control group.

EEG Analyses: P300 Lag 8 (Mean amplitude and Peak latency)

Mean Amplitude Results

An ANOVA with a 2 x 2 x 2 design was executed on P300 mean amplitude. Specifically, the within-subject was the Time (pre- and post-training) and the Target (L1 and L2), while the between-subject was the Group (AVG+hf-tRNS and AVG+sham). The results did not show a significant main effect of time ($F_{(1,16)}$=0.058, p=0.812), target ($F_{(1,16)}$=2.445, p=0.137) and group ($F_{(1,16)}$=1.027, p=0.326) factors. Importantly, such analysis revealed a significant interaction between times, target and group main factors ($F_{(1,16)}$=6.372, p=0.023; See Figure 22). Accordingly, we performed post-hoc t-tests to investigate P300 modulations following AVG+hf-tRNS and AVG+sham training, separately for L1 and L2 targets. Such analysis revealed a significant P300 mean amplitude decrease following AVG+hf-tRNS at L1 target (pre: M=1.10, SD=1.25; post: M=0.61, SD=1.30; $t_{(9)}$=2.220, p=0.026), and a larger P300 amplitude at L2 target (pre: M=0.87, SD=1.08; post: M=2.12, SD=1.50; $t_{(9)}$=-3.453, p=0.004). On the contrary, such analysis did not show significant modulations of P300 mean amplitude following AVG+sham training both at L1 (pre: M=0.64, SD=0.95; post: M=0.45, SD=1.37; $t_{(7)}$=2.290, p=0.29) and L2 (pre: M=1.26, SD=0.87; post: M=0.89, SD=1.46; $t_{(7)}$=0.577, p=0.709) targets.

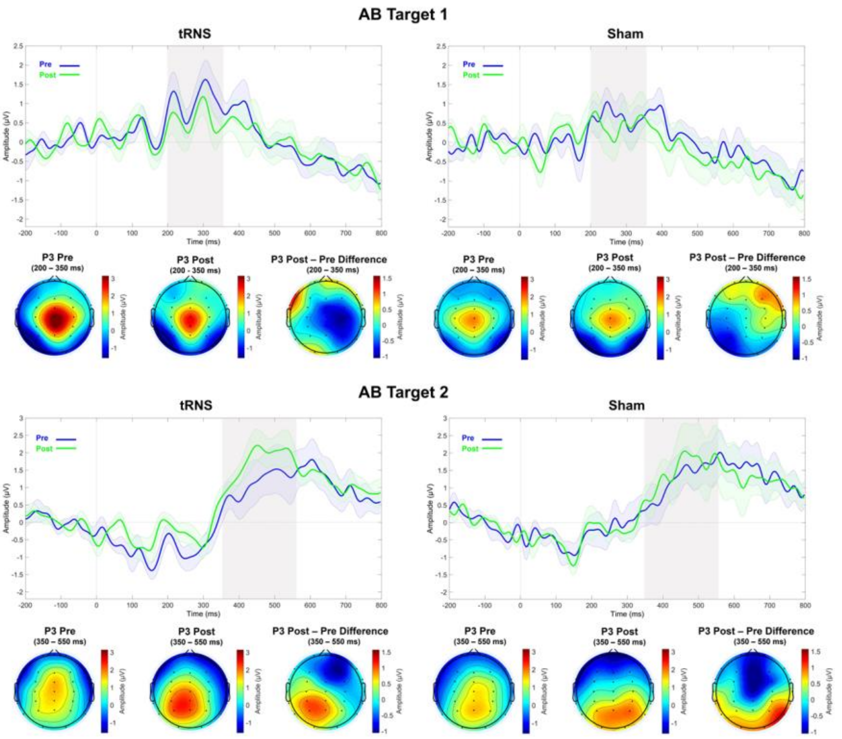

Figure 22. EEG analysis results of P300 amplitude (in □V) in temporal attention task (AB) of AVG+hf-tRNS and AVG+sham training groups, separately for L1 (AB Target 1) and L2 targets (AB Target 2).

Peak Latency Results

The same ANOVA run on P300 peak latency with the aim of testing whether the neural activity was influenced by the Time, Target and Group factors showed a significant main effect of Target ($F_{(1,16)}$ = 183.12, p<0.001), revealing a delayed P300 peak latency for L2 (M=457.97, SD=56.39), with respect to L1 target (M=275.71, SD=47.97; $t_{(17)}$=-13.532, p<0.001), as expected given that L1 and L2 peak latency were indexed in two different time windows (L1: 200-350 ms; L2: 350-550 ms). On the contrary, such analysis did not reveal a significant main effect of the Time ($F_{(1,16)}$=0.189, p=0.67) and Group factors ($F_{(1,16)}$=1.637, p=0.219. Importantly, this analysis did not show significant interactions between main factors (all ps>0.183), suggesting no P300 peak latency differences following AVG+hf-tRNS and AVG+sham training.

2.3.3 Discussion

The study aimed to compare the effect of intensive and brief AVG training combined with hf-tRNS, compared to sham stimulation, on reading and temporal attentional skills in adults with dyslexia. The results showed that only the combination of AVG training with posterior parietal hf-tRNS enhances pseudowords reading efficiency and several visual attention mechanisms. The study also found that the optimal deployment of temporal attention on two visual targets was enhanced by only AVG with bilateral hf-tRNS of the parietal cortex, decreasing both stimulus-driven attention capture on the first salient visual target and inattentive errors on both visual targets. Moreover, the enhancement of phonological reading efficiency was stable after 4 months at the end of the combined training. This suggests that hf-tRNS can boost the effect of AVG training, as demonstrated in other studies with perceptual learning paradigms (Cappelletti et al., 2013). Furthermore, coupling an intensive and brief AVG training with hf-tRNS to critical brain regions for attention skills, such as the posterior parietal cortex, resulted in long-lasting improvement transferable on untrained abilities, such as phonological reading, that shares common cognitive and neuronal components with visual attention (Cappelletti et al., 2013).

The increase in the P300 amplitude recorded during the execution of the temporal attention task is in line with the results of Mishra and colleagues (2011), as the P300 wave amplitude is linked to the ability to inhibit the processing of distractors (Wu et al., 2012). These specific changes in the P300 amplitude suggest that both reading and temporal attention enhancements could be obtained by reshaping goal-directed and stimulus-driven fronto-parietal attentional network interplay (see Corbetta & Shulman, 2002 for a review). In particular, our P300 amplitude results could indicate a decreased activation of VAN combined with an increased activation of DAN. These findings suggest that attentional control enhancement induced by the combination of bilateral hf-tRNS on the posterior parietal lobe and AVG training in the developed brain involves an optimal distribution of processing resources rather than a general neuroplastic enhancement of processing resources (Wu et al., 2012; see von Bastian et al., 2022 for a recent review). In addition, these findings could partially confirm the functional interactions within and between the stimulus-driven and the goal-directed attentional control networks in video game players (Jordan & Dhahala, 2023), and also suggest a causal link in the interplay of these two attentional networks for reading and attention enhancement also in atypical brain development.

This means that AVG combined with bilateral hf-tRNS on the posterior parietal lobe enhances attentional control and the ability to resist distraction, as pointed out by Green and Bavelier (2015) and recently demonstrated by Zhang et al. (2021) and resulted in a long-lasting improvement transferable on an untrained ability, such as reading, that shares common cognitive and neural components with visual attention, confirming the evidence that links reading skills with visuo-spatial attention in children with and without DD (Puccio et al., 2023 for a meta-analysis; Pasqualotto et al., 2022). However, our results suggest that the link between reading and attention involves not only spatial but also temporal domains.

We conclude that the bilateral hf-tRNS on the posterior parietal cortex used as a boost for an intensive but brief AVG training has strong potential to augment temporal attention and reading skills in adults with DD. Indeed, 15 hours with only AVG training is too short to elicit enhancements in these skills in adults with reading difficulties. In sum, our results show long-lasting plastic changes when AVG training is coupled with neuromodulatory intervention.

Overall Discussion and Conclusion

The aim of these studies was to evaluate and measure the possible effects of AVGs training on cognitive functions in children and adults with DD or reading difficulties. In agreement with the systematic review of Peters and colleagues (2019), the results demonstrate that AVGs training is able to induce both near-transfer effects on visual attention abilities, and far-transfer effects on reading and phonological abilities, that are cognitive skills not directly stimulated during AVGs training. Considering the relationship between attention and reading abilities (see Perry & Long, 2021 for a critical review), it is possible to assume that AVGs training produces a direct effect on domain-general skills, such as spatial and temporal deployment of attention. Then, cascade effects on domain-specific skills are generated, such as on reading and phonological processing also in an atypically developing brain (see Bediou et al., 2018 and Ren et al., 2023 for meta-analyses, Sampalo et al., 2023 for a systematic review on young-adults). According to Bavelier and colleagues (2012), this attentional and perceptual training produces clear near-transfer effects on directly stimulated skills, but also far-transfer effects by producing improved efficiency in the learning process (see von Bastian et al., 2022 for a review on cognitive training-induced changes).

It is possible to speculate that the specific demands and characteristics of these video game experiences may promote a more optimal allocation of spatial and temporal attention (e.g., Foerster et al., 2023; Green & Bavelier, 2003). Indeed, the cross-sectional meta-analysis of Bediou and colleagues (2018), indicates that habitual adult AVG players show a robust positive impact of gaming in perception ($g=0.77$), spatial cognition ($g=0.75$) and top-down attention ($g=0.62$). More stringently, the intervention meta-analysis in young adults tested on five different cognitive domains (i.e., spatial cognition, top-down attention, perception, multitasking and verbal cognition) shows a global effect size in the medium range ($g=0.34$; Bediou et al., 2018), which is in line to our results in the GCO ($g=0.38$). Considering the near transfer effect of the AVGs training on cognition, differently to Bediou and colleagues (2018), the effect size of VA in our meta-analysis ($g=0.71$) appears larger than the effect size in their three cognitive domains mainly linked to VA abilities (i.e., spatial cognition, top-down attention and perception, mean $g=0.33$). Although this difference could be simply due to the different attentional tasks used in the studies considered in the two meta-analyses, it could not be excluded that this difference is also due to the larger neuroplasticity of atypically developing brains in children with DD. Another possible explanation is linked to VA deficits that characterise children with DD (see Valdois, 2022 for a recent review; Gavril et al., 2021, and Lonergan et al., 2019, for two meta-analyses) leading to more beneficial effects (larger effect size). Thus, the need to make decisions and execute motor actions under severe time constraints may have enhanced the attentional control for resource deployment as well as the rapid shifting between focused and distributed attention also in children with a neurodevelopmental disorder, such as DD (Bavelier & Green, 2019).

A recent meta-analysis considered the effect of gaming training on different neurodevelopmental disorders, including DD (Ren et al., 2023). The effect size found by the authors on attentional abilities in children with DD is in line with the improvements found in the present meta-analysis in VA (g=0.71 vs. g=0.70 in Ren et al., 2023). Moreover, training effects also appear in reading fluency, confirming the far transfer effect also found in the present meta-analysis on RS (g=0.44). It is important to note that the RS improvements could be explained as a direct effect of enhanced VA on orthographic processing of letter-strings induced by AVGs training in children with DD. Recently, Foerester and colleagues (2023) found an enhanced ability to detect visual asynchronies in AVG players, confirming that experience with AVGs might improve the speed of processing. The power and phase coherence of occipitoparietal alpha-band oscillations provides a possible neurophysiological correlate for this enhanced speed of processing in AVG players. The use of AVGs, thus, seems to be related to functional brain modifications. For example, Richlan and colleagues (2018) reported an increased BOLD signal in AVG players in frontoparietal regions during a visual stimuli detection task. Föcker and colleagues (2019) reported a greater activation in the middle frontal gyrus, in the right temporoparietal cortex and in the superior parietal cortex in adult expert AVG players. This evidence collected through event-related potentials (ERPs) signals seems to be associated with better task performance in visual attention abilities. Interestingly, a large overlap in the right frontoparietal attentional network has been found between spatial attention and lexical, as well as sub-lexical reading (Ekstrand et al., 2020; see also Aboud et al., 2018). Thus, the fast-paced experience of AVGs might facilitate the processing of rapidly presented visual targets in other tasks, such as word and pseudoword reading. However, training studies are necessary to demonstrate the causal effects of AVGs on reading neural networks both in typical and atypical brain development.

In contrast, the phonological process improvements after AVGs training cannot be explained by visual attention enhancements (near transfer effects). A possible auditory attention enhancement could be suggested as a plausible explanation of this far transfer effect induced by AVGs training in children with

DD. Some studies have indeed shown that gaming experience was correlated to better auditory attention and phonological skills in adults (e.g., Green et al., 2010; Mancarella et., 2022; Wu et al., 2021). In our meta-analysis, no studies have directly investigated auditory attention, but it is possible to suppose that a similar effect could be found in children with DD after AVGs training. Interestingly, AVGs training could also work on the auditory dorsal stream in which both "where" (spatial) and "when" (temporal) mechanisms of attention are the basis of the sensorimotor phonological system (see Rauschecker, 2018 for a review). Indeed, the primary auditory cortex receives top-down information from the attentional posterior parietal cortex and from other multisensory areas (prefrontal cortex and superior temporal multisensory area). However, we cannot exclude that these far transfer effects on PP are mediated by dorsolateral projections from primary and secondary visual cortices or/and by bottom-up inputs from thalamic regions (see Schroeder et al., 2008 for a review). We suggest that these complex interactions across top-down, lateral and bottom-up connections could be the neurobiological basis of both near and far transfer effects of AVGs training mediated by the rate at which multisensory information is perceived (i.e., speed of processing). It is important to note that this auditory sampling rate is crucial for the efficient development of phonemic discrimination and awareness (e.g., Facoetti et al., 2010; Hari & Renvall, 2001; Mancarella et al., 2022; Manning et al., 2022; Stefanac et al., 2021; Tallal, 2004; see Goswami et al., 2021 for a review).

Moreover, our results confirm that an AVG training induces transfer effect (Green & Bavelier, 2015), and that this effect is most strongly present when we associate cognitive training (i.e., AVG) with brain stimulation (i.e., tRNS; Cappelletti et al., 2013). This evidence is in line with Cappelletti and colleagues (2013) in which a bilateral tRNS on the posterior parietal lobe (i.e., P3 and P4), administered for 5 consecutive days, 20 minutes each, during a numerosity discrimination task, induced an enhancement in the trained numerosity task that is retained up to 16 weeks after training. Furthermore, the improvement was transferred to untrained abilities that share both cognitive and anatomical resources with the numerosity task, such as time and space processing (Cappelletti et al., 2013).

It is therefore possible to conclude that this evidence supports the causal role of multisensory attention not only in reading but also in phonological processing, promoting the use of AVGs as an ecological, fun, child-friendly and functional remediation program for persons with DD.

Further studies using training causal designs are necessary to investigate the neural networks linked to the auditory and phonological effects of AVGs in persons with and without DD. This unconventional reading remediation program could be combined with the already existing reading-based rehabilitation (e.g., reading acceleration, phonological, grapheme-to-phoneme mapping) tools for improving everyday reading skills, also reducing the risk of dropping out.

General Limitations and Future Directions

The main limitation of the meta-analysis is the small number of studies that met the inclusion criteria and the sample size involved. In addition, many of the papers considered were from the same authors or research lab, and the potential non-independence of authors may not be representative of all conducted training with AVGs. However, the strict selection criteria made it possible to compare the effectiveness of AVGs training with other types of treatments in a clinical population with specific cognitive characteristics. All studies used robust criteria for diagnosing DD following standards set by the DSM-5 (APA, 2013) or ICD-10 (WHO, 1993). In addition, pre- and post-treatment measures made it possible to re-analyze treatment outcomes and measure their effect from the original data. The studies involved were homogeneous in terms of sample age and type of treatment proposed, allowing direct comparison of the effectiveness of rehabilitation treatments in children with DD. In any case, more studies from different research labs, from both alphabetic and logographic languages, are needed to improve the precision of attentional, reading and phonological outcomes. More data are also needed to determine if AVGs training effects in children with DD are moderated by other factors, such as reading disorder severity, other neurocognitive disabilities, device type (e.g., video game console, computer, smartphone or virtual reality), video games genre (e.g., driving or fighting games), intensity, duration or playing engagement. For example, even though the studies involved in this chapter did not refer to gender differences in baseline and treatment outcomes, some studies revealed that the strategy and benefit of video games training could also vary depending on the participant's biological sex (Chaarani et al., 2022; de Castell et al., 2019; see Palaus et al., 2017 for a systematic review on the neural basis of video gaming) and that 10 hours AVGs training can nullify gender differences in spatial attention (Feng et al., 2007). Thus, future studies should also consider training efficacy as a function of this variable. In addition, none of the studies considered the role of enjoyment experienced during play. In agreement with the findings of Franceschini and colleagues (2022a), it might be interesting to evaluate whether the improvement in attentional and reading-related skills caused by AVGs training correlates with the emotions experienced during play and/or the type of (video) game itself. Indeed, according to Klasen and colleagues (2012), changes in emotional state support better attentional shifting and promote an improved gaming performance (see also Gong et al., 2016; but see Pasqualotto et al., 2022).

Although our results show some limits, it is interesting to note how AVGs training is also able to enhance RS without any orthographic and/or phonological stimulation. It could be hypothesized that an optimal combination of phonics, attentional programs and tRNS stimulation might be more efficient for reading remediation in individuals with DD.

Chapter 3. Short-Term Effects of Games and Positive Emotions on Reading-Related Skills

Introduction

Play occurs not only in humans and primates but also in multiple mammalian species, as well as in birds, reptiles, fishes and cephalopods (Graham & Burghardt, 2010; Lillard, 2017; Pellis & Pellis, 2009). The (re)appearance of play in the phylogeny of multiple animal species despite the high costs directly in terms of energy consumed, risks of predation and indirectly in parental and social care needed, has led to the assumption that this behaviour must have positive effects on the fitness of individuals and/or their groups (Berghänel et al., 2015; Graham & Burghardt, 2010). Nevertheless, to date, none of the long-term effect theories developed in the last two centuries can fully explain the reason for the presence of this costly but funny behaviour. Failure in the explanation of the long-term effects of play through a single core theory probably lies in the fact that such an ancient behaviour may, over time, have assumed multiple positive effects on fitness. Indeed, the function of play may differ across species and within species can vary according to age, sex, dominance relationships, context and environment (Burghardt, 2005; Fagen, 1981; Graham & Burghardt, 2010; Palagi et al., 2006). It is interesting to note that despite play peaks during the juvenile phase - especially in mammalian species - it is still present in adulthood (Fagen, 1981; Loizos, 1967; Burghardt, 2005), and also for adult play, multiple theories have been proposed. Some theories assume that play conditioning has become so established that it is impossible to be interrupted (Groos, 1898). Instead, other theories argue that the possibility of interacting with the environment with patterns bound by the pleasantness of play could still indirectly improve fitness: e.g. adults may use play fighting to assess the strength of potential competitors or to reduce tension with unfamiliar partners during courtship (Graham, & Burghardt, 2010), whereas parents may invest in play behaviour to assist offspring development (Graham & Burghardt, 2010). However, the most widely accepted theories consider play as a mechanism for promoting instinct practice, providing physical training, developing sensorimotor and cognitive skills, performing social assessment, and as a tool to have more nuanced responses to a variety of unexpected situations (Andersen et al., 2023; Graham & Burghardt, 2010; Pellegrini, 2006; Špinka et al., 2001). In this sense, play's cognitive, affective and physiological activation seems to encourage the execution of unusual behaviour in response to stimuli.

In particular, the (chemical of) pleasantness could induce the use of large neural networks that usually are not associated with the processing of that specific stimuli, making a behaviour pleasant to be performed and facilitating the acquisition of new stimuli-response mapping underlying an enhancement of learning abilities, mainly controlled by the DAN e/o CEN. Indeed, it has also been supposed that the juvenile play experience could refine the brain to be more adaptable later in life (Pellis & Pellis, 2013; Spinka & Newberry, 2001; Panksepp & Burgdorf, 2000). Recently, Andersen and colleagues (2023) have argued that a predictive processing framework may provide elements for a proximate play model in which young and adult animals are considered Bayesian learners. In particular, they have proposed that play emerges as a variety of niche constructions where the organism modulates its physical and social environment to maximize the productive potential of surprise. This framework can unify a range of well-established findings in play and developmental research that highlight the basic role of play in learning enhancement (see Hedges et al., 2013; Bavelier & Green, 2019 and Peters et al., 2019 for reviews; Bediou et al., 2018; 2023 for meta-analyses). Nowadays, video gaming is one of the most popular forms of playing in children, and a recent review tries to identify how common features between video gaming and traditional games affect development and learning (Nguyen & Bavelier, 2023). The impact of an AVG in a child, as well as social play in a rat, could engage similar emotional and reward signals (Franceschini et al., 2022), and in combination with specific features of the games, could induce far-transfer learning enhancements (Johann & Karbach, 2020). For this reason, not all video games have the same impact on behaviour and the developing brain (Franceschini et al., 2013). Green and colleagues (2010) proposed an improved probabilistic inference as a general learning mechanism underlying AVGs' wide transfer and multisensory effects. In particular, the rate of accumulation of sensory evidence is improved in gamers. Thus, the AVG experience results in more efficient use of sensory evidence. This enhanced learning capacity is termed learning to learn (Bavelier et al., 2012; 2022).

Most of the theories' results mainly focused on the long-term benefits of play, probably because of the apparent pointlessness of play in the immediate future. However, a complete understanding of play requires considering the multifunctional aspects of this behaviour and, especially at this stage, should become compelling to identify its emotional and behavioural immediate effects, in connection with context and environment. In this direction, Palagi and colleagues (2006) demonstrated that during daily activity routines, both chimpanzees and bonobos increase the use of play in specific moments, one of these was the period before feeding: play in this context appears as a way to prevent and reduce tension improving peaceful co-feeding in the immediately following period (Palagi et al., 2004; 2006). Observing non-human primates, play appears a tool to activate cognitive functions suitable for dissipating excess activation by the initiation of emotional, sensorimotor and cognitive functions useful during play (Pellis & Pellis, 2013) that incidentally could become useful also during the moment that immediately follow the game (i.e., feeding time). When you ask human primates why they use video games, one of the most popular forms of play among adults in modern society, they confirm that play brings joy, that they play to relax, to fill time waiting, to be comforted by something familiar, to provide stress relief (Entertainment Software Association, 2023). Video gaming appears in terms of effects comparable to solitary, social and object play observable in other primates (see Nguyen & Bavelier, 2023 for a recent review). Literature about the influence of video game play on mental health confirms that multiple kinds of video games positively influence mood increasing happiness (see, for example, Raudenskà et al., 2023 for a review about the play as a stress-protective factor during the pandemic), favouring emotional regulation, reducing state and trait anxiety (Kowal et al., 2021; Horne-Moyer et al., 2014; Holmes et al., 2010). It could be supposed that emotional and psychophysiological activation induced by playing video games should be useful for executing subsequent stressful activities.

Although not extensive on long-term effects (Granic et al., 2014), literature about the immediate (short-term) effects of video games on cognitive skills shows that players, immediately after the use of video games, transiently improved their performance in several cognitive domains, compared to baseline performance (pre-video gaming) and compared to the performance of video gamers that simply watched other video gamers playing (Kozhevnikov et al., 2018). Video gamers boost their competence in tasks involving visuo-spatial and perceptual abilities like mental rotation and tasks involving visual memory and temporal attention measured with an AB task (Kozhevnikov et al., 2018). Weaker evidence was obtained on tasks that engage complex executive functions, like the Eriksen flanker task (Eriksen & Schultz, 1979), a paradigm that involves the CEN (Kozhevnikov et al., 2018). In this sense, positive emotions triggered by play activity seem to induce a transient reallocation of resources in a large-scale brain network - the SN - that promotes specific cognitive and behavioural skills, favouring in particular automatic sensorimotor behaviour and attention mechanisms (Hermans et al., 2014) leaving unaffected or negatively influencing others cognitive network enrolled in the goal-directed functions controlled by

CEN and/or DAN (Baas De Creu & Nijstad, 2008, Huntsinger, 2012; see Van Oort et al., 2017 and Schwabe et al., 2022, for reviews).

The play could make activating and stressful situations more manageable through the chemistry of pleasure. The neurochemical effects of arousal and emotional activation connected with play activity induce a transitory short-term effect that could still be observed for about twenty minutes after the end of the positive experience. After this period, the effect disappeared (Kozhevnikov et al., 2018). The beneficial effects of play and positive emotions also fit with the definition of placebo effects: positive expectation and classical conditioning are involved in both cases and the neurobiological basis overlaps (Finniss et al., 2010). Distinguishing the effect of play on the SN and/or VAN, implicated in the detection and integration of emotional and sensory stimuli (Downar, Crawley, Mikulis & Davis, 2000), and on the CEN and/or DAN, that could improve reading-related abilities, become useful to understand better the general effects of play activity and its possible application in clinical and educational settings.

Franceschini and colleagues (2022) investigated the relationship between video-game play activity, positive emotions, and short-term effects on sensorimotor and cognitive enhancement in children diagnosed with DD and developmental coordination disorder. The funnier and more activating game, also in this case, enhanced visual perception improving the processing speed of salience global Navon figures, without affecting the processing speed of local Navon figures, the task that involves conflict resolution and executive processing (Navon, 1977). These data suggest that play activity induces an activation that mainly facilitates the extraction of salience stimuli. Moreover, it was observed that children with neurodiversity ameliorated sensorimotor and reading disorders. A second experiment in healthy young adults confirmed that positive emotions improved after game plays were linked with text reading enhancement (Franceschini et al., 2022).

Overall, the outcomes reflect the effects described already in the literature concerning the short-term influence of positive emotions on human visuo-perceptual: inducing a positive and active state, happiness and fun experiences promote fluency and lexico-semantic abilities (see Baas et al., 2008 for a meta-analysis, Fredrickson, 2001, 2013; Rowe et al., 2007), as well as the global extraction of visual stimuli (Basso & Lowery, 2004; Fredrickson, 2004; Fredrickson & Branigan, 2005; Johnson et al., 2010).

Overall Aim and Studies

Beginning with the findings of Franceschini and colleagues (2022), the goal of the present research chapter was to investigate whether a single session of play activity - through the modification of the emotional and psychophysiological state - could affect the neuropsychological outcome of sensorimotor, attentional, executive and reading skills, impacting on the salience (automatic or stimulus-driven) and/or the executive (voluntary or goal-directed) processing. Thus, we compared different types of games in different populations with and without neurodevelopmental disorders.

Specifically, the first study presented in this chapter ("Study 4. The Short-Term Effects of Games and the Role of Emotions in School-Age Children: A Preliminary Study") is a preliminary research involving 18 typically developing children attending the first primary grade. The objective was to compare the same AVG used by Franceschini and colleagues (2022) with a visuo-constructive board game. The same board game was used and compared in the second study with a driving game ("AVG-like", according to the definition of Nguyen and Bavelier, 2023) on 47 children attending preschool ("Study 5. The Short-Term Effects of Games and the Role of Emotions in Preschool Children"). Moreover, the effects of the game were evaluated in 60 university students with and without reading difficulties ("Study 6. The Benefits of Playing Action-Like Video Games on Salience Processing").

Our hypothesis was that in young adults, video game play, modulating the emotional and psychophysiological activation by the improvement of positive emotion and consequently the regulation of the stress level, could enhance automatic sensorimotor and cognitive processing as a consequence of selective activation of the SN. In contrast, performance in complex goal-directed executive tasks - regulated by the activation of the CEN that involves prefrontal brain areas - will result unaffected or worsened by the playfulness activity.

Study 4. The Short-Term Effects of Games and the Role of Emotions in School-Age Children: A Preliminary Study

Abstract

Although play characterizes the animal kingdom from humans to cetaceans, from young individuals to the elderly, its evolutionary significance is mostly speculative. Some studies have investigated the role of entertainment in the ability to integrate and extract information from the visual scene and in semantic-lexical skills. Other research, however, has demonstrated promising outcomes of video games in clinical-rehabilitation settings. This study fits into the recent strand of research investigating the short-term effects of gaming induced by the release of specific neurotransmitters. Through the use of an AVG and a board game, judged to be equally enjoyable by the 18 children who participated in the research, it was possible to demonstrate improvement in lexical reading skills, sensorimotor skills and implicit memory from the AVG vs. baseline comparison alone. Although visual search efficiency seems to decrease both after the session with the AVG and after the board game compared with the baseline, the only advantage that emerges from the direct AVG-board game comparison appears to be in implicit memory. It is concluded that the game-induced enlargement of attentional focus, combined with the intense rapid peripheral stimulation of the AVG, may be causally related to the enhancement of specific cognitive functions that require the integration of multiple sources of information.

3.1.1 Materials and Method

Participants

Nine females and 9 males who were first-year primary students and native Italian speakers were included in the study's sample (M=6.88 years; SD=0.27 years; all right-handed). No sensory deficit (auditory, visual, or motor) or cognitive impairments (such as ADHD, language disorders, or autism spectrum disorders) were reported.

For the descriptive analysis of the experimental group, the data from the sub-test “Block Design” of the Wechsler Intelligence Scale for Children (WISC-IV, Wechsler et al., 2003) were used. The analysis showed that it could include the entire sample without rejecting participants because values were within the norm in the IQ estimation (M=12.11, SD=2.22).

Adherence to the study was entirely voluntary, requiring the signatures of both parents or those with parental authority over the kid. The families were given a form clearly stating the goals, procedures, and schedule to acquire data.

The planned project was written in compliance with the European Union Standards of Good Clinical Practice and authorized by the University of Padua's Ethics Committee (research protocol number: 1849).

Procedure

The study involved three experimental conditions, each comprising three 60-minute sessions held three days apart. The initial session established the child's baseline cognitive functioning. The subsequent sessions assessed short-term cognitive effects following a 20-minute gaming session. Half the participants played "Tangram" (board game) in the second session and "Geometry Wars: Galaxies" (AVG on Nintendo® DS) in the third, while the other half followed the reverse order. The study employed a within-subject design. Moreover, the game-playing experimenter was different from the one evaluating cognitive effects, guaranteeing the single-blind procedure. A neuropsychological battery and two games (AVG and board game) were used in quiet, well-lit classrooms.

The data collection phases were as follows:

1) The first session included assessments of general cognitive functioning, phonological abilities, reading abilities, visual-attentional mechanisms, and sensorimotor abilities.

2) The second and third sessions comprised a 20-minute board game or AVG session, followed by a self-assessment questionnaire on emotions (adapted version from Franceschini et al., 2022). The same tests from the first session were re-administered.

Participants were assigned alphanumeric codes consisting of a sequential number from 1 to 18 and the initials of the children’s names. Assignment to the groups was random and determined by a computerized generator and the order of session games. See Figure 23 for a graphical description of the experimental design.

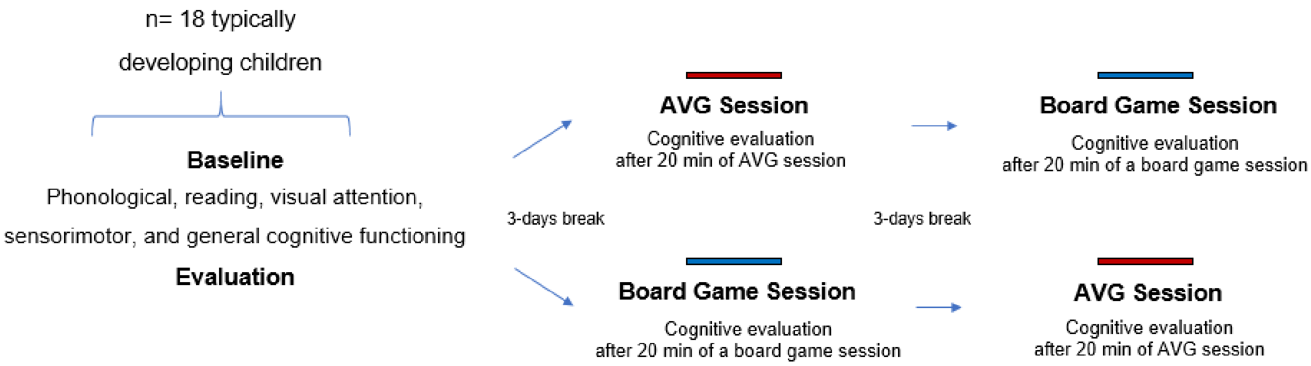

Figure 23. Schematic representation of the Study 4 design.

Neuropsychological battery

Block Design (WISC-IV; Wechsler, 2003)

The subtest "Block design" (Kohs, 1920) evaluated the child's visual-perceptual reasoning and, more specifically, the visuo-constructive skills. The child was shown fifteen geometric pictures of increasing difficulty. Using red and white wooden coloured cubes, the participant would need to reconstruct the design in the least amount of time feasible. Time and accuracy were recorded for each figure, and the test was halted once three things received a score of 0. Following that, the total raw scores were weighted in accordance with the WISC-IV Handbook (Orsini et al., 2012).

Phonological short-term memory test

This test assesses phonological processing and short-term memory abilities. It involves presenting a child with a series of nonsense trigrams (pseudowords) grouped into pairs, with each pair increasing in length up to a maximum of 16 trigrams. The child's task is to repeat the pairs of trigrams in the exact order presented by the experimenter. The child's performance is evaluated based on the number of correctly repeated phonemes in each sequence of pseudowords, with no time constraints. The test is considered completed when the child gets both sets of trigrams of the same length wrong.

Three different versions of the test can be found in the Appendix Section.

Reading tasks

1. Word List Reading (Batteria De.Co.Ne. per la lettura, Franceschini et al., 2016)

The word-reading test allows one to test lexical reading skills by administering lists of words that exist in the spoken language. Specifically, the child is asked to read as quickly and accurately as possible a list of words that are longer or shorter and more or less frequent in everyday language (and therefore familiar to the child). The 3 lists consisted of 30 words (74 syllables) each, equalized by difficulty and frequency of use. For each list, the time spent reading, and the errors made were then measured: each word read incorrectly, without spontaneous self-correction, was counted as 1 error. Through these two indices (i.e. number of syllables and time in seconds), it became possible to extract the reading speed parameter understood as syllables read per second (syll/sec). A composite inefficiency index that accounts for both the speed parameter (syll/sec) and errors made during the reading test was used to determine the efficiency of the word reading test.

2. Pseudoword List Reading (Batteria De.Co.Ne. per la lettura, Franceschini et al., 2016)

The pseudoword reading test assesses the participant's sub-lexical skills by administering nonsense word lists. The child is specifically asked to read a list of pseudowords of varied lengths as soon and precisely as possible. The 3 lists consisted of 16 pseudowords (50 syllables) each. The time spent reading, and the errors made were then measured for each list: each non-word read incorrectly, without spontaneous self-correction, was counted as 1 error. Syllables read per second (syll/sec) and an inefficiency index were calculated.

Visual search task

The paper-and-pencil test allows children's visual-spatial attention to be assessed. Specifically, subjects are asked to scan, identify and mark the target stimulus amid other distractor stimuli in a series of five sheets (see Figure 24). The first baseline sheet was stripped of distractors and allowed the child to become familiar with the target and the task. This baseline assessed both the attentional and motor components and, therefore, the time required for barrage alone to estimate the functioning of the more automatic mechanisms of the SN. Next, two visual search sheets characterised by two different display sizes were administered: one large (5 targets and 34 distractors) and the other smaller (5 targets and 22 distractors). The order of administration was determined by casual randomisation. The fourth re-test sheet was the same as the second one and was used to assess visual long-term memory. The targets were always distributed in the same order in the sheet: two in the right hemifields, two in the left hemifields, and one in the center. Finally, the fifth sheet consisted of an explicit memory task: the delivery given to the child was to mark the animals seen in the previous sheets (even those that were distractors before) amidst the other animals, some of which were completely new, measuring the incidental long-term memory by a recognition task. The time taken by the child to find the target (but explicit memory task), the number of correct targets identified, and the number of incorrect items were measured for each sheet.

The participants' performance was evaluated using an inefficiency index that considered both the time required to complete the task and the accuracy with which it was completed (time in seconds/errors) in the display size with large and small conditions.

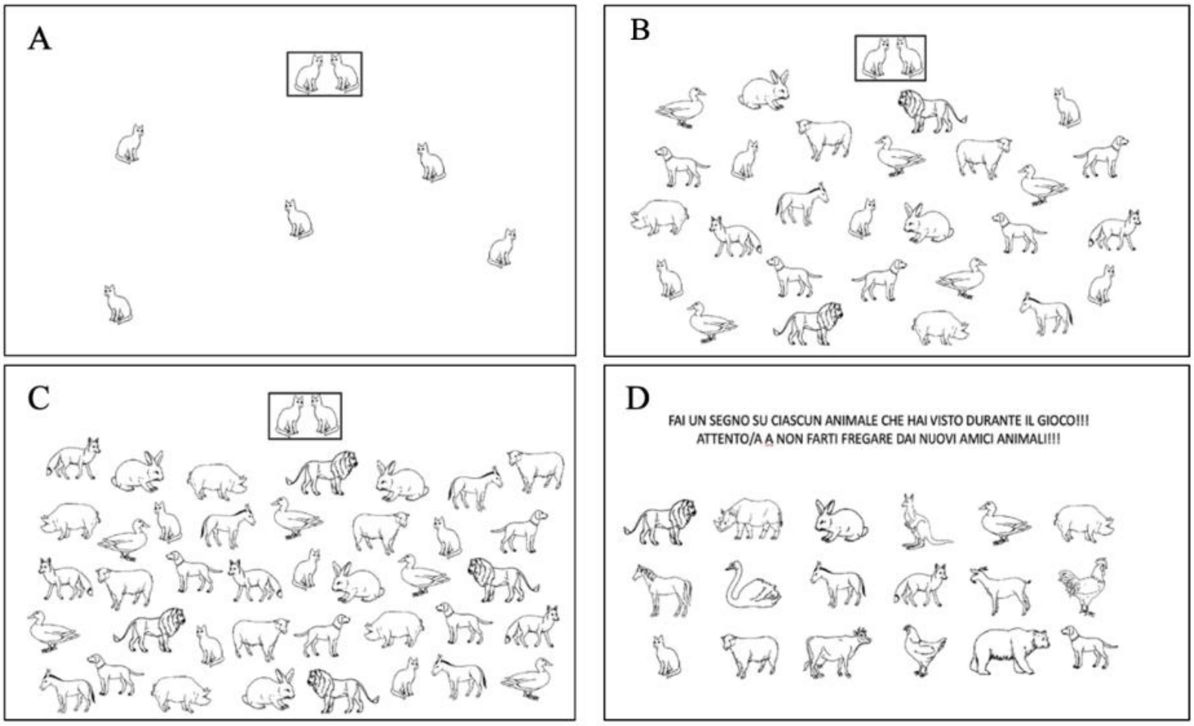

Figure 24. Representation of the visual search task used in the baseline session (distractor=0). Panel A represents the first barrage sheet; in panel B, the small display size (distractors=22); in panel C, the large display size (distractors=34); in panel D, the sheet assesses the incidental long-term memory. The same instrument was used in the AVG and board game sessions, but the targets were dogs or geese, depending on randomisation.

Bank Box (MABC-2; Henderson et al., 2007)

The “Bank Box” subtest is used to investigate manual dexterity in children. The 12 coins are arranged in three rows of four tokens, approximately 2.5 cm apart. When the experimenter says "go," the child must hold the bank box steady with one hand, take the coins one by one with the other hand and insert them as quickly as possible. After the practice trial (with 6 practice coins), the formal test follows, always starting with the dominant hand and then the non-dominant hand. For example, if the right-dominant hand is being evaluated, the child must insert the coins using the right hand while holding the bank box steady with the left hand. To evaluate the other hand, it is necessary to reverse the position of the bank box and the coins. For each hand, the number of errors made (i.e., coins placed incorrectly in the bank box slot on the first attempt, violation of a rule) and the time taken to complete the test are registered. Note that this sensorimotor task engages an action of grasping.

Games

Geometry Wars: Galaxies (AVG)

"Geometry Wars: Galaxies" (PEGI: 3 years old) is a video game on Nintendo® DS. The game centers on a player-controlled spacecraft navigating through a dynamic, abstract space environment, engaging in combat with geometric shapes and enemy entities. The game was chosen as AVG based on the characteristics identified by Green and Bavelier (2012) and is the same used in Franceschini and colleagues’ study (2022). The game session lasted 20 minutes for each child, without interruption, and was always preceded by a short practice run with the experimenter (about 3 minutes).

Tangram (Board game)

The Chinese puzzle board game "Tangram" involves assembling prepared images using uniquely coloured geometric shapes. The images that were to be recreated were picked out of the game file and shown to the children in progressively more challenging levels. The execution time and accuracy (whether the figure was accurately replicated or not) for each of the suggested images were recorded.

Games and Self-Evaluation Questionnaire (adaptation from Franceschini et al., 2022)

This survey was conducted right away following the gaming session. It had five components in all. On a 3-point scale (ranging from "almost nothing" to "a lot"), participants were asked to rate the game (i.e., difficult and funny) and how they were feeling after the gaming session (i.e., tense, vivacious, happy).

3.1.2 Results

Phonological Short-Term Memory Test

The t-test on the number of phonemes correctly repeated by the participants in the short-term memory task of pseudowords showed a significant improvement in board game session (M=30.39, SD=12.28; $t_{(17)}$=-2.727, p=0.14) compared to the baseline session, (M=24.17, SD=9.41). However, the difference between the baseline and the AVG sessions is not significant (M=30.06, SD=13.16; $t_{(17)}$=-1.722, p=0.103) as well as the difference between the two games ($t_{(17)}$=-0.100, p=0.922; see Figure 25, panel A). These results show that children's performance improved after the board game and AVG sessions. However, only after the board game this improvement was statistically significant.

Word List Reading

The t-test on the inefficiency of the word reading test showed a significant improvement in the AVG session (M=1.35, SD=0.32) compared to the baseline session (M=1.51, SD=0.38; $t_{(17)}$=2.576, p=0.020). Instead, the difference between the baseline and the board game sessions is not significant (M=1.41, SD=0.26; $t_{(17)}$=1.406, p=0.103) as well as the difference between the two games ($t_{(17)}$=-1.229, p=0.236; see Figure 25, panel B). These results show that children's performance improved after the AVG and board game sessions. However, only after the AVG this improvement was statistically significant.

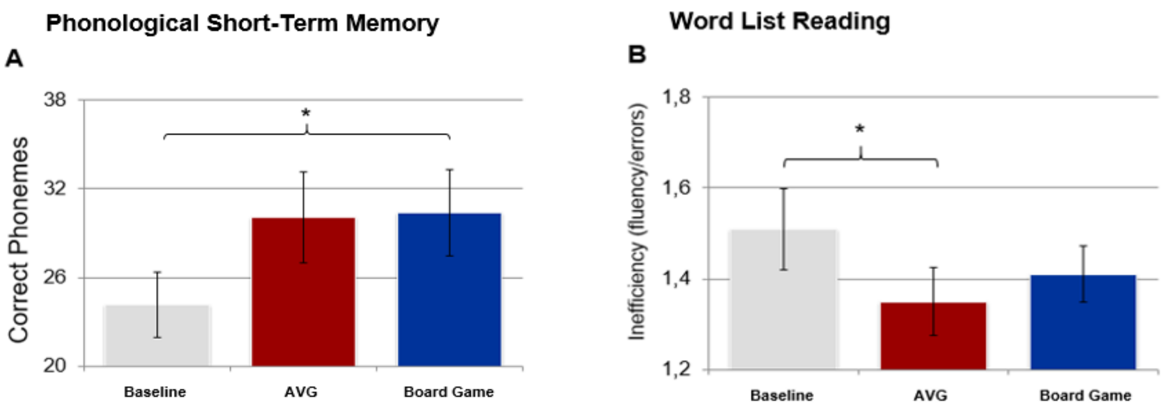

Figure 25. Performance of children in the baseline condition and after the two-game sessions (AVG and board game) in the phonological short-term memory (A) and in the word list reading (B). Data are reported as means ± standard errors. The asterisks indicate the significant differences.

Pseudoword List Reading

The t-test on the inefficiency of the pseudoword reading test showed no significant differences between AVG (M=1.59, SD=0.43) and the board game (M=1.69, SD=0.39) compared to the baseline session, (M=1.56, SD=0.60; $t_{(17)}$=-0.169, p=0.868 and $t_{(17)}$=-0.708, p=0.488, respectively). No significant differences emerge between the two playing conditions ($t_{(17)}$=-0.966, p=0.348). These results show that a 20-minute game session does not produce significant changes in phonological decoding skills, regardless of the type of game.

Visual Search Task

The effects of the game on visuospatial attentional skills were investigated through t-test analyses of children's performance on the visual search task.

Analyses showed that inefficiency in the condition with 34 distractors increases significantly after the AVG session (M=34.18, SD=13.91) compared to the baseline (M=24.43; SD=4.31; $t_{(17)}$=-2.852, p=0.011). In contrast, no statistically significant differences were observed in the condition with 22 distractors after the AVG session (M=23.36, SD=5.70) when compared with the baseline (M=21.20, SD=6.16; $t_{(17)}$=-1.668, p=0.114).

On the other hand, after the board game session an increase in inefficiency emerges both in the situation with 34 distractors (M=35.88, SD=10.79) compared with baseline (M=24.43, SD=4,41; $t_{(17)}$=-4.178, p=0.001) and in the situation with 22 distractors (M=26.64, SD=8.81) compared again with baseline

(M=21.20; SD=6.16; $t_{(17)}$=-2.502, p=0.023). However, a direct comparison between the two games shows no significant difference in the condition with 34 distractors ($t_{(17)}$=5.621, p=0.350) as well as in the condition with 22 ($t_{(17)}$=1.823, p=0.155; see Figure 26, panel A).

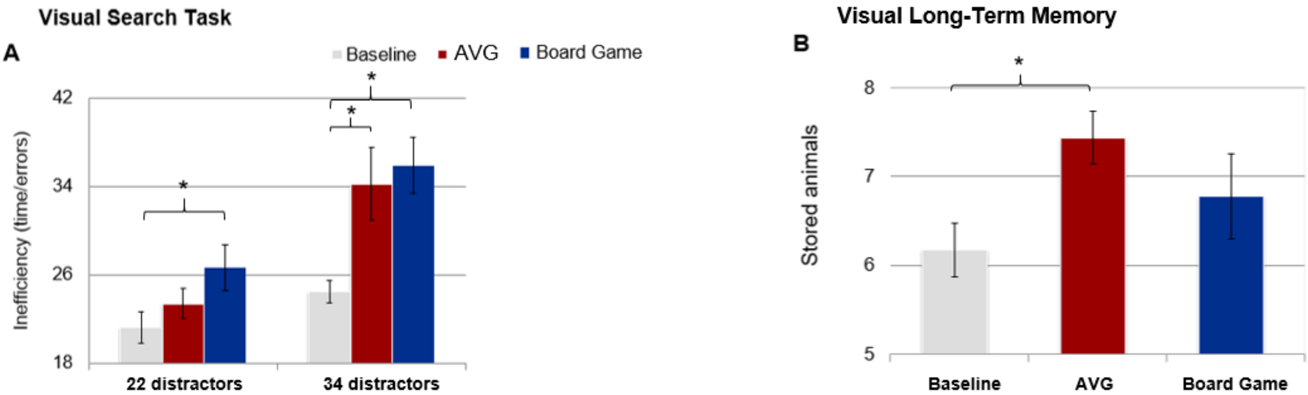

Figure 26. Performance of children in terms of inefficiency (time/errors) in the visual search task in small and large display sizes condition (A) and in the memory sheet (B). Data are reported as means ± standard errors. The asterisks indicate the significant differences.

A t-test was conducted on the results of the last sheet of the task, i.e., the one in which the child had to cross out all the animals (targets and distractors) seen during the task. The results show a significant improvement in the AVG session (M=7.44, SD=1.25) compared to the baseline (M=6.17, SD=1.29; $t_{(17)}$=3.465, p=0.003), but not between the board game (M=6.78, SD=2.02) and the baseline ($t_{(17)}$=1.057, p=0.305). However, the direct comparison between the two games is not significant ($t_{(17)}$=1.587, p=0.131). These results show that children's visual long-term memory performance improved after the AVG and board game sessions. However, only after the AVG this improvement was statistically significant (See Figure 26, panel B).

Bank Box Test

To investigate the effects on the efficiency of manual dexterity and to exclude a possible trade-off between speed and accuracy, the composite inefficiency index (i.e., the ratio of time in seconds to accuracy in frequency) on the performance of both hands (dominant and non-dominant) was calculated. Driven by the previous finding (Franceschini et al., 2022), one-tail t-tests revealed that a significant decrease in inefficiency was found between the baseline (M=30.87, SD=6.76) and AVG session (M=27.04, SD=6.04; $t_{(17)}$=1.894, p=0.036), but no differences emerged between baseline and board game session (M=28.61, SD=6.04; $t_{(17)}$=1.046, p=0.155) and between the two games ($t_{(17)}$=-1.023, p=0.161). These results show that children's visual grasping performance improved after the AVG and board game sessions. However, only after the AVG this improvement was statistically significant (See Figure 27).

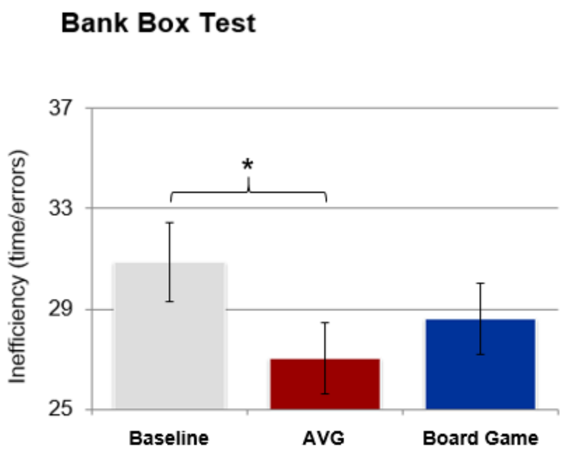

Figure 27. Performance of children in terms of inefficiency (time/errors) in the bank box task with dominant and non-dominant hands. Data are reported as means ± standard errors. The asterisks indicate the difference.

Games and Self-Evaluation Questionnaire

According to the results of Franceschini and colleagues (2022), the questionnaire responses regarding the enjoyment experienced and the degree of activation perceived during the two games were averaged. Specifically, the t-test shows a significant difference between the responses given to the questionnaire after the AVG (M=2.89, SD=0.21) and board game sessions (M=2.75, SD=0.31; $t_{(17)}$=2.557, p=0.020; see Figure 28).

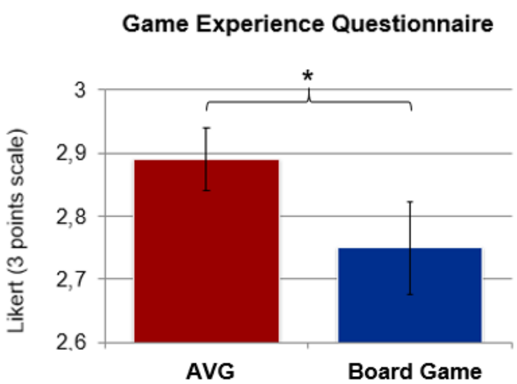

Figure 28. Responses to the adaptation from the Self-Evaluation Questionnaire (Franceschini et al., 2022) were administered after the game session with AVG (red bars) and a board game (blue bars) in “funny” and “tense” items. Data are reported as means ± standard errors. The asterisks indicate the significant differences.

3.1.3 Discussion

The aim of this research was to investigate the transient impact of game experience and the associated positive emotions on phonological reading-related, visuo-spatial attention, visual long-term memory and sensorimotor skills after two short gaming sessions: one with an AVG (Geometry Wars) and one with a classic construction board game (Tangram).

Building on recent findings (Franceschini et al., 2022), which demonstrated improved reading skills after a single longer gaming session with AVG, this study aimed to compare the same AVG with a new game condition in which a traditional board game was used. The goal was to explore further the influence of game characteristics and the intrinsic enjoyment experienced during gameplay. Although it was observed that typically developing first-grade children were more fun and activated after playing the AVG in comparison to the board game, in the neurocognitive functions measured here, no significant difference was shown when the two different games were directly compared. These null effects could be explained by the earlier chronological age as well as the typical development of our sample in comparison to the sample by Franceschini et al. (2022). In contrast, comparing the post-game with the baseline session, it was noted that neurocognitive performance significantly improved mainly after the AVG session, but in visual search tasks. These findings suggest a more efficient transient effect on measured neurocognitive functioning after a more fun and activating game that involves the typical visual and multisensory features of the AVG. In particular, there were lexical-level improvements in word reading efficiency after the AVG session. However, there were no significant differences in sub-lexical reading of pseudowords (phonological decoding). These result patterns confirm the findings by Franceschini and colleagues (2022) in which healthy adults selectively improved lexical reading without any effect on phonological decoding. Interestingly, the results in the bank box task show a selective improvement after the AVG session: children significantly improved their performance in the grasping action. Again, considering the role of emotions in sensorimotor abilities (see Braine & Georges, 2023 for a recent review), this result highlights the effect of SN and/or VAN in a task that does not involve inhibition or executive control, only after the game session perceived as more fun and activating. Finally, also visual memory performance was significantly improved only after AVG session. Since this task probably indexes the general learning mechanism, it could be suggested that a brief experience with AVG is causally linked with improved visual learning. Again, the optimal activation and positive emotions associated with this specific game could explain its greater efficiency. It is possible that the major fun and activation derived after AVG may be associated with the release of specific neurotransmitters and neuromodulators (see Vanderschuren et al., 2016 for a review), possibly contributing to an efficient widening of attentional focus. In an almost mirror way, positive emotions seem to facilitate the execution of automatic stimulus-driven actions. Positive emotions facilitate access to well-established linguistic information (Baas et al., 2008; Rowe et al., 2007) and maximise the spontaneous global perception of visual processing (Fredrickson & Branigan, 2005; Gasper & Clore, 2002; Ji et al., 2019). This widening, induced by the game, may lead to decreased selectivity but simultaneously allows for greater reception of stimuli due to a broader attentional focus. Indeed, a potential downside or "cost" of enjoyable gaming was identified in the atypical distribution of visuo-spatial attention leading to reduced efficiency in visual search tasks. After both gaming sessions, there was a deterioration in visual search under conditions with more distractors and increased crowding. This finding could reveal a possible deterioration in the CEN processing, probably associated with a widening of attention focus (Bertoni et al., 2023) that, in this specific case, hinders target identification and the process of perceptual salience. At the same time, it is possible to assume that the effect of the game sessions is due to the prevalence of VAN over the DAN. Consequently, the reduced efficiency in visual search tasks, resulting from an expanded attentional window induced by the games, appears to suggest that the word lexical recognition, grasping and visual learning mainly involve the activation of SN and/or VAN combined with the deactivation of CEN and/or DAN.

However, challenging these argumentations, a significant improvement was observed in auditory-phonological short-term memory only after the board game session, requiring further investigations. A possible, even if speculative, explanation could sustained that the auditory components of SN were not activated during the traditional visuo-constructive board game, allowing to the CEN optimal memory flexibility, which could be reflected in a significant improvement in the auditory-phonological short-term memory task (see Schwabe et al., 2023 for a review).

In conclusion, although a direct comparison of the two games did not reveal significant differences, the comparison between baseline and post-game conditions might suggest greater efficiency of the salience processing over executive control after AVG. However, further studies are needed to disambiguate the roles of game type vs. the associated enjoyment in neurocognitive enhancements.

Study 5. The Short-Term Multisensory Effects of Games and the Role of Emotions in Preschool Children

Abstract

Several research studies have demonstrated positive long-term outcomes of video games training on the development of attentional control, but what are the immediate effects of a single game session underlying these improvements? In a group of 45 preschoolers, several neuropsychological functions were measured immediately after two counterbalanced conditions of AVG (Mario Kart 8 Deluxe on Nintendo® Switch) or traditional board game (Tangram), compared with the control condition (no game - baseline). Phonemic perception and target barrage without distractors improve, while phonological short-term memory, target barrage with many distractors (visuospatial attention), and aiming in extrapersonal space worsen immediately after the two-game conditions. Moreover, the game experience seems to nullify the spatial focusing effect of the cue shown in the baseline. However, some specific effects related to video games also emerge: children seem to improve their fine sensorimotor grasping performance with the non-dominant hand (showing a reversal of manual dominance) but also worsen their response inhibition skills. The game appears to temporarily activate the primitive salience circuitry but reduces prefrontal top-down control, which is still developing. Furthermore, the characteristics of the video game, combined with the increased enjoyment, might activate the sensorimotor control of grasping skills. Transient deactivation of the neural circuit would be followed by long-term reactivation, typically detected in rehabilitation training. Our results suggest the possible neurobiological basis of new preventive strategies for developmental motor coordination disorders that often occur in comorbidity with specific learning and autism spectrum disorders.

3.2.1 Materials and Methods

Participants

The study involved a sample of 47 native Italian-speaking children, including 20 females and 27 males, attending the third year of kindergarten (M=5.41 years; SD=0.36 years; 7 left-handed, about 15%). The children reported no diagnosis of neurodevelopmental disorder (e.g., ADHD, language disorders, autism spectrum disorders) and/or sensory deficits (auditory, visual, or motor).

The results obtained from the sub-tests (Block Design and Vocabulary) of the Wechsler Preschool and Primary Scale of Intelligence (WPPSI-IV, Wechsler et al., 2012) were used for the cognitive analysis of the experimental group. Scores below the norm would have resulted in exclusion from the study; however, based on the findings of the analysis, it was possible to involve the whole sample without excluding participants since values were within the norm in both Block Design (M=10.62, SD=3.73) and Vocabulary test (M=13.84, SD=5.01).

The statistical analyses of some tasks refer only to part of the sample involved. Two children were excluded from the analysis of visual search tasks and in sensorimotor tasks, because they were outliers, whereas 14 children were not included in the gaze cueing task for a delay in the development of computerised task programming. Participation in the research was voluntary, upon the signature of both parents or those exercising parental authority over the child. The form that was given to families made explicit the methods, objectives and timing of data collection. The proposed project was written per the European Union Standards of Good Clinical Practice and approved by the University of Padua Ethics Committee (research protocol number: 1849).

Procedure

Data were collected during three different experimental conditions. For each participant, three meetings lasting approximately 60 minutes were arranged and distributed one week apart; therefore, each child was involved one hour per week for three weeks.

The first session delineated the child's baseline cognitive functioning (baseline). On the other hand, the next two sessions aimed at assessing the short-term cognitive effects induced by a single 30-minute play session. Half of the sample played the second experimental session with “Tangram” (board game) and in the third session with “Super Mario Kart 8 Deluxe” (AVG on Nintendo® switch); the other half of the sample played the AVG and then the board game. The study was conducted single-blind: the experimenter who played with the child was not the same one who then evaluated the cognitive effects of the games. The tests were administered in two preschools in quiet, well-lit classrooms.

The phases of experimental data collection were the following:

1) The first experimental session consists of the assessment of general cognitive functioning (Block Design and Vocabulary of the WPPSI-IV, Wechsler, 2012); phonological abilities (phonemic perception and repetition of pseudowords tasks); visual attention (visual search and gaze cueing tasks) and sensorimotor abilities assessment (Bank Box and Bean Bag Throwing Tasks of the Movement Assessment Battery for Children, MABC-2, Henderson et al., 2007).

2) The second experimental session was composed of a session of board game or AVG for 30 minutes and assessing games' effects. Immediately after the game session, the experimenter who played with the child proposed the self-assessment questionnaire on emotions experienced during the play session (Franceschini et al., 2022). Then, another experimenter administered the same tests in the first experimental session.

3) The third experimental session followed the same pattern as in Session 2. Each child was associated with an alphanumeric code consisting of a sequential number from 1 to 47 and the initials of the school attended by the child. Children who played with the AVG in the second experimental session played with the board game in the third experimental session, and vice versa (see Figure 29). Assignments to the groups were random and determined by a computerised generator.

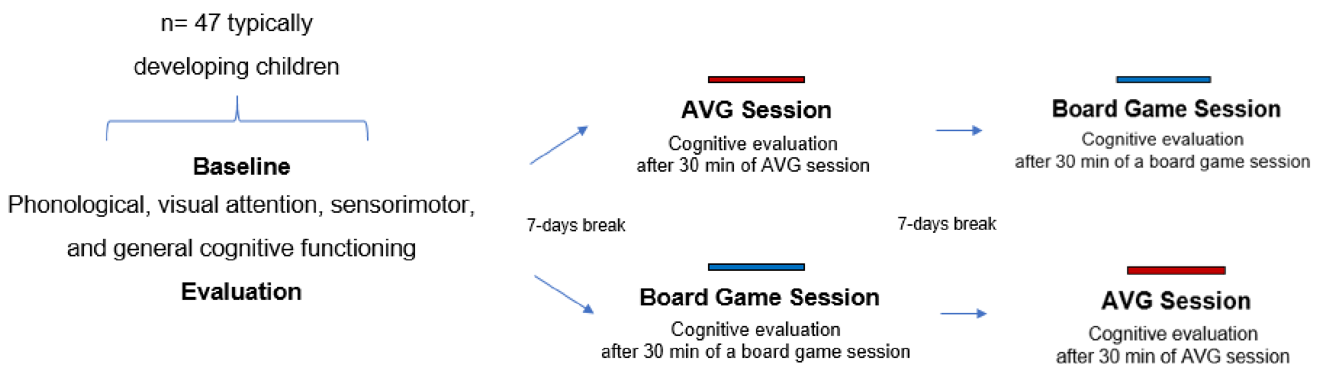

Figure 29. Schematic representation of the timeline of Study 5.

Neuropsychological battery

Intelligence Quotient Estimation (only in baseline condition)

Two subtests from the fourth edition of the WIPPSI-IV battery (Wechsler et al., 2012) were selected to assess general cognitive functioning.

1. Block Design (WPPSI-IV; Wechsler, 2012)

The "Block Design" subtest (Kohs, 1920) assessed the child's visuo-constructive skills. Fifteen geometric compositions of increasing difficulty were presented to the child. The participant would have to reconstruct in the shortest possible time the design using wooden colored cubes (red or white). For each figure, time and accuracy were recorded; after three items with a score of 0, the test was stopped. The total raw scores were then converted to weighted scores according to the WPPSI-IV Handbook (Saggino et al., 2019).

2. Vocabulary (WPPSI-IV; Wechsler, 2012)

The “Vocabulary” subtest allowed the assessment of lexical knowledge and the formation of verbal concepts. The raw scoring considers a range of 0 to 2 points, awarded based on the correctness and completeness of the response. After three incorrectly defined vocabulary items and thus scored 0, the test was discontinued. The total raw scores were then converted to weighted scores according to the WIPPSI-IV Handbook (Saggino et al., 2019).

Phonological Abilities

1. Phonemic perception (adaptation from CMF; Marotta et al., 2008).

This test is an adaptation version of the CMF test (“Valutazione delle competenze meta-fonologiche”; Marotta et al., 2008) and allows an assessment of phonological skills in children between the ages of 5 and 11. The test’s directions are as proposed in the test guidelines, "Listen carefully: Now I am going to tell you some words that do not exist, and you will have to tell me whether they are the same or not. For each pseudoword pair, the experimenter notes the accuracy or inaccuracy of the child's response. The test is considered completed if the child misses more than three discriminations in sequence and the test score coincides with the total number of correct answers. Each list of the test has a maximum of 15 minimum pairs: 11 pairs consist of two different pseudowords and 4 of the same pseudowords. See the Appendix Section for the three versions of the test.

2. Short-Term Memory of Pseudowords

This task makes it possible to estimate phonological processing and short-term memory skills. Regarding the mode of administration, the child was presented with a list of nonsense trigrams (pseudowords) divided into pairs of two of increasing length for a maximum total of 16 trigrams. The subject's task was to repeat the pairs of trigrams proposed by the experimenter in the exact order. For each sequence of pseudowords, the number of phonemes correctly repeated by the child was considered, with no time limit. The test was to be considered completed if the subject got both lists of the same length wrong. See the Appendix Section for the three versions of the test.

Visual Attention

1. Visual Search Task

This paper-and-pencil test assesses visual-spatial attention and visual learning in children. It involves a series of five sheets, with the first serving as a baseline for target familiarity and task understanding. The following two sheets vary in display size and assess automatic attentional mechanisms. A fourth sheet is identical to the second, testing implicit and procedural memory. The fifth sheet evaluates visual learning by having children mark previously seen animals among new ones. Metrics include the time to find the target, the number of correct targets identified, and the number of incorrect selections. See the Material section in Study 4 for a more detailed task description.

2. Gaze and Arrow Cueing Task

This paradigm is used to study how individuals automatically orient their attention in response to the gaze or arrow direction, providing insights into social cognition and attentional orienting underlying cueing effects.

The experiment and task data were collected with OpenSesame (Mathôt et al., 2012), running on a 13-inch laptop (1024x768). In this task, participants were seated at 60cm from the screen and presented with an initial central fixation point (for 995 milliseconds) followed by a neutral cue (frontal gaze or single bar, both for 995 milliseconds). After this interval, follow the cue (gaze or arrow) oriented to the right or left and immediately after the target stimulus (cartoon chick). The gaze or the arrow either averts its target toward one side (valid condition) or in the opposite direction (invalid condition). Participants are then asked to respond to a target stimulus that appears on one side of the screen as fast as possible, pressing the spacebar. Two different stimulus-onset asynchrony (SOA) were arranged, i.e., two different periods for the target's appearance following the cue (280 or 780 milliseconds). The maximum time to respond to the target stimulus was 1500 milliseconds. The target remained visible until a response was made and was followed by visual right/wrong feedback via a red or green dot placed in the center of the screen (500 milliseconds). After 8 familiarization trials, the actual task would begin. Accuracy (in rate) and response times (in milliseconds) were recorded for each of the 100 trials (See Figure 30 for task timeline).

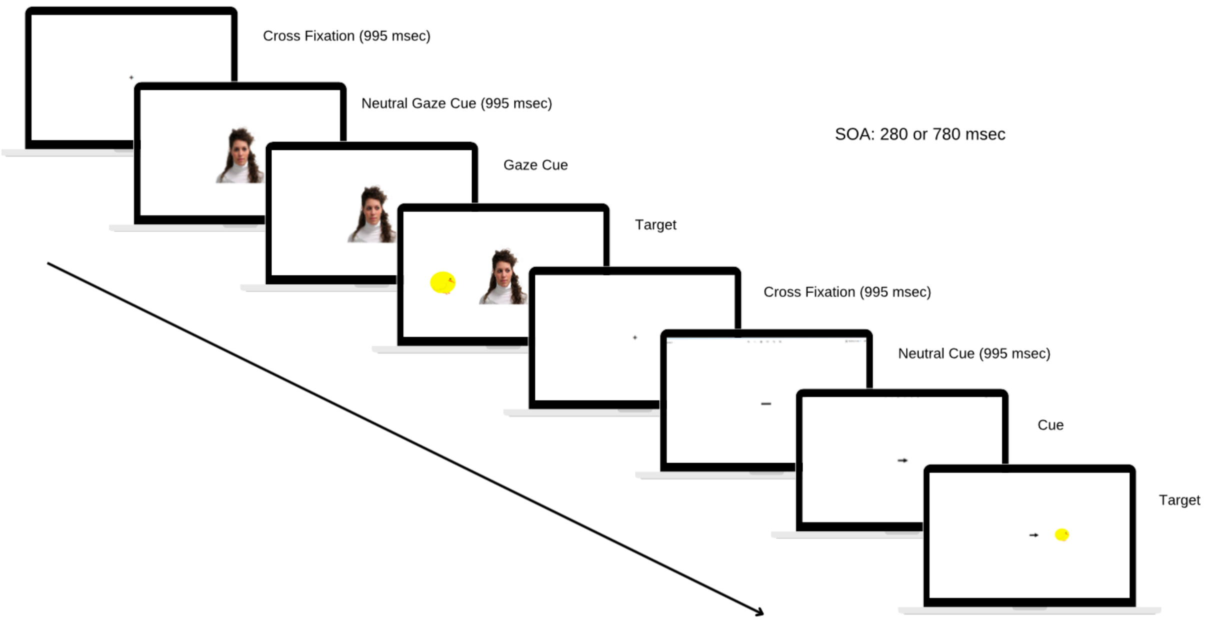

Figure 30. Representation of the gaze and arrow cueing task. Arrow and gaze cueing alternated within the trial in a randomized pattern. The direction of the gaze or arrow could be congruent with the target's position (valid condition, first example representation) or incongruent (invalid condition, second example representation).

Sensorimotor Abilities

1. Bank Box (MABC-2; Henderson et al., 2007)

The "Bank Box" subtest assesses manual dexterity in children. It involves arranging 12 coins in three rows, and the child's task is to insert them into the bank box as quickly as possible, starting with the dominant hand and then the non-dominant hand. Errors are recorded, such as placing coins in the wrong slot and the time taken for each hand. This test provides insights into a child's manual dexterity and grasping with dominant and non-dominant hands.

See the Material section in Study 4 for a more detailed task description.

2. Beanbag Throwing (MABC-2; Henderson et al., 2007)

The “Beanbag Throwing” subtest is an aiming task of the Movement Assessment Battery for Children - second edition (Henderson et al., 2007). This task aims to hit the target (a mat placed 1.8 meters away from the child) by throwing a bag. Just as in the Bank Box test, the dominant hand is evaluated first and then the non-dominant hand. The child has 10 throws for each hand, which are immediately preceded by a practice phase consisting of five practice throws for each hand. The final score coincides with the total number of centers made with each hand.

Games

Mario Kart 8 Deluxe (AVG)

"Mario Kart 8 Deluxe" (PEGI: 3 years old) is a video game on Nintendo® Switch that replicates a car race featuring characters from Super Mario Bros. The goal of the race is to collect the most coins along the circuit and finish the race in the shortest time and in the best possible position. Each child involved in the quest chose their favorite character while keeping the characteristics of the racing vehicle (50cc) identical for all. At the end of each run, the ranking positions and the number of coins the child could collect were recorded. The game was chosen as AVG because it is an action-like videogame based on the characteristics identified by Green and Bavelier (2012) and Nguyen & Bavelier (2023). The game session lasted 30 minutes for each child, without interruption, and was always preceded by a short practice run with the experimenter (about 3 minutes).

Tangram (Board Game)

“Tangram” is a Chinese puzzle board game that involves composing predetermined images using specially designed coloured geometric shapes. The game session lasted 30 minutes for each child, without interruption, and was always preceded by a short practice run with the experimenter (about 3 minutes).

See the Games’ section of Study 4 for a more detailed description.

Games and Self-Evaluation Questionnaire (Franceschini et al., 2022)

This questionnaire was taken immediately after the game session. It was composed of 5 items. For each item of the questionnaire, participants were invited to indicate on a 9-point scale (from "almost nothing" to "a lot") the game characteristics, (i.e., difficult and funny), and how they were feeling after the gaming session (i.e., tense, vivacious and happy).

3.2.2 Results

Phonological Abilities

Phonemic Perception

The one-way ANOVA on the number of correct responses given in the phoneme discrimination task shows a significant main effect of the experimental session ($F_{(1,46)}$=8.407, p=0.006).

Specifically, in the baseline session, participants provided fewer correct responses (M=8.45, SD=4.63) than in the AVG (M=9.92, SD=4.58) and board game sessions (M=10.02, SD=4.56). The t-test comparison between the baseline session and the AVG is significant (p=0.024), as well as between the baseline and the board game session (p=0.006). In contrast, the direct comparison between the correct answers given after the two games is not significant (p=0.850). These results indicate that children's performance improves after the play session, regardless of the type of play (see Figure 31).

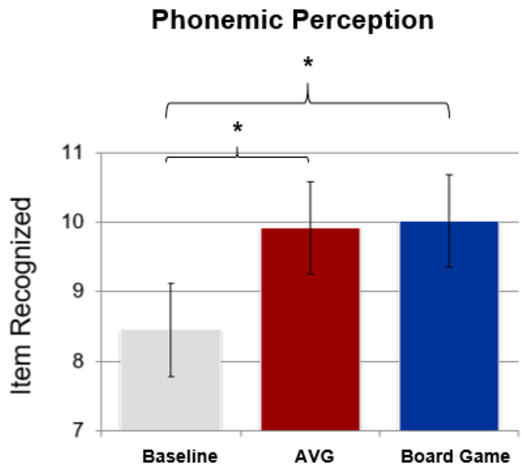

Figure 31. Performance of children in the baseline condition and after the two-game sessions (AVG and board game) in phoneme discrimination task. Data are reported as means ± standard errors. The asterisks indicate the significant differences.

Short-Term Memory of Pseudowords

The one-way ANOVA on the number of phonemes correctly repeated by the participants in the short-term memory of pseudowords showed no significant effect related to the Time (even if $F_{(1,46)}=3.093$, $p=0.085$). Specifically, in the baseline session, the number of correctly repeated phonemes (M=25.21, SD=10.99) is higher than after the AVG (M=22.79, SD=11.57) and board game sessions (M=22.45, SD=11.97). However, also the direct comparisons between the baseline and the two game sessions were not significant ($p=0.165$ and $p=0.085$, respectively), as well as the difference between the two games ($p=0.829$). Interestingly, although these results were not statistically significant, children's performance worsens after the game session and this decline does not depend on the type of game.

Visual Attention

Visual Search Task

The effects of the game on visuospatial attentional skills were investigated through a repeated measured ANOVA with a 3́ x 2 design. Specifically, the within-subject variables were the Time (baseline, AVG and board game) and the Display sizes (22 and 34 distractors). Children's performance on the visual search task was assessed through an inefficiency index that considered the time taken to perform the task and the accuracy in performing the task (i.e., the ratio of time in seconds/accuracy in rate). The analysis showed a main effect related to the Time ($F_{(1,44)}=14.63$, $p<0.001$) and also a main effect of the Display size ($F_{(1,44)}=40.982$, $p<0.001$). Finally, also their interaction was significant ($F_{(1,44)}=5.321$, $p=0.02$; see Figure 32, panel A). In detail, analysis of the data collected in the performance of the 32 distractors, revealed an increase in mean levels of inefficiency in the AVG (M=42.70, SD=21.86) and board game (M=45.50, SD=19.71) sessions, compared with the baseline (M=32.66, SD=14.35). T-test analyses between the baseline and AVG session ($p=0.002$), as well as between the baseline and board game session ($p<0.001$), were significant. In contrast, the comparison between the levels of inefficiency measured following the two different types of games was not significant ($p=0.48$). Therefore, after playing, children appeared to have more difficulty identifying target stimuli when these were present, along with many distractors. No similar effect emerged in the display size with 22 distractors. Participants showed similar levels of inefficiency in the baseline session (M=28.56, SD=15.27) and in the AVG and board game sessions (M=33.69, SD=17.99 and M=33.47, SD=18.48, respectively). T-test analyses between baseline and AVG sessions ($p=0.074$), as well as between baseline and board game sessions (p=0.070), and between the two game sessions in the small dimension (p=0.944) were not statistically significant. Thus, the game sessions did not significantly affect children's performance when they performed the visual search task in the most simple condition with a low level of visual noise.

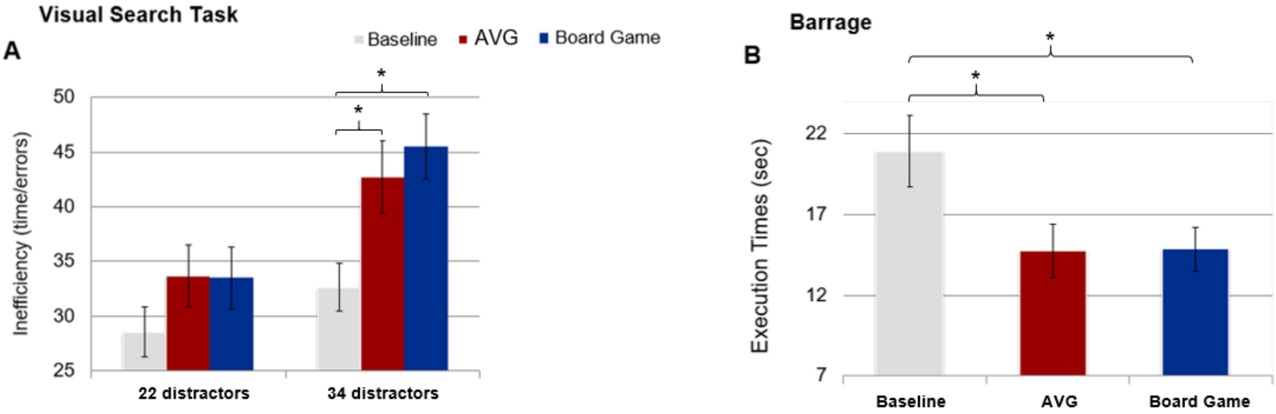

Figure 32. Performance of children in terms of inefficiency (time/errors) in the visual search task in small and large display sizes condition (A) and in the barrage sheet (B). Data are reported as means ± standard errors. The asterisks indicate the significant differences.

A one-way ANOVA was conducted on the results of the first sheet of the task, i.e., the one in which the child had to cross out the targets (presented without distractors) during the three experimental sessions (baseline, AVG and board game).

The results show a statistically significant effect related to the session ($F_{(1,43)}$=4.468, p=0.017). Specifically, participants significantly reduced the time taken to barrage targets following the two game experiences (AVG: M=14.74, SD=11.00 and board game: M=14.86, SD=8.90) compared with the baseline session (M=20.91, SD=14.69). Specifically, the difference between the baseline session and the two game sessions was significant (p=0.009 and p=0.006, respectively), but not the direct comparison between the two games (p=0.939). These results show an intriguing result, similar to those observed in phonological tasks. In particular, children are slower to track the target stimulus after playing the game only when the level of visual noise was highest (i.e., 34 distractors), whereas when the sensory noise was minimal, the children' performance was improved, regardless of the type of game (See Figure 32, panel B). This specific pattern of results shown both in auditory (phonological tasks) and visual (spatial attention task) modality suggests a possible contro-balanced interplay between SN (or VAN) and CEN (or DAN) processing.

Gaze and Arrow Cueing Task

Reaction Times

A repeated measure ANOVA with a 3 x 2 x 2 x 2 design was executed. Specifically, the within-subject variables were the Time (baseline, AVG and board game), the Cue (arrow and gaze), the SOA (280 msec and 780 msec), and the Condition (valid or invalid). The results reveal a significant main effect of SOA ($F_{(1,32)}$=17.707, p<0.0001), indicating an alerting effect, but also a significant interaction between SOA and Time ($F_{(1,32)}$=6.238, p=0.018), as well as between Time and Condition ($F_{(1,32)}$=5.174, p=0.030). T-test analysis showed no significant difference between the short SOA and the long SOA in baseline (M=839.82, SD=126.63 and M=826.11, SD=134.15, respectively; p=0.171) and in the AVG (M=836.58, SD=130,96 and M=808.62, SD=157,50, respectively; p=0.057), while a statistically significant difference emerged between the two SOAs in the board game condition (p<0.001). Specifically, children showed longer reaction times in the condition with short SOA than in the condition with long SOA (M=871.21, SD=168.24 and M=824.58, SD=162, respectively; see Figure 33, panel A). However, a finer analysis of panel A could suggest an alternative pattern of the finding. In particular, at short SOA, when the tonic alerting effect should have the major impact, the target detection was similar between baseline and after the AVG session, whereas it appeared slowed after the board game session. In contrast, at long SOA, when the phasic alerting effect should have the major impact, the target detection appears faster after AVG session. In fact, the phasic alerting effect predicts faster detection at long cue-target intervals in comparison to short one, suggesting that this effect could be considered significant also after AVG session. In contrast, even if fully significant, the alerting effect after the board game session appears to indicate a reduction of the tonic alerting effect.

Regarding the interaction between the Time and Condition, the t-test results show a significant difference in baseline between reaction times in the valid versus invalid condition (M=819.82, SD=135.28 and M=846.82, SD=124.66, respectively; p=0.005), indicating the typical facilitation effect induced by visuo-spatial attention focusing, regardless of the SOA (short or long) and the type of spatial cue (i.e., arrow) or social (i.e., gaze). However, the difference between valid and invalid cues is no more significant in the same participants after the AVG (M=818.39, SD=204,22 and M=826.82, SD=146,77, respectively; p=0.611) and the board game (M=842.11, SD=173,12 and M=853.67, SD=167,17, respectively; p=0.511), indicating that the game activity seems to nullify the visuo-spatial attention focusing effect (see Figure 33, panel B).

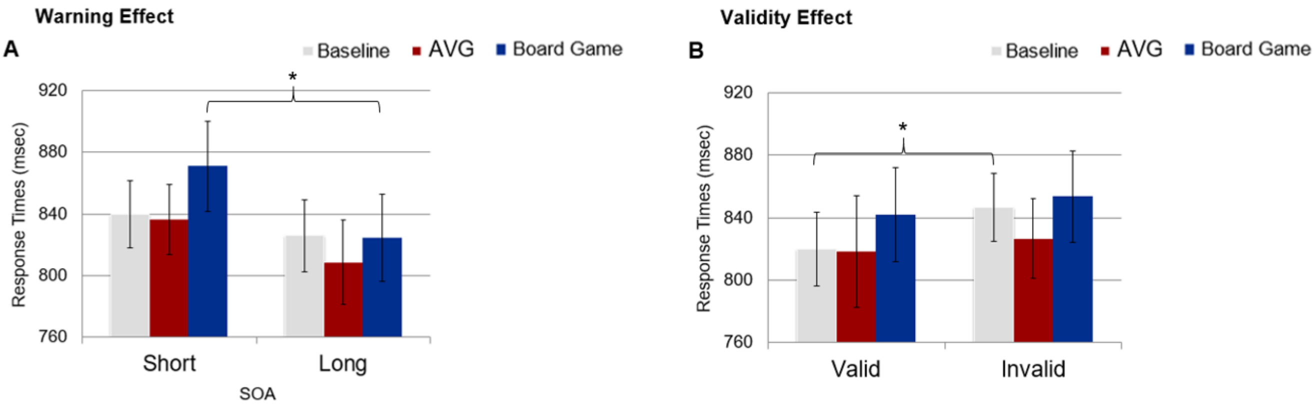

Figure 33. Performance of children in the cueing task at short (280 msec) and long (780 msec) SOA condition (A), and in the valid and invalid condition (B). Data are reported as means ± standard errors. The asterisks indicate the significant differences.

Accuracy

Regarding accuracy, the same ANOVA with the 3 x 2 x 2 x 2 design shows a significant main effect of the Time ($F_{(1,32)}$=17.379, p<0.001).

Specifically, the t-tests show a significant difference between performance at baseline (M=0.84, SD=0.11) and AVG (M=0.77, SD=0.027; p=0.013) and between baseline and board game (M=0.73, SD=0.19; p<0.001) with a reduction in accuracy after both game sessions. In contrast, no significant difference emerges between AVG and board game sessions (p=0.188; see Figure 34, panel A).

Catch Trials

Finally, in the ANOVA on the catch trials (i.e., the infrequent trials in which the target was not presented after the cue, inserted in the task to prevent the child from impulsive responses regardless of the presence of the target), a Time main effect emerged ($F_{(1,32)}$=4.26, p=0.018). T-test analyses show a significant reduction in accuracy in these "false trials" only in the AVG session (M=0.87, SD=0.17) compared to the baseline (M=0.92, SD=0.11; p=0.013), indicating that only AVG there is a reduction in the response inhibition skill to automated responses to the target that typically follows cue presentation. In contrast, there was no significant difference between the baseline and board game (M=0.91, SD=0.11; p=0.354) and between the two post-game sessions (even if p=0.062; see Figure 34, panel B).

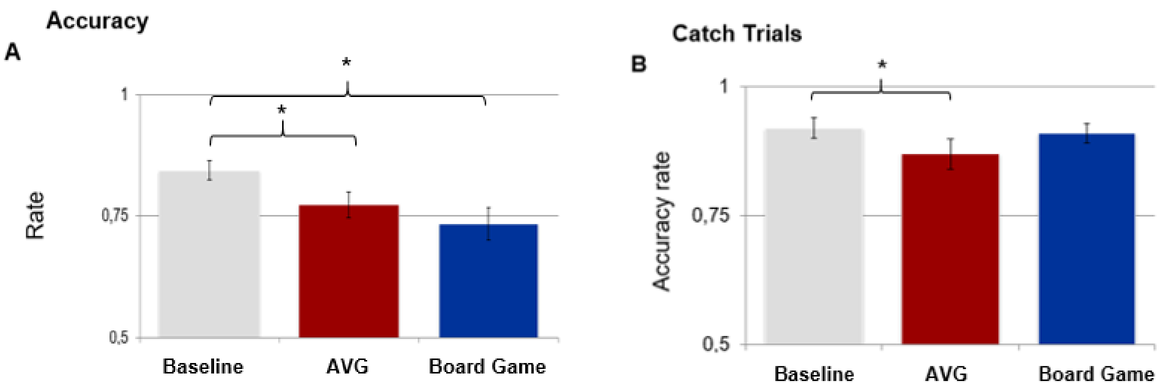

Figure 34. Accuracy rate of children in the cueing task (A) and in the catch trials (B). Data are reported as means ± standard errors. The asterisks indicate the significant differences.

Sensorimotor Abilities

Bank Box

Two ANOVAs with a 3 x 2 design were conducted on execution times and errors. Specifically, the within-subject factors were the Time (baseline, AVG, and board game) and the Hands (dominant and non-dominant).

Execution Times

The ANOVA on execution time shows a significant effect of the Time ($F_{(1,44)}$=5.897, p=0.019), but also a significant interaction between the two variables considered ($F_{(1, 44)}$=12.625, p=0.001).

In particular, children take significantly less time in task execution in the AVG session (M=27.08, SD=8.734) compared with the baseline session (M=30.40, SD=6.62, p=0.013) but not after playing with a board game (M=29.55, SD=6.08, p=0.397). However, the two-game conditions are not statistically different (even if p=0.064).

Regarding the Time x Hand interaction, the analyses show no statistically significant differences between the baseline condition (M=29.94, SD=8.20), AVG condition (M=28.67, SD=7.44) and board game condition (M=28.56, SD=6.35, all ps>0.282). In contrast, in the non-dominant hand's analysis, a significant improvement in performance was found in the AVG session (M=25.50, SD=11.63) compared with both the baseline (M=30.85, DS=7.58, p=0.002) and board game sessions (M=30.54, DS=8.04; p=0.011), but not between the board game and baseline conditions (p=0.830). The t-test analysis also reveals a significant and interesting difference in the AVG condition between the dominant hand and the non-dominant hand ($p=0.019$), which reveals a reversal of hand dominance exclusively after the playing session with AVG.

Errors

The ANOVA on errors made during the test reveals a main effect of the Time, regardless of the Hand used ($F_{(1,44)}=9.236$, $p=0.004$). The t-test shows a significant increase in the number of errors compared with baseline (M=0.64, SD=0.832) in both the AVG (M=1.01, SD=0.93; $p=0.018$) and board game (M=1.04, SD=1.11; $p=0.004$) conditions. In contrast, no significant difference emerges from the direct comparison between the two games ($p=0.850$).

Inefficiency Index

To control for a possible trade-off between speed and accuracy, the composite inefficiency index (i.e., the ratio of time in seconds/accuracy in rate) was calculated.

A repeated-measures ANOVA with the same 3 x 2 design showed a significant interaction between Time and Hand ($F_{(1,44)}=10.924$, $p=0.002$). Specifically, t-tests revealed that no significant differences were found across the baseline (M=31.30, SD=9.31), AVG (M=31.92, SD=11.54) and board game (M=31.10, SD=8.67) session in the dominant hand (all ps>0.607). In contrast, a significant reduction in inefficiency was found after AVG (M=28.81, SD=14.46) compared to baseline (M=33.81, SD=9.51, $p=0.028$) and the board game (M=34.99, DS=11.45, $p=0.019$) sessions. Instead, the direct comparison between the board game and the baseline is not significant ($p=0.551$). A significant reduction in inefficiency (i.e., an increase in efficiency) was found in the non-dominant hand alone after the AVG session (see Figure 35, panel A).

Beanbag Throwing

The ANOVA with a 3 x 2 design conducted on the aiming test showed the main effect of the Time ($F_{(1,44)}=4.486$, $p=0.040$) and the Hand ($F_{(1,44)}=5.729$, $p=0.021$). As expected, analyses show that children perform better with their dominant hand than their non-dominant hand ($p=0.014$). More interestingly, the t-tests show that children make a greater number of baskets in baseline (M=5.58, SD=2.09), compared with the AVG (M=4.52, SD=2.16; $p=0.001$) and board game (M=4.933, DS=2.428; $p=0.040$) conditions, showing a significant worsening in task performance after both games. The direct comparison of performance after AVG and board game was not significant (p=0.154; see Figure 35, panel B and Table 6 for details).

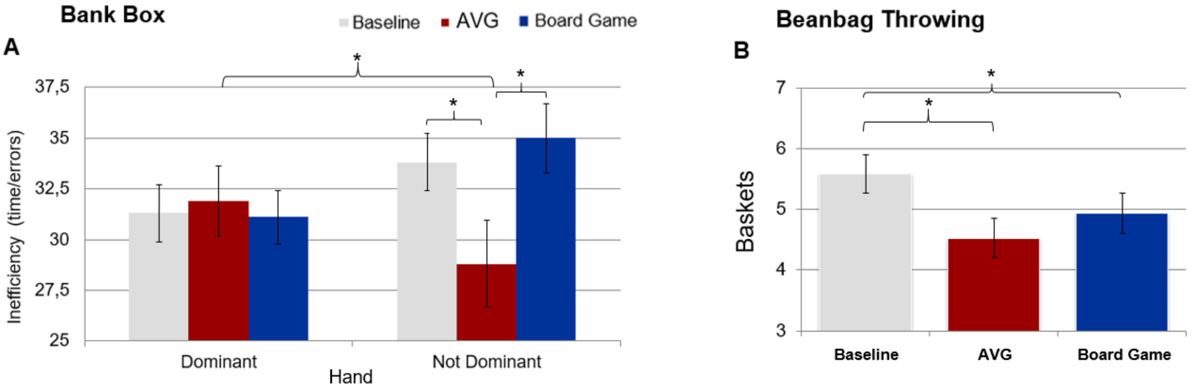

Figure 35. Bank Box inefficiency index [time(sec.)/accuracy(rate)] in dominant and non-dominant hands (A) and the number of baskets in the aiming task (B). Data are reported as means ± standard errors. The asterisks indicate the significant differences.

	Hand	
Session	Dominant (SD)	Not Dominant (SD)
Baseline	5.89 (2.59)	5.27 (2.43)
AVG	4.71 (2.46)	4.33 (2.35)
Board Game	5.15 (2.51)	4.71 (2.56)

Table 6. Performance of children in baseline, AVG and board game in the beanbag throwing task with dominant and not dominant hands. Data are reported as means ± standard deviations.

Games and Self-Evaluation Questionnaire

The ANOVAs conducted on the questionnaires of emotions experienced during play showed no significant differences in participants' perceived tense after the session with AVG (M=4.22, SD=3.09) and after the session with the board game (M=4.13, SD=3.18) ($F_{(1,44)}$=0.044, p=0.834), as well as in perceived happiness (M=7.07, SD=1.86; M=6.42, SD=2.5, respectively; $F_{(1,44)}$=2.054, p=0.159) and vivacity after session games (M=6.11, SD=2.61; M=6.55, SD=2.62, respectively; $F_{(1,44)}$=1.120, p=0.296). There were also no significant differences in the perceived degree of difficulty during play with the AVG and board game (M=3.93, SD=3.00 and M=4.62, SD=2.81, respectively; $F_{(1,44)}$=1.464, p=0.233). However, the analysis showed a significant difference in the degree of enjoyment experienced by the children during the two games ($F_{(1,44)}$=4.221, p=0.046). In particular, the experience with AVG

(M=8.18, SD=1.64) was rated as more fun than that with the board game (M=7.40, SD=2.04, see Figure 36).

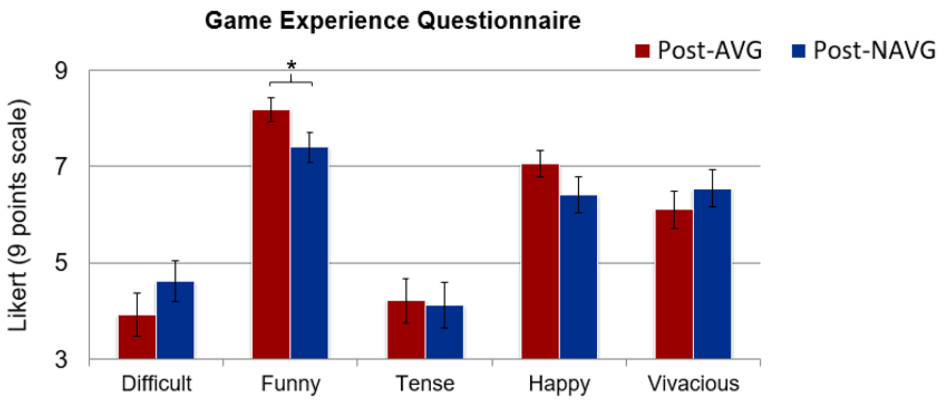

Figure 36. Responses to the Self-Evaluation Questionnaire (Franceschini et al., 2022) administered after the game session with AVG (red bars) and board game (blue bars). Data are reported as means ± standard errors. The asterisks indicate the significant differences.

3.2.3 Discussion

The results of this empirical study allow us to compare the short-term effects of a single play session following two different play experiences in developing brains, adding new evidence to previous studies (e.g. Franceschini et al., 2022; Study 4 in the present PhD Thesis). The main result demonstrates that, in preschool children, a driving action-like video game not only induces similar neurocognitive effects when compared with a traditional educational board game, but it also selectively enhances the performance in a sensorimotor task engaging both grasping and fine oculomotor coordination, but only of their non-dominant hand. This last result could indirectly suggest a possible starting neurobiological basis of the powerful impact of this specific game experience (see Bavelier & Green, 2019 for a review and Bediou et al., 2023 for a meta-analysis). The interplay between cognition and emotional neural networks is confirmed since the AVG experience induces a more positive emotional state in preschool children.

The data suggest that the play experience, no matter what it is, has different transient effects, even within the same cognitive (i.e., phonological, visuo-attentional and sensorimotor) domain, depending on the specific processing required of the neuropsychological task. In particular, the results indicate improvement in phonemic perception and barrage without distractors that require salience processing controlled by SN and/or VAN, in which processing speed plays a critical role. In fact, also phoneme discrimination is based on rapid (auditory) processing (see Tallal, 2004 for a review). In contrast, performance worsens in phonological short-term memory, target barrage with many distractors and sensorimotor aiming skills. All these tasks require executive processing and goal-directed attention in which the inhibitory functioning of sensory and sensorimotor noise-exclusion mechanisms must be engaged and are mainly controlled by the CEN and/or DAN. In the same vein, the game experience seems to nullify the typical spatial facilitation effect of the focusing cue. SN activation was also suggested by the significant reduction in the accuracy of the cueing task. Although this result was shown in a smaller group of our preschool children sample, the attentional focusing effects are based on inhibitory mechanisms of irrelevant information mainly controlled by CEN and/or DAN (see Reynolds & Heeger, 2009 for a review). DAN is focused on specific goals inhibiting irrelevant events during the execution of a cognitive task, but VAN could block DAN if the SN detects an unexpected event (Corbetta & Shulman, 2002). To detect unexpected but now relevant events, SN has to widely distribute attentional resources on global sensory processing. Franceschini and colleagues (2022) have demonstrated that the more activating and funnier game engages the global processing of visual events in atypical developmental children. Accordingly, also the selective effect on lexical word efficiency and visual learning involving the wide processing of visual events was shown in typical developmental children in Study 4. Interestingly, it is plausible to suggest that the game experience could positively impact the attentional disengagement deficit causally linked with the development of the autism spectrum condition in children (Elsabbagh et al., 2013), reducing their attention zoom-out impairment (Ronconi et al., 2012, 2013, 2018) that is controlled by the right frontoparietal networks (Ronconi et al., 2014). The role of an SN underconnectivity and autism spectrum conditions appears confirmed (see Uddin & Menon 2009 for a review).

These more general findings agree with the model suggested by Hermans and colleagues (2014) that the relationship between the CEN and the SN is inverse and asymmetric but also flexible and adaptive. Specifically, following acute stress, resources are reallocated to restore equilibrium (Barsegyan et al., 2010; Zhou et al., 2018). In this way, the SN is inhibited, while CEN reactivation promotes enhanced cognitive function, increased flexibility and long-term goal adjustment (Hermans et al., 2014). Indeed, transient de-activation of the neural circuit would be followed by long-term re-activation, typically detected in rehabilitation training (e.g., Bertoni et al., 2021 Study 1).

However, some specific effects related to the AVG also emerge: children seem to improve their fine motor performance with the non-dominant hand (showing a reversal of manual dominance), but also worsen their response inhibition mechanism in the cueing task. Finally, the phasic alerting effect also appears more efficient after the action-like game. All these findings confirm a specific and more activation of right-lateralized SN and/or VAN during and after the single session AVG experience. As suggested by Franceschini and colleagues (2022) and in the recent review of Braine and Georges (2023), the specific effects related to the AVG on manual dexterity might depend on the emotional involvement of the game. Indeed, we recall that Mario Kart 8 Deluxe was considered more fun than the traditional educational game. Thus, the critical role of the positive emotions and the concomitant DA and NA neuromodulation - intrinsically linked with the game experience - could also be suggested.

In conclusion, although the results of the present study do not yet allow us to disambiguate the role of game type from the role of emotions, they allow us to identify cognitive functioning outcomes related more to the degree of cognitive control required rather than the more general cognitive domain. However, it should be specified that the results found in typically developing preschool children may not extend to other populations. Indeed, the immaturity of the large neural networks (see Johnson, 2012 for a review), particularly CEN with the PFC, may exacerbate the effects of positive stress induced by play. Further studies in atypical developmental and adult populations are needed.

Study 6. The Benefits of Playing Action-Like Video Games on Salience Processing

Abstract

Play is essential for cognitive and social development and appears to be a powerful remediation tool in neurodiversity. Indeed, the play might enhance learning by stimulating the attentional control development of the CEN. However, it is still unclear which cognitive, affective and physiological mechanisms are transiently stimulated during a single session of a game experience. Here, we investigated in a single-blind randomised crossover experiment the behavioural and psychophysiological effects induced by 30 min of Mario Kart in comparison to a traditional puzzle board game on the attentional control and the salience processing in 60 young adults, including 16 poor readers. Improving positive and reducing negative emotions, playing video games increases the performance of salience processing without any effect on executive control. Interestingly, only poor readers showed an improvement in reading speed. We propose that the selective and transient role of playing video games on salience processing could be necessary for optimal interaction between executive control and default processing underlying the enhancement of game-driven learning.

3.3.1 Materials and Methods

Participants

The study involved 60 young adults selected from a total of 128 students attending the School of Psychology at the University of Padova (10 males and 3% left-handed) native Italian speakers. In the voluntary recruitment phase, each participant was given a short questionnaire to investigate the presence of specific neurodevelopmental disorders (e.g., learning disabilities, ADHD and autism spectrum disorder), neurological difficulties (e.g., epilepsy and migraine) and habits: type of game (board games and video games) and time spent weekly playing was investigated and recorded (see Method section). According to their self-declaration, only participants who did not report epilepsy or familiarity history with it, sensory deficits (auditory, visual, or motor) or cognitive impairments were recontacted. Participants excluded from this study were still given the opportunity to participate in other scientific research experiences. Based on their performance on the post-games reading tests, participants were divided into typical readers (TR) and poor readers (PR). More specifically, we calculated the mean z-score (speed and accuracy) to estimate the reading abilities of participants after the two game sessions: all students with a mean score at or below -1.5 SD under the average were classified as PR (n=16, 19% male, M=-3.23 z-score, SD=0.70), whereas all others were classified as TR (n=44, 16% male, M=-0.34 z-score, SD=1.87). The two groups (TR and PR) were not significantly different in chronological age (M=20.9, SD=1.7 and M=20.9, SD=1.3, respectively; p=0.927), board game experience (M=1.35 hour/week, SD= 2.64 and M=0.60, SD=0.79, respectively; p=0.268) and video game experience (M=1.47 hour/week, SD= 2.70 and M=1.54, SD=2.85, respectively; p=0.931). The procedure and the goals for data collection were made explicit on the form that was given to participants. The study was written in compliance with the European Union Standards of Good Clinical Practice, and it was authorized by the University of Padua's Ethics Committee (Protocol number: Protocol number: 1452; Code: D32B2B803B68E2600F95F0CF66DC42D8).

Procedure

All participants were evaluated two times, one week apart, in a well-lit and quiet laboratory at the Department of General Psychology, University of Padua. Evaluations were scheduled at the same hours, and in both experimental sessions (lasting approximately 60 minutes each), the same fixed order of neuropsychological tasks (with counterbalanced content, see Questionnaires section) was administered.

At the beginning of each evaluation, two self-report questionnaires (i) the Positive and Negative Affect Schedule (PANAS; Thompson, 2007) and (ii) the Y form of the State-Trait Anxiety Inventory (STAI; Lazzari & Panchieri, 1980) were administered. Then, the participant played one of the two games: half of the sample played first “Tangram” (board game) and in the second session “Super Mario Kart 8 Deluxe” (AVG on Nintendo® switch); the other half of the sample played the AVG and then the board game. Immediately after the game session, participants filled in a questionnaire about the game experience (adaptation from Franceschini et al., 2022). The tests provided by the neuropsychological battery were then offered in the following fixed order: Eriksen Flanker Task, PANAS questionnaire (again), Purdue Pegboard Test, Remote Association Tasks, Text Reading and State STAI questionnaire (again).

The study was conducted single-blind: the experimenter who played with the participants was not the same one who then evaluated the cognitive effects of the games (see Figure 37).

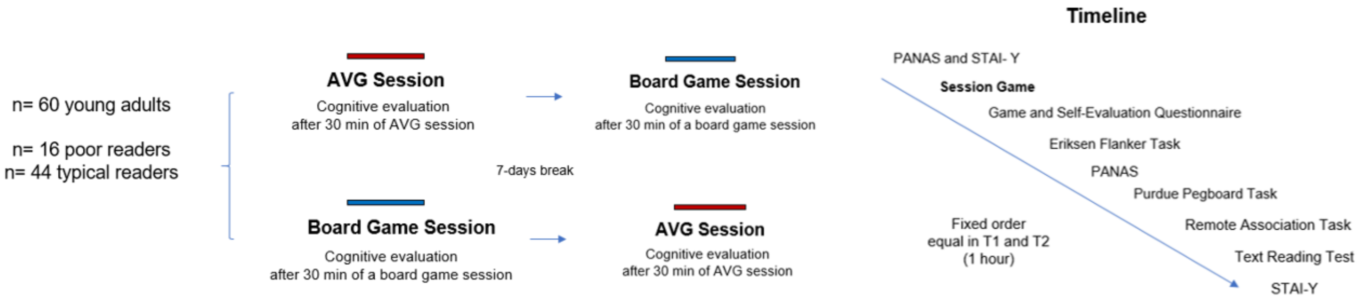

Figure 37. Schematic representation of the experimental design and timeline of the Study 6.

Questionnaires

1. Habits Questionnaire

This questionnaire was shared on the internet page of the Department of General Psychology of the University of Padua and was used as a screening tool for recruiting participants and collecting data on some lifestyle habits. Specifically, the questionnaire investigated the presence of any specific neurodevelopmental disorders (e.g., learning disabilities, ADHD and autism spectrum disorder), neurological difficulties (e.g., epilepsy and migraine) or cognitive and sensory disabilities. In addition, gaming habits were investigated. More specifically, participants were asked to indicate whether, in the past 6 months, they had played video games and/or board games, indicating, for each response, the console used, the title of the game, the frequency (from “once a month” to “every day”), and the duration (from “less than 15 minutes” to “3 hours or more”) for each gaming session.

Participants who did not report epilepsy, cognitive and sensory disabilities and who did not meet the requirements of action video gamers (more than 5 hours per week of AVG; Green & Bavelier, 2012) were then contacted.

2. Positive and Negative Affect Schedule (PANAS; Thompson, 2007)

The Positive and Negative Affect Schedule (PANAS) is a self-report questionnaire that consists of two 10-item scales. This questionnaire was taken two times (at the beginning and in the middle of the session), to measure positive and negative affect“ at that very moment”. Each item is rated on a 5-point Likert scale, from 1 (“not at all”) to 5 (“very much”). The sum of scores in each of the two areas was calculated and analysed.

3. State Anxiety Evaluation (STAI-Y; Lazzari & Panchieri, 1980)

We used the Y form 20-item questionnaire adapted from the State-Trait Anxiety Inventory (STAI; Lazzari & Panchieri, 1980). This questionnaire was taken two times (at the beginning and at the end of the session) to assess any pre-existing elevated anxiety levels and to quantify any variations in anxiety and activation produced by the examination and game sessions. Participants must indicate how they feel "at that very moment" for each item. The total score was measured and analysed.

4. Games and Self-Evaluation Questionnaire (adaptation from Franceschini et al., 2022)

This questionnaire was taken immediately after the game session. It was composed of 6 items. For each item of the questionnaire, participants were invited to indicate on a 9-point scale (from "almost nothing" to "a lot"), the game characteristics (i.e., difficult, boring and funny) and how they were feeling after the gaming session (i.e., calm, vivacious, happy). See the Italian version of the questionnaire in the Supplementary Materials.

Neuropsychological battery

Eriksen Flanker Task

The Flanker Task was designed by Eriksen and Eriksen (1974) to assess the size of the attentional spotlight in target identification by altering the nature and proximity of surrounding noise stimuli.

The experiment and task data were collected with E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA) running on a 13-inch laptop (1024x768). Participants sat 60cm from the screen and were shown an initial yellow central fixation point on a blue screen (for 900 milliseconds) followed by the target (a central yellow triangle; 2x2cm) that appeared alone or crowded by two other identical triangles that indicated the same direction (congruent) or the opposite direction (incongruent). Triangles could appear immediately adjacent or separated by a space of 30 mm from the target. Participants had to indicate as fast and accurately as possible (in a maximum of 3000 msec) the direction (right or left) of the target triangle using keyboard keys ("A" or "L", respectively).

The target remained visible until a response was made and was followed by visual right/wrong feedback via a red or green dot placed in the center of the screen (500 milliseconds). After 12 trials, the actual task would begin. Accuracy (in rate) and response times (milliseconds) were recorded for each of the 50 trials (See Figure 38 for the task timeline).

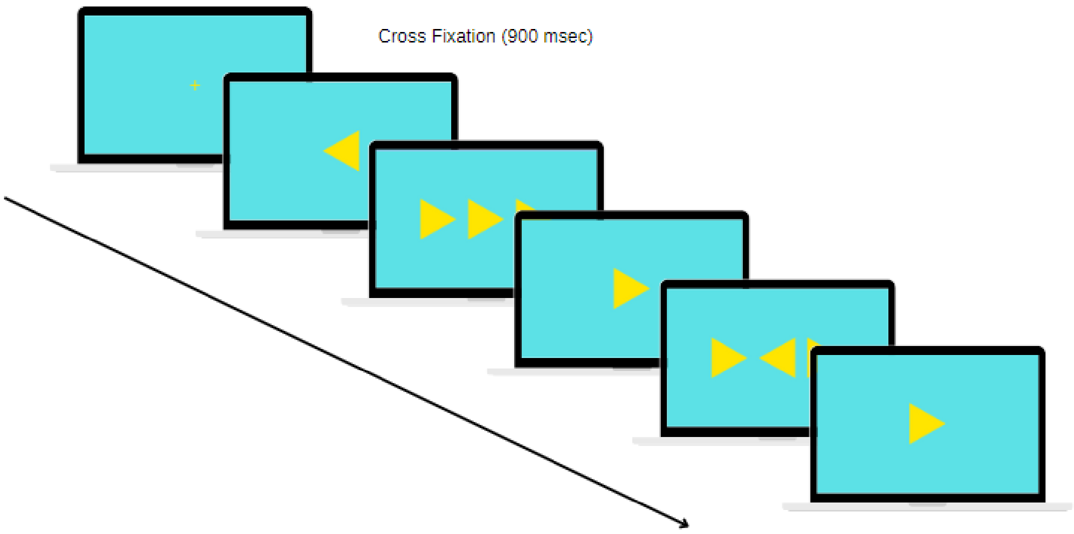

Figure 38. Representation of the Eriksen Flanker task used. The central yellow triangle (target) appeared alone or crowded by two other identical triangles. The direction of the triangles could be congruent with the target direction (first example representation) or incongruent (second example representation). The sizes and the proportion of the stimuli are not real.

Purdue Pegboard Test (Tiffin & Asher, 1948)

The Purdue Pegboard Test is a widely used neuropsychological assessment tool designed to measure manual dexterity and fine sensorimotor skills. Participants were asked to take the pins from a bowl at the top of the pegboard and place them in the row of holes indicated by the experimenter. Participants have to place as many pins as possible in the board holes (30 total in each column), firstly with their dominant hand, then with their non-dominant hand. Following a series of practice trials, participants were given 30 seconds to place as many pegs as possible. The score reported was the number of pins placed for each condition.

Remote Association Task (RAT; Salvi et al., 2016)

RAT is a widely used tool for measuring creativity, specifically the ability to create semantic associations. This complex cognitive task mainly requires executive control. In particular, in this computerised task (collected using E-Prime 2.0 software on a 13-inch laptop), three words were presented on the screen (font: Courier new, size: 18). The participants were invited to find and say out loud (over a microphone) a fourth word that could be combined with the list, in order to compose a compound word or a semantic association. The four factors of executive control: 1) response inhibition; 2) working memory; 3) set-shifting and task-switching; and 4) interference control are engaged in RAT. Twenty items from the Italian validation of RAT (Salvi et al., 2016) were selected and paired for difficulty in order to create two lists of 10 trials (see Supplementary Materials). Lists were presented in the two evaluation times in counterbalanced order. For each item, participants had a maximum of 15 seconds to find a possible answer, then a new trial was administered. Three trials were used to familiarise with the task. Accuracy and response times (recorded through the use of a response box connected to the microphone) were collected and evaluated.

Text Reading (Judica & De Luca, 1993)

Text reading abilities were evaluated using two texts of similar length and reading difficulty (Judica & De Luca, 1993). Reading speed (second per syllable) and number of errors were measured. The two texts were administered in a counterbalanced order in the two sessions between the different participants. Participants were invited to read each text aloud as quickly and as accurately as possible. Based on manual instruction, reading speed and accuracy were transformed into z-scores.
See the Material section of Study 3 for more details.

Games

In each session, participants played for 30 minutes without interruption, and the game session was always preceded by a short practice run with the experimenter (about 3 minutes). In the AVG session, participants played “Mario Kart 8 Deluxe” on a Nintendo® Switch (PEGI:3 years), a driving simulation game. In the control session, participants played Tangram, a board puzzle game composed of seven coloured geometric shapes made up of triangles, a square, and a parallelogram that can be arranged together to compose a variety of forms. The two games were selected because both were free of complex game rules and were able to stimulate attentional control and oculomotor coordination. In our hypothesis, the AVG, in comparison to the board game, could largely spark positive emotion compared to the Tangram, allowing us to study the effects of play and positive emotion compared to a play session with lower positive activation.

The games selected are the same ones used in Study 5. The Short-Term Effects of Games and the Role of Emotions in Preschool Children" (see “Materials and Methods” Section) but, in this case, the engine capacity of the vehicles was increased to 150cc and the Tangram images were selected from the most difficult boards proposed by the game itself, so as to make the game more challenging for young-adult participants (see Joessel et al., 2023).

3.3.2 Results

Positive and Negative Affect Schedule (PANAS)

An ANOVA with a 2 x 2 x 2 x 2 design was executed using the raw score in the PANAS questionnaire as the dependent variable. In particular, the within-subject factors were the Time (pre- and post-gaming), the Emotions (positive and negative), and the Games (AVG and board game), while the between-subject factor was the Group (TR and PR).

The main effects of Time ($F_{(1.58)}$=64.400, p<0.001), Emotion ($F_{(1,58)}$=256.084, p<0.001) and their interaction were significant ($F_{(1,58)}$=76.891, p<0.001). Also, Game x Emotion ($F_{(1,58)}$=4.594, p=0.036) and Time x Emotions x Game interactions were significant ($F_{(1,58)}$=5.330, p=0.025; see Figure 39). We run the analysis on the pre- and post-game session scores separately. No other main effect or interaction was significant (all ps>0.391).

The ANOVA on the pre-gaming score showed that only the main effect of Emotion ($F_{1.58)}$=166.481, p<0.001) was significant. No other main effect or interaction was significant (all ps>0.391).

The ANOVA on the post-gaming score showed that the main effect of Games ($F_{(1,58)}$=8.954, p=0.004), Emotions ($F_{(1,58)}$=285.544, p<0.001), and their interaction ($F_{(1,58)}$=30.370, p<0.001) were significant. Planned comparisons showed a significant enhancement in the positive emotions (p<0.001) after AVG (M=30.48, SD=7.12) in comparison to the board game (M=26.47, SD=6.33). In contrast, in negative emotions a significant reduction (p=0.001) was found after AVG (M=11.93, SD=3.23) in comparison to the board game (M=13.750, SD=4.79).

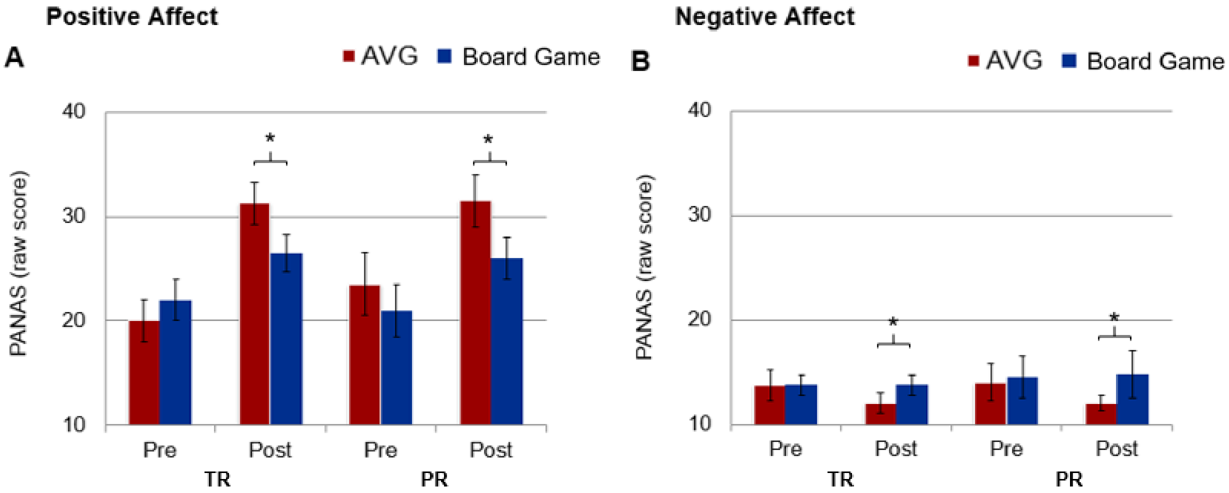

Figure 39. Raw scores in positive (A) and negative (B) affect of typical readers (TR) and poor readers (PR) in the PANAS questionnaire. Responses refer to self-perceived affectivity before (pre) and after (post) the game sessions (AVG and board game). Data are reported as means ± standard errors. The asterisks indicate the significant differences.

State Anxiety Evaluation (STAI-Y)

A mixed ANOVA with a 2 x 2 x 2 design was executed using the raw score in the STAI questionnaire as the dependent variable. In particular, the within-subject factors were the Time (pre- and post-gaming), and the Game (AVG and board game), while the between-subject factor was the Group (TR and PR). The results showed that the main effect of Time was significant ($F_{(1,58)}$=16.648, p<0.001). Specifically, in the final part of the post-gaming evaluation, the participants showed a significantly greater level of anxiety than in the pre-gaming evaluation (M=40.18, SD=9.68 and M=37.27, SD=9.45, respectively), regardless of the type of game (see Figure 40).

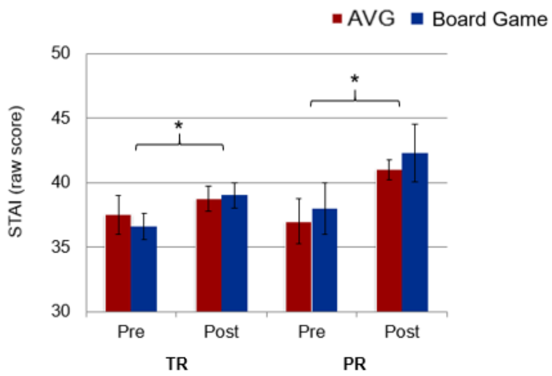

Figure 40. Raw scores of typical readers (TR) and poor readers (PR) in the STAI-Y questionnaire. Responses refer to self-perceived anxiety before (pre) and after (post) the game sessions (AVG and board game). Data are reported as means ± standard errors. The asterisks indicate the significant differences.

Games and Self-Evaluation Questionnaire

A mixed ANOVA with a 2 x 2 design was executed for each of the six items of the questionnaire. Specifically, the within-subject was the Games (AVG and board game), while the between-subject factor was the Group (TR and PR). In each ANOVA, only the main effect of the Game was significant (all other ps>0.124). See Table 9 for means, standard errors, F and p values.

Variable	Board Game (SD)	AVG (SD)	F value	p value
How much the game was:				
Difficult	7.97 (0.86)	4.05 (1.59)	207.845	<0.001
Boring	4.17 (2.17)	2.25 (1.70)	31.102	<0.001
Fun	4.55 (1.90)	7.48 (1.45)	85.953	<0.001
Now how much do you feel:				
Calm	4.52 (2.06)	5.70 (1.80)	9.115	0.004
Happy	4.24 (1.75)	7.12 (1.60)	82.924	<0.001
Vivacious	4.14 (1.97)	6.77 (1.59)	52.302	<0.001

Table 9. Scores (mean and standard deviation), F, and p values in the six ANOVAs on the items of the questionnaire about game experiences after AVG and board game are indicated.

Eriksen Flanker Task

Single target condition

Two mixed ANOVAs with a 2 x 2 design were executed on accuracy and response times as dependent variables. Again, the within-subject was the Games (AVG and board game), while the between-subject factor was the Group (TR and PR).

The results on the accuracy did not show significant effects (all ps>0.683): the accuracy was at the ceiling (M= 0.99, SD=0.02) in both games and in both groups.

In contrast, the results on the response times showed a significant main effect of Game ($F_{(1,58)}$=6.429, p=0.014). Specifically, in the AVG session, the participants were faster in identifying the correct target than in the board game session (M=402msec, SD=62.11 and M=422msec, SD=71.84, respectively; see Figure 41). No other main effect or interaction was significant (all ps>0.662).

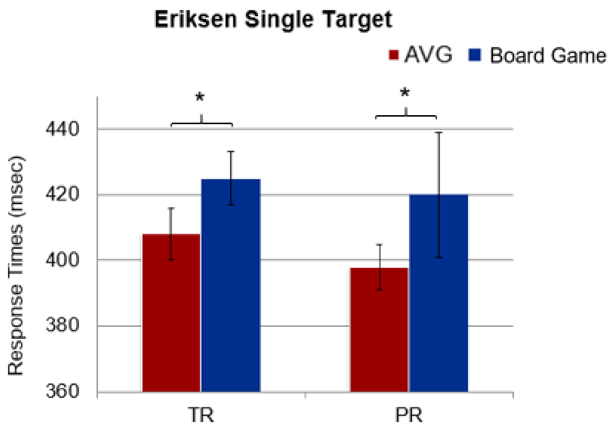

Figure 41. Response times (in milliseconds) of typical readers (TR) and poor readers (PR) in the Eriksen Flanker Task (single target condition) AVG and board game sessions. Data are reported as means ± standard errors. The asterisks indicate the significant differences.

Target with Flankers condition

Two mixed ANOVAs with a 2 x 2 x 2 x 2 design were executed on accuracy and response times as dependent variables. In particular, the within-subject factors were the Game (AVG and board game), the Flanker conditions (congruent and incongruent) and the Spacing (small and large), while the between-subject factor was the Group (TR and PR).

Analysis of accuracy showed that the main effect of the Flanker condition ($F_{(1,58)}=44.203$, $p<0.001$) was significant. Specifically, in the congruent condition, the accuracy rate was at the ceiling, and it was higher than the accuracy in the incongruent condition (M=0.99, SD=0.02 and M=0.95, SD=0.05, respectively). Also, the Flanker condition x Group interaction was significant ($F_{(1,58)}=4.628$, $p=0.036$). Planned comparisons showed that whereas the accuracy rate in TR and PR was equivalent in the congruent condition (M=0.99, SD=0.02 and M=0.99, SD=0.04, respectively; p=0.541), a marginal difference was present in the incongruent condition (M=0.96, SD=0.05 and M=0.94, SD=0.09, respectively; p=0.067). Also the main effect of Spacing ($F_{(1,58)}=13.213$, $p=0.001$) and the Flanker condition x Spacing interaction was significant ($F_{(1,58)}=15.734$, $p<0.001$). The planned comparison showed that in the congruent condition, the accuracy rate was at the ceiling in the large as well as in the small spacing condition (M=0.99, SD=0.03 and M=0.99, SD=0.02, respectively; p=0.517). Instead, in the incongruent condition accuracy rate was higher in the large compared to the small spacing condition (M=0.97, SD=0.04 and M=0.92, SD=0.09, respectively; p<0.001). No other main effect or interaction was significant (all ps>0.174).

Again, the results on the response times showed that the main effect of the Flanker condition ($F_{(1,58)}$=213.412, p<0.001), Spacing ($F_{(1,58)}$=149.824, p<0.001) and their interaction ($F_{(1,58)}$=57.901, p<0.001) were significant. In the large spacing condition, the difference between the congruent and incongruent (M=411msec, SD=63.83 and M=440msec, SD=71.70, respectively; p<0.001) was smaller than the difference between congruent and incongruent in the small spacing condition (M=426msec, SD=69.99 and M=503msec, SD=74.18, respectively; p<0.001). These results are confirmed by a t-test comparison of the delta score (congruent minus incongruent condition) between large and small spacing conditions ($t_{(59)}$=8.645, p<0.001). No other main effect or interaction was significant (all ps>0.083).

Purdue Pegboard Test

Two mixed ANOVAs with a 2 x 2 design on dominant and non-dominant hand scores were carried out. Specifically, the within-subject factor was the Game (AVG and board game), while the between-subject factor was the Group (TR and PR).

Analysis on the dominant hand shows the main effect of Game ($F_{(1,58)}$=13.355, p=0.001). In particular, participants obtained higher raw scores in the AVG session compared to the board game session (M=15.45, SD=1.91 and M=14.51, SD=1.94, respectively). The Game x Group interaction was not significant ($F_{(1,58)}$=2.092, p=0.153).

Regarding the non-dominant hand, the analysis did not show any significant main effect or interaction (all ps>0.334; see also Figure 42).

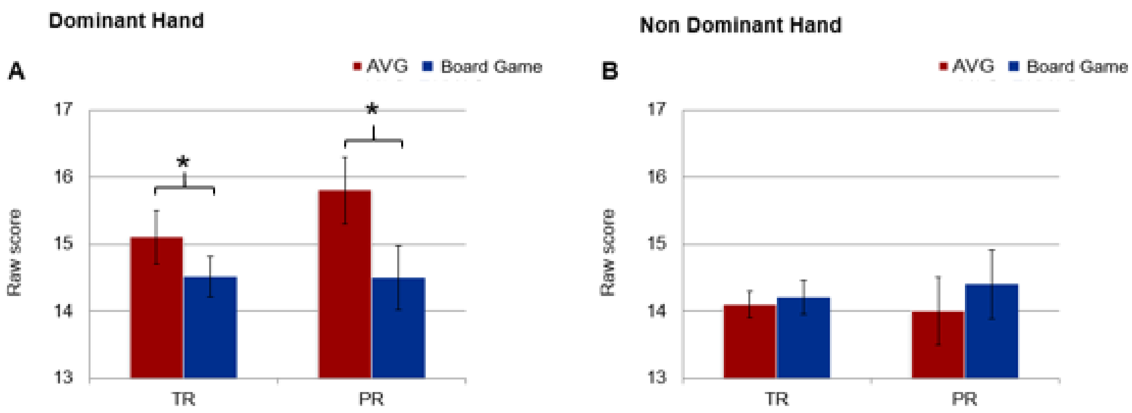

Figure 42. Performance of typical readers (TR) and poor readers (PR) in the Purdue pegboard test with dominant (A) and non-dominant hands (B). Data are reported as means ± standard errors. The asterisks indicate the significant differences

Remote Association Task

Two mixed ANOVAs with the same design were executed on accuracy rate and response times (msec) as dependent variables.

The results on accuracy did not show significant effects or interaction (all ps>0.104).

In contrast, the results on response times showed that only the main effect of the Group was significant ($F_{(1,56)}$=7.047, p=0.010, η^2_p=0.112). In particular, TR were faster in their responses compared to the PR (M=5496msec, SD=1332.76 and M=6474msec, SD=2825.45, respectively). See Table 10 for details.

	Typical readers		Poor readers	
	Board Game	AVG	Board Game	AVG
RAT response time (msec)	5577 (219)	5398 (219)	6475 (371)	6528 (332)
RAT response accuracy (rate)	0.55 (0.025)	0.50 (0.028)	0.46 (0.047)	0.46 (0.041)

Table 10. Remote association task speed and accuracy (mean and standard error) of typical readers and poor readers after the two-game sessions

Text Reading

Two mixed ANOVAs with a 2 x 2 design were executed on errors and reading speed z-score as dependent variables. The results on errors showed the main effect of the Group ($F_{(1,58)}$=71.292, p<0.001); no other main effect or interaction was significant (all ps>0.781, see Table 11).

	Typical readers		Poor readers	
	Board Game	AVG	Board Game	AVG
Text reading speed (z score)	0.53 (0.13)	0.48 (0.16)	-0.97 (0.33)	-0.71 (0.32)
Text reading error (z score)	-1.13 (0.19)	-1.22 (0.21)	-5.77 (0.86)	-5.69 (0.93)

Table 11. Text reading speed and error (mean and standard error of the mean) of typical readers and poor readers after game sessions (AVG and board game).

The results on reading speed showed the main effect of the Group ($F_{(1,58)}$=19.182, p<0.001) and a significant Group x Game interaction ($F_{(1,58)}$=5.560, p<0.022; see Table 11). Planned comparisons showed that whereas TR did not show a significant reading speed difference between AVG and board game sessions (M=0.48 z-score, SD=1.12 and M=0.53 z-score, SD=1.02, respectively; p=0.431), the PR showed a significant reading speed improvement in AVG session compared to the board game (M=-0.709z-score, SD=1.12 and M=-0.968z-score, SD=1.02, respectively; p=0.027; see Figure 43). However, the t-test analyses in reading speed show that the TR and PR groups post-board game condition ($t_{(58)}$=-5.030, p<0.001) continue to differ in the post-avg condition ($t_{(58)}$=-3.608, p=0.001).

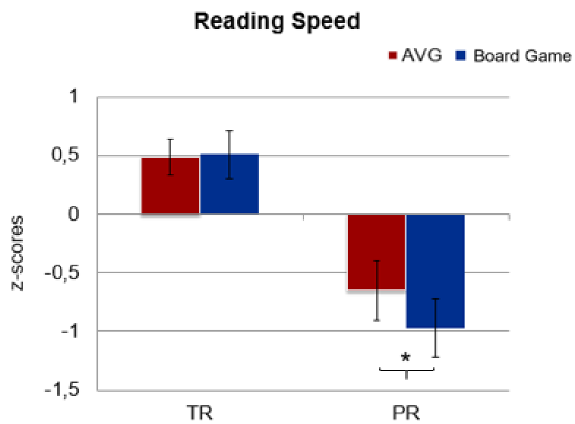

Figure 43. Text reading speed (z score) of typical readers and poor readers after game sessions (AVG and board game). Data are reported as means ± standard errors. The asterisks indicate the significant differences

Partial Correlation between Emotions and Neuropsychological Tasks

Correlational analyses conducted on the pre-gaming mean score (in both games) of PANAS negative emotions showed that this was significantly related to the initial mean score in the STAI questionnaire (r=0.81, p<0.001). Additionally, the PANAS positive emotion score was related to the negative one (r=0.44, p<0.001) but not to the STAI scores (r=0.14, p=0.274).

Delta scores (post minus pre-gaming evaluation) were calculated for the PANAS (positive and negative scores separately) and the STAI questionnaires.

Partial correlation analysis between responses to self-evaluation questionnaire and performance in the Eriksen single-target-condition showed that, after controlling for response times shown in the board game session, response time in the AVG session was related to the delta score in the PANAS positive emotion questionnaire (r=-0.43, p=0.001) and the vivacious item of the game experience questionnaire (r=-0.31, p=0.019): higher scores in positive emotion and vivaciousness were related to faster single target response times. No other correlations were significant (all ps>0.106).

Moreover, after controlling for the score in the board game session, partial correlation analysis shows that the PANAS positive emotion questionnaire, as well as the boring item of the game experience questionnaire, was significantly related to the manual dexterity score after the AVG session (r=0.38, p=0.003 and r=-0.26, p=0.048, respectively). Partial correlation analysis on the entire sample shows that, after controlling for the score in the board game session, the manual dexterity score after the video game session was significantly related to the delta score in the PANAS positive emotion questionnaire (r=0.38, p=0.003), as well as to the boring (r=-0.26, p=0.048) item of the game experience questionnaire. No other correlation was significant (all ps>0.150).

Due to the significant interaction with the Group variable, partial correlation analyses were conducted separately on the TR and the PR group. In both cases, after controlling for the score in the board game session, the manual dexterity score after the video game session was significantly related to the delta score in the PANAS positive emotion questionnaire (TR: $r_{(41)}$=0.36, p=0.016; PR: $r_{(14)}$=0.57, p=0.028). No other correlation was significant (all ps>0.072).

On the other hand, with regard to reading performance controlling for reading speed z-score, partial correlation analysis showed only a marginal correlation between reading speed after the AVG session and game difficulty item of the game experience questionnaire (r=0.23, p=0.043 one tile). Due to the significant interaction with the Group variable, partial correlation analyses were conducted only for the PR group. After controlling for the reading times (seconds per syllables) in the board game session, reading times after the AVG session were significantly related to the boring ($r_{(13)}$=-0.51, p=0.049), and fun ($r_{(13)}$=0.52 p=0.047) items of the game experience questionnaire. No other interaction was significant (all ps>0.059).

Correlation between Improvements in Neuropsychological Tasks

Correlational analyses were performed separately between groups on the significant play-driven neuropsychological changes (i.e., AVG minus board game performance), that are: (i) the single target response times in the Eriksen Flanker task; (ii) the dominant hand score in the Purdue Pegboard task; and only in PR; (iii) time score in the text reading task.

In the TR, the play-driven change in the Eriksen task was significantly related to the play-driven change in the dominant hand Purdue Pegboard ($r_{(44)}$=-0.47, p=0.001): the higher the improvement in the Eriksen task response time, the higher the improvement in the score in the Purdue Pegboard task. No other relation was significant (all ps>0.070). In the PR group, no relation was significant (all ps>0.082).

3.3.3 Discussion

In order to identify the effects of emotions associated with play experience, we compared the effects of two different game experiences.

As expected, we observed that the AVG experience, compared to the board game, was perceived as more fun, less boring and less overly difficult, capable of inducing calm, happiness, and vivaciousness in the players. Moreover, the AVG experience, compared to the board game, reduces the negative emotions and improves the positive ones. The play-driven changes in positive and negative emotions were linked to changes in behavioural performance, confirming the causal link between the emotional states induced by game experience and neuropsychological functioning. In particular, improvements after the AVG session were observed in the Purdue Pegboard task execution, which involves grasping and fine sensorimotor coordination, specifically in the dominant hand. We could suppose that with the dominant hand, the task was executed mainly automatically compared to the non-dominant hand, which requested the activation of more voluntary control of sensorimotor coordination abilities. Similarly, improvements were also observed in the Eriksen Flanker task, but only in the absence of distractors, involving lesser response inhibition and interference control executive. Crucially, the observed improvements obtained in these tasks were linked to the improvement in positive emotions experienced at the end of the game session and during the task administration.

Lastly, improvements were observed in the reading task, specifically in those participants with reading difficulty, and improvements were related to the level of fun perceived during the video game. This data confirms the feasibility of increasing reading skills in poor readers by modifying their emotional state (Franceschini et al., 2022). No effects were observed in those tasks that involved executive functions like response inhibition and interference control - the Eriksen Flanker task with distractors -, and all 4 executive control domains involved in the RAT task (Niendam et al., 2012). These data exclude a generalised effect of improved performance across all cognitive functions after the video game activity. The optimal activation of this stimulus-driven large-neural network, regulated by the motivation and pleasure systems (Trezza et al., 2010), seems to facilitate performance in specific neuropsychological functions that are perceived as stressful (Palagi et al., 2004). By showing an increase in anxiety levels after the neurocognitive assessment, our results further this hypothesis.

In conclusion, by regulating emotional and psychophysiological activation, gaming could enhance salience network functioning. These short-term effects could support the long-term beneficial effects of gaming on learning and memory. Although additional neurobiological evidence is necessary to demonstrate this hypothesis, our psychophysiological findings suggest that a transient stimulation of salience processing could be necessary for a long-term play-driven learning enhancement. Our findings provide initial evidence for the development of efficient training and education programs for enhancing learning skills in children, adults and the elderly.

Overall Discussion and Conclusion

The studies included in this chapter had the overall goal of comparing the short-term outcomes of a single game session with an action-like video game and with a visuo-constructive board game. The first two studies were conducted on a population consisting of children without neurodevelopmental difficulties, and the third on university young adults with and without reading difficulties.

Given the different nature of the proposed games (AVG vs board game) and the role that emotions play on cognitive functions (Franceschini et al., 2022; see Brosch et al., 2013 for a review), we recorded the emotions elicited by the two game sessions in all our samples. In general, it can be asserted that AVGs (Geometry Wars in the preliminary study of school children and Mario Kart in the study of preschoolers and young adults) were always considered to be more fun and more activating than Tangram by the different participants. The results confirm the previous literature that describes playing, particularly AVGs, as an activity enjoyable and entertaining (Franceschini et al., 2022; Kozehevnikov et al., 2018; Palagi et al., 2004), including in rehabilitation settings (see Baas et al., 2008 for a meta-analysis and Horne-Moyer et al., 2014 for a review). More interestingly, the improvement associated with the game and emotions experienced during sessions with action-like compared to the board games seem to result in different effects of the attentional control on neuropsychological functions, but also on the specific stage of brain development.

The exploration of short-term cognitive effects stemming from play experiences in children unveils a nuanced relationship between gaming stimuli and cognitive domains. Two distinct studies shed light on these dynamics, revealing differential impacts depending on the nature of the game and its emotional involvement.

In the first study, comparing an AVG and an educational puzzle board game sought to understand the influence of game characteristics on neurocognitive functioning in school children. It emerged that AVG sessions prompted lexical-level improvements in word reading efficiency, while the board game notably enhanced auditory-phonological short-term memory. This divergence suggests that different game types engage disparate cognitive processes, each contributing uniquely to cognitive enhancement (Franceschini et al., 2022).

The funny experiences derived from gaming could be linked to the release of neurotransmitters and neuromodulators (see Vanderschuren et al., 2016 for a review), possibly widening the attentional focus and improving visual memory and learning. Positive emotions associated with gaming facilitate automatic actions and stimulus-driven attentional control and promote global perception as well as memory and learning (Fredrickson & Branigan, 2005; Gasper & Clore, 2002; Ji et al., 2019). However, this expanded attentional window might reduce selectivity and the optimal noise-exclusion control of CEN, resulting in reduced efficiency in visual search tasks after gaming sessions.

Building upon these findings, the second study delves deeper into the intricate effects of play experiences on specific neurocognitive domains. It highlights that regardless of the play experience, transient effects manifest differently across the cognitive functions. Phonetic perception and visuomotor performance without distractors improve, yet phonological short-term memory, visuomotor performance with many distractors, and aiming skills decline following play sessions. Additionally, the emotional involvement with the game, induced by Mario Kart 8 Deluxe being judged funnier than Tangram, is associated with specific cognitive outcomes, such as fine sensorimotor performance improvement, but also worsened response inhibition skills, partially replicating the results by Franceschini and colleagues (2022) in school children with atypical development. Since this fine sensorimotor enhancement was shown only in the non-dominant hand, it could be suggested that a single session of an action-like experience impacts mainly the right sensorimotor network in the developing brain.

In conclusion, these studies emphasise the complexity of the relationship between play experiences, emotional engagement and short-term cognitive effects in children. Such investigations hold promise in educational realms and therapeutic interventions, elucidating the adaptable nature of neural responses to gaming stimuli. For example, phoneme and speech-sounds perception deficits are consistently considered the main causal cognitive factor of developmental language and specific learning disorders (see Gabrieli, 2009 and Goswami, 2011 for reviews), while fine sensorimotor skills are considered the main causal cognitive factor in developmental coordination disorder (see Fuelsher et al., 2018 for a meta-analysis). Interestingly, in early phases of development, enhanced local perception or over-focused attention, as well as attentional disengagement deficits, are linked with future autism spectrum disorder (e.g., Elsabbagh et al., 2013; Gliga et al., 2015; see Dawson et al., 2023 for a recent review). Thus, action-like games could be used as enjoyment tools to fight several neurodevelopmental disorders efficiently, transiently stimulating the salience processing for a long-term improvement of goal-directed executive processing (Hermans et al., 2014; see Schwabe et al., 2022 for a recent review).

The comprehensive understanding of play experiences and their impact on neurocognitive functions extends to a third study involving young adults, contributing valuable insights into emotional activation and its relationships with behavioural performance. This study aimed to discern the effects of emotions associated with play experiences by comparing the same games used in Study 5.

Before deepening into game activities, participants' emotional states were assessed, ensuring that any observed effects were not confounded by pre-existing emotional differences. The study revealed that the AVG activity, in contrast to the board game, induced more positive emotions, reduced negative emotions, and was perceived as more enjoyable, less boring, and less difficult. These emotional distinctions were linked to behavioural performance improvements, notably in sensorimotor coordination tasks, such as the Purdue Pegboard task executed with the dominant hand.

Moreover, positive emotional experiences during the AVG session were associated with enhancements in the Eriksen Flanker task (absence of distractors), suggesting a connection between emotional states and salience visuomotor skills. The observed improvements align with cross-sectional studies indicating the potential long-term positive effects of play activity on processing speed and sensorimotor skills in children (Hong et al., 2023; Pujol et al., 2016). Notably, the data reinforce the functional role of cerebellar circuits in the development of play behaviour in primates (Lewis & Barton, 2004).

The study further demonstrated improvements in a reading task for participants with reading difficulties, correlating with the level of fun perceived during the AVG session. This supports the idea that modifying the processing modality can enhance reading skills in individuals with difficulties, as previously suggested by Franceschini and colleagues (2022). However, no improvements were observed in typical readers, possibly indicating the need for tailored interventions or different game types.

Crucially, the study did not find generalised improvements across all cognitive functions, particularly in tasks involving executive functions like response inhibition, noise-exclusion mechanisms and working memory. Instead, the findings suggest an increase in the activation of the SN, facilitated by motivation and pleasure systems. This neural network, regulated by the brain's intimate conscious integration of autonomic feedback and responses with internal goals and environmental demands, seems to enhance performance in specific activities, particularly those perceived as stressful (Seeley, 2019).

The observed improvements are postulated to be associated with the long-term augmentation of attentional control (Green et al., 2010; see Bavelier & Green, 2019 and Peters et al., 2019 for reviews; Bediou et al., 2018; 2023 for meta-analyses). It is suggested that the neurocognitive circuits implicated in the immediate effects of visuo-spatial attention are linked to the activity of the SN, encompassing the amygdala, hypothalamus, striatum, anterior insula, anterior cingulate cortex, and the inferotemporal and temporoparietal regions, along with midbrain and brainstem nuclei, including the LC (Hermans et al., 2014). These areas generate a neuroendocrine response mediated by neurotransmitters such as catecholamines (e.g., NA and DA) and corticosteroids (Droste et al., 2009; Joëls & Baram, 2009). Activation of this network appears to inhibit the CEN associated with top-down and goal-directed attention (see Schwabe et al., 2022 for a review) while favouring bottom-up and stimulus-driven attention, optimising perceptual noise-exclusion mechanisms (Aston- Jones & Cohen, 2005; see Baghdadi et al., 2020 and Ridder et al., 2023 for reviews). This hypothesis gains support from various studies reporting an increase in neuroendocrine response immediately after engaging in video game play (Porter & Goolkasian, 2019; see Beun et al., 2005 for a meta-analysis).

As indicated by prior research, long-term visual-attentional improvements resulting from AVG usage are sustained by enhanced prefrontal activation, particularly in the dorsolateral prefrontal cortex and premotor areas, associated with increased control of top-down processes in visuomotor transformations (Granek et al., 2010; Gong et al., 2017). It can be further postulated that the repeated demand to alternate sustained and selective attention may, over the long term, lead to improved coordination between endogenous and exogenous attentional control during task execution (Bavelier & Green, 2019), that is the integration between DAN and VAN (see Kim, 2014 for a meta-analysis). However, it is specified that while the results on the children population are well explained by the Hermans and colleagues' model (2014), the data on the young adults sample do not perfectly fit with the model just cited. The results obtained in Study 6 in university students with and without reading difficulties suggest that the temporary activation of SN is not strongly combined with the deactivation of CEN (see Fuelscher et al., 2018 for a meta-analysis). It is possible to speculate that this difference is because the model of Hermans and colleagues (2014), formulated on studies that "integrate animal data at the cellular and systems levels with an emerging human literature", is closer to the functioning of children than to the specialized cognitive functioning of adults, in whom even more general executive and cognitive control is greater. In addition, differences in the data obtained on sensorimotor skills in children and adults suggest that play experiences, as well as the emotions experienced, involve the two hemispheres differently. Specifically, in children it appears that the play experience has greater effects on the right hemisphere, acting on the non-dominant hand, while in young adults the effects seem to be more associated with the left hemisphere and the dominant hand.

A second concept to consider in explaining suboptimal sensorimotor performance is the potential effect of enjoyment in increasing arousal levels (Yerkes & Dodson, 1908). Specifically, the Yerkes-Dodson Law (1908) establishes that an optimal level of arousal is necessary for optimal performance, and deviations in either direction can lead to decrements in performance. Indeed an excessive arousal of the LC, with an over-release of NA, might interfere with goal-directed performance, inducing a state of distractibility (Aston-Jones & Cohen, 2005; Hanoch & Vitouch, 2004; Wainstein et al., 2022) (see Figure 44).

However, further investigations into neural circuits and the neuroendocrine system associated with immediate AVG effects are necessary to elucidate these hypotheses.

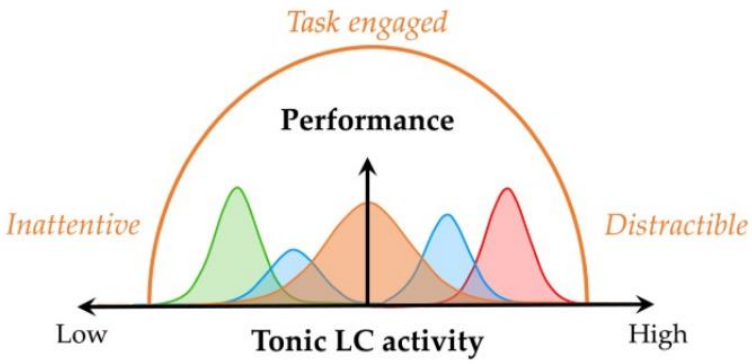

Figure 44. Performance related to the locus coeruleus (LC) activity and bowing. Image from Wainstein, G., Müller, E. J., Taylor, N., Munn, B., & Shine, J. M. (2022). The role of the locus coeruleus in shaping adaptive cortical melodies. *Trends in Cognitive Sciences*, *26*(6), 527-538. https://doi.org/10.1016/j.tics.2022.03.006

General Limitations and Future Directions

The results from the three studies offer important insights into the short-term cognitive and emotional effects of play experiences among children and young adults. However, a comprehensive understanding requires acknowledging general limitations across these studies and avenues for future exploration. In particular, all studies face the common limitation of relatively small sample sizes, raising concerns about the generalizability of findings. More specifically, future research should prioritise a more balanced typical- and atypical-development population and more diverse participant pools to enhance the external validity of results and allow for a more comprehensive understanding of the broader population. Moreover, the studies, especially the second one focusing on preschool children, tend to concentrate on task-specific outcomes. Broader implications for daily cognitive functioning or transfer effects to real-world scenarios remain underexplored. Future research should adopt a more holistic approach, considering a wider array of neuropsychological functions and their applicability in diverse contexts.

Concluding, the emotional and cognitive impacts of play experiences are intricate and dynamic, involving diverse cognitive domains and emotional states. The findings collectively underscore the need for customised interventions, recognising the individual differences in cognitive function and emotional responses to play stimuli, contributing to the development of targeted educational and therapeutic interventions.

Chapter 4. Effect of Caffeine on Attentional Control

Introduction

Caffeine (1,3,7-trimethylxanthine), a natural psychoactive substance affecting the central nervous system, has long captivated the interest of scientists and the general public alike. As estimated by the European Food Safety Association (EFSA), European adults consume daily caffeine doses ranging from 37 to 319 mg in popular beverages like tea, coffee and cola. Caffeine's well-known effects include reducing drowsiness and enhancing mental alertness after moderate doses (see Nehlig, 2010 and McLellan et al., 2016 for reviews). This molecule is rapidly absorbed after administration, reaching peak concentrations in the circulation within an hour (Blanchard & Sawers, 1983; Robertson et al., 1981 but see Chait, 1992; Desbrow et al., 2009; Retey et al.,2007; Skinner et al., 2013).

Caffeine operates through various mechanisms, such as antagonizing adenosine and benzodiazepine receptors, inhibiting phosphodiesterase, and releasing intracellular calcium (Fredholm, 1979). Despite weak effects on the latter two mechanisms, caffeine's primary action is its antagonistic effect on adenosine receptors, particularly at low doses (Fredholm, 1995; Ribeiro & Sebastião, 2010; see Reichert et al., 2022 for a recent review). Specifically, caffeine's antagonistic activity on adenosine receptors, notably the A_1 and A_{2A} receptors, accounts for the majority of its biological effects. These receptors regulate sleep, arousal, and cognition across widespread brain areas (Ribeiro & Sebastiao, 2010). According to Landolt (2008), both receptor subtypes are expressed in the brain and periphery, with high concentrations of A_1 receptors in the hippocampus, cortex, cerebellum, and hypothalamus. Conversely, the A_{2A} subtype is prevalent in brain regions like the striatum, nucleus accumbens, and olfactory tubercle, areas rich in dopamine-containing fibres (see Nehlig, 1999 for a review). Caffeine, by reducing the inhibitory function of adenosine, can potentially affect any area of the brain (Ribeiro & Sebastião, 2010). Although no direct effects of caffeine on receptors other than adenosine receptors have been identified, many indirect effects of caffeine due to the blockade of adenosine receptors on the release of NA, DA, Ach, 5-HT, glutamate, GABA and perhaps neuropeptides have been identified (Daly et al., 1994). It is important to note then that another of the significant effects of caffeine in the brain is increased dopaminergic release, probably in more specific areas such as the caudate nucleus and PFC (De Paula & Farah, 2019; McLellan et al., 2016; Nehlig, 2004; Ferrè et al., 1997; Fredholm 1995). Given the link between the neurotransmitters involved in caffeine intake and their role in emotions (Lövheim, 2012; see Alexander et al., 2021 for a review), some research has focused on the effects of caffeine on mood. In particular, some studies demonstrated that the habitual consumption of caffeine is associated with a trend of continuous mood enhancement throughout the day (Hindmarch et al., 2000), but also with a lower risk of suicide (Lucas et al., 2014) and a better fatigue tolerance (see Barcelos et al., 2020 for a recent review). However, the possible relationship between caffeine and anxiety seems to be a debated topic. In particular, Smith's (2002) systematic review summarizes that only a few studies have found an increase in anxiety following caffeine administration, and many of these found it only in subjects who were vulnerable because they had anxiety disorders or had high levels of anxiety at the time (see also Bertasi et al., 2021). In contrast, the studies that found increased anxiety in "healthy" people mostly reported intakes of high doses of caffeine at a single time (300 to 600 mg) (Smith, 2002; see also DSM-5, APA, 2013).

In a study by Barry and colleagues (2005), researchers found that caffeine has "pure" effects on increased arousal: the authors found an increase in the level of skin conductance and global alpha frequency and a decrease in global alpha power (all measures of a psychophysiological increase in arousal) in the resting state. Given the consistent evidence that highlights acetylcholine’s important role in attentional mechanisms (Hayward et al., 2017; Himmelheber et al., 2001; see dos Santos Coura & Granon, 2012 for a review), especially on the top-down control of attention (Klinkenberg et al., 2011, Sarter et al., 2001; Thiele & Bellgrove, 2018; Villano et al., 2017), it is plausible to hypothesize an effect of caffeine on attentional systems.

Interestingly, the same neurotransmitter systems that result in a general increase in arousal after caffeine intake (via its effects on adenosine) are found in some studies to be at least partially lateralized in the right hemisphere. For example, it has been found that binding between the dopaminergic D_2 receptor and its ligand is more efficient in the right striatum than in the left (Larisch et al., 1998), serotonergic indices such as the metabolite 5-HIAA and imipramine are more significant in the right hemisphere (Arato et al., 1991), as also NA is found to be greater in some areas of the right hemisphere (Oke et al., 1978). Therefore, it is possible that caffeine has a major effect on the right hemisphere. To corroborate this claim, Brunyé and colleagues (2012) report two studies from which increased activation of the right hemisphere after caffeine intake was found to increase activation of the right anterior cingulate cortex (Koppelstaetter et al., 2008) and increased brain activation in the right hemisphere while involving complex attentional task (Lorist & Snel, 1997).

Indeed, caffeine acts in modulating the activity of the fronto-parietal control networks, which extend from the anterior cingulate cortex through the DLPFC and to the parietal cortex. This network is primarily oriented in the right hemisphere, playing an essential role in response anticipation and executive control (Wang et al., 2010). Moreover, brain regions in this network are rich in DA, which appears essential for effective attentional control (Davidson et al., 2004) and global coherence during speech processing (Brunyé et al., 2012). Brunyé and colleagues (2012) found that caffeine appears to improve the analysis of global sentence form as participants improved their ability to detect morphosyntactic violations in a review task, while the ability to detect single misspelt words remained unaffected. In addition, some studies have found that caffeine improves accuracy (Haskell et al., 2005) and speed (Warburton et al., 2001) in the sentence verification task, a verbal comprehension test in which participants must quickly judge the veracity of specific sentences. Franceschini and colleagues (2020) found an increase in global perception and reading speed of a text following caffeine intake, while other abilities were unaffected (see also Nehlig, 2004; Weiss & Laties, 1962). Consistent with a possible involvement of global processing, controlled by the right hemisphere, in reading efficiency, Franceschini and colleagues (2017) showed a specific deficit in global perception in children with DD. Specifically, two different visual remediation programs based on reading sentences with time limits and one based on AVG improved both global perception in a Navon task and reading efficiency (Franceschini et al., 2017). Hoeft and colleagues (2011), studying the neural systems involved in reading difficulties recovery, showed that the right inferior frontal gyrus and the right arcuate fasciculus are critical for reading improvements in children with DD. Together, these studies show that the right frontoparietal areas are involved in the information processing of complex patterns such as text reading.

There are also many studies concerning the ameliorative effect that caffeine has on global information processing, such as on global spatial processing (Giles et al., 2013) and on increasing global perception performance in a Navon task (Franceschini et al., 2020; Mahoney et al., 2011), that typically involves a global stimulus processing and a right hemisphere specialization.

Several studies have also reported increased activation of the right hemisphere with regard to noncaffeine-related arousal. For example, Kheirkhah and colleagues (2021) found that emotional stimuli eliciting very high arousal activated the right temporoparietal area more than all other brain areas. Other studies show a connection between right hemisphere lesions and impairments to some arousal indices, such as electrodermal response and heart rate (Morrow et al., 1981; Zoccolotti et al., 1986).

Overall Aim and Study

This study aims to investigate the role of caffeine with its underlying complex neuromodulation on some neuropsychological tasks, which were also used in the previous game study, to better understand the role of salience processing and executive control in these tasks. Indeed, this psychostimulant substance is typically used to enhance attentional control. In particular, the functioning of salience processing was indexed by using the reading score in the contextual reading task involving the global processing of the letter-strings. A single session of 30 minutes playing an action-like game was able to increase the contextual reading speed in the PR sample in Study 6. Consistently, also in school children a single session of AVG increased parallel lexical reading, but not serial phonological decoding, as shown in Study 5. In contrast, the goal-directed executive functions were indexed by using the complex RAT engaging, in addition to semantic linguistic knowledge, response inhibition and set-shifting skills, as well as working memory capacity. Finally, the impact of caffeine on experienced emotions induced by the puzzle board game were also measured.

It is hypothesized that caffeine, similarly to action-like games, could enhance the contextual reading skills, as well as the RAT, which was instead unaffected by action-like games, by rebalancing overlapping neural mechanisms in the right ventral fronto-parietal network (SN) and bilateral dorsal fronto-parietal network (CEN). To test our hypotheses, we involved a large sample of healthy young adults in a crossover, double-blind, randomized, placebo-controlled stud

Study 7. The Short-Term Effects of Caffeine: Two Cups to Improve Text Reading Abilities, Semantic Association and to Make Activities More Fun

Abstract

The psychostimulant effects of caffeine have been investigated through numerous studies that have shown improvement in global perception, typically associated with the right brain hemisphere. To investigate caffeine's cognitive and psychophysiological effects, we involved a sample of 54 healthy young adults in a crossover double-blind, randomized, placebo-controlled trial. We supposed that 200mg of caffeine could improve reading and semantic abilities in connection with an improvement of positive emotion. We administered caffeine or a placebo to the participants and invited them to play a board game for 25 minutes. At the end of the game session, we asked them to evaluate the game and their activation state. Then, we administered text reading and semantic association tasks. Our study shows an improvement in reading speed and the ability to find semantic associations between words after administering a single dose of caffeine. The effect on perceived emotion is even more interesting: participants report that the same game experience performed during the two experimental sessions is more fun after caffeine intake. These effects are unrelated to sleep deprivation or other self-perceived psychophysiological activation.

4.1 Materials and Methods

Participants

The study involved 54 healthy young adults (15 males and 12% left-handed; M=23.75y.o. SD=1.79) attending the School of Psychology at the University of Padova, native Italian speakers and habitual caffeine consumers (M=161.54mg, SD=91.68).

During the voluntary recruiting phase, each participant completed a brief questionnaire to assess the diagnosis of specific neurodevelopmental disorders (e.g., learning impairments, ADHD and autism spectrum disorder) and neurological difficulties (e.g., epilepsy and migraine). Participants report no epilepsy or familiarity history with it, sensory deficits (auditory, visual, or sensorimotor), or cognitive impairments. A medical certificate completed by the referring physician, mandatory to participate in the study, was also used to ascertain a general state of good health. General cognitive abilities estimated through the subtest of the WAIS-IV (Wechsler, 2008; see Material section) made it possible to exclude potential cognitive difficulties and thus include all participants in the research (weighted scores to Block Design: M=10.83, SD=2.86).

Two participants did not complete both the experimental sessions, while another participant was excluded only from analyses on the RAT because results outlier in the test timing. Therefore, the analysis of some tests refers only to part of the sample recruited. The procedure and the goals for data collection were made explicit on the form given to participants. The study was written in compliance with the European Union Standards of Good Clinical Practice, and it was authorized by the Human Inspired Technology Research Centre (HIT) Ethics Committee of the University of Padua (Protocol number: 2018_19 R2).

Procedure

All individuals were tested twice, one week apart, in a well-lit and calm laboratory at the University of Padua's Department of General Psychology. The evaluations were planned at the same hours, and the same fixed order of neuropsychological tasks (with counterbalanced content, see Materials section) were administered in both experimental sessions (lasting roughly 60 minutes each).

At the beginning of each evaluation, participants were asked to indicate how many hours they had slept the previous night and whether they had consumed coffee in the hours before the experimental session. In fact, it is specified that participants were asked not to consume caffeine in the 12 hours before and after the experimental session so that the effects of the administered dose alone could be assessed.

The experimental sessions start with the administration of the Y form of the State-Trait Anxiety Inventory (STAI; Lazzari & Panchieri, 1980) and the masked drink administration. Specifically, half of the sample assumed first the drink with 200mg of caffeine (1 capsule of a dietary supplement by Warnke Vitalstoffe dissolved in a glass of water and lemon soda) and in the second session, the placebo drink (a glass of water and lemon soda). The other half of the sample assumed the placebo and then the caffeine drink. Immediately after, participants were administered the “Vocabulary” subtest (always in the first experimental session) and the “Block Design” subtest (always in the second experimental session), both tasks of the WAIS-IV (Wechsler, 2008; see Materials section). In the half-hour required to assimilate any caffeine in the drink, participants were asked to play the puzzle board game Tangram for 30 minutes (see study 6 for more details) and to evaluate their experience by filling in a questionnaire ("Self-Evaluation Questionnaire", Franceschini et al., 2022). The tests provided by the neuropsychological battery were then offered in the following fixed order: Remote Association Tasks, Text Reading and State STAI questionnaire (again).

The study was conducted double-blind: an outside experimenter who was not present during the experimental sessions prepared the drink glasses. Analyses were also performed blind (see Figure 45).

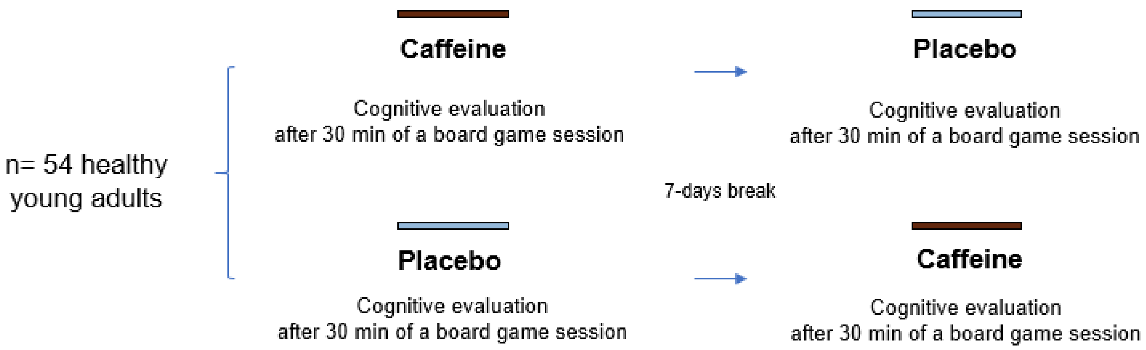

Figure 45. Schematic representation of the experimental design of Study 7.

Questionnaires

1. State Anxiety Evaluation (STAI-Y; Lazzari & Panchieri, 1980)

The study utilized a 20-item questionnaire Y-form from the STAI (Lazzari & Panchieri, 1980) to assess anxiety levels and variations resulting from examination and game sessions with participants indicating their current feelings. The total scores were analyzed (see Questionnaires section of Study 6 for more details).

2. Games and Self-Evaluation Questionnaire (Franceschini et al., 2022)

The questionnaire was administered post-game session, asking participants to rate the game's difficulty, boredom, and humour and their post-game feelings on a 9-point scale (see Questionnaire section of Study 5 for details).

Neuropsychological battery

Intelligence Quotient Estimation

1. Block Design (WAIS-IV; Wechsler, 2008)

The visuo-constructive skills of the subjects were evaluated by the "Block Design" subtest (Kohs, 1920). The student was given fourteen geometric compositions ranging in difficulty. The task for the participant was to use wooden coloured cubes (red and white) to reconstruct the pattern as quickly as possible. Time and accuracy were noted for each figure; the test was terminated when three items scored zero. The total raw scores were then converted to weighted scores according to the WAIS-IV Handbook (Orsini & Pezzuti, 2013).

2. Vocabulary (WAIS-IV; Wechsler, 2008)

Lexical knowledge and the development of verbal concepts were evaluated using the "Vocabulary" subtest. Based on the accuracy and thoroughness of the response, a range of 0 to 2 points are awarded in the raw score. The test was stopped when three vocabulary items were erroneously obtaining a score of zero. The total raw scores were then converted to weighted scores according to the WAIS-IV Handbook (Orsini & Pezzuti, 2013).

Remote Association Task (RAT; adaption from Salvi et al., 2016)

The RAT is a computerized task that measures the ability to create semantic associations. Participants were asked to find and say a fourth word that could be combined with three words on a screen to compose a compound word or semantic association. Twenty items from the Italian validation of RAT were selected and paired for the difficulty to create two lists of 10 trials. Participants had a maximum of 15 seconds to find a possible answer, then a new trial was administered. Accuracy and response times were collected and evaluated (see Neuropsychological battery section of Study 6 for details).

Text Reading (Judica & De Luca, 1993)

The study evaluated reading abilities using two similar texts, measuring reading speed and errors. Participants were given the texts in a counterbalanced order and asked to read each text aloud as quickly and accurately as possible (see Neuropsychological battery section of Study 3 for details).

4.2 Results

State Anxiety Inventory

A repeated-measures ANOVA with a 2 x 2 design was conducted on the ponderate score of the state anxiety questionnaire to assess possible variations in anxiety at different times during the research. Specifically, the within-subject variables considered were the Drink administered (caffeine and placebo) and the Time of administration (pre- and post-). The analyses show that only the main effect related to the Time of administration was significant $F_{(1,51)}=13.962$, $p<0.001$; see Figure 46). More specifically, perceived anxiety increased from the previous stage (M=35.55, SD=26.31) to the final stage of administration (M=43.01, SD=27.41), regardless of caffeine or placebo intake.

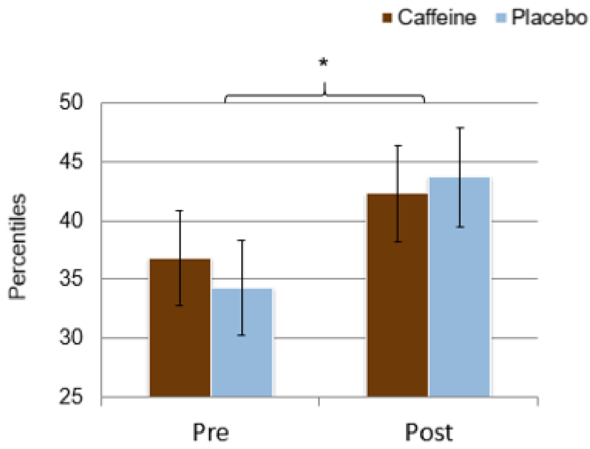

Figure 46. Responses to the STAI-Y questionnaire on anxiety level before (pre-) and after (post) drink assumption (caffeine in brown, placebo in sky blue). Data are reported as means ± standard errors. The asterisks indicate the significant differences.

Games and Self-Evaluation Questionnaire

Comparison by paired-samples t-test carried out on the scores of the game-related questionnaire shows that after taking caffeine, participants rated the same experience of playing Tangram as more fun, compared with after taking placebo (M=5.92, SD=2.01 and M=5.44, SD=2.30, respectively; $t_{(51)}=2.394$, p=0.02). In contrast, the game's difficulty and the perceived level of tension, happiness and vivacity showed no statistically significant differences after taking the placebo over caffeine (all ps>0.352; see Figure 47).

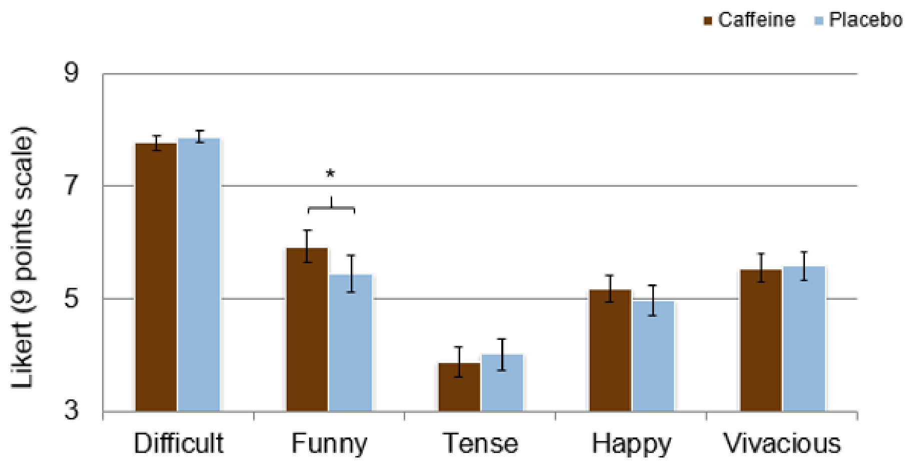

Figure 47. Responses to the Self-Evaluation Questionnaire (Franceschini et al., 2022) administered after the assumption of caffeine (brown bars) and placebo drink (sky blue bars). Data are reported as means ± standard errors. The asterisks indicate the significant differences.

RAT

An independent samples t-test was used to analyze performance following caffeine intake rather than the placebo drink. Participants' performance was assessed using an inefficiency index that considers the speed of execution and the level of accuracy (milliseconds/accuracy rate). The results show a significant effect of caffeine intake on inefficiency ($t_{(50)}$=-2.754, p=0.008). Notably, participants' performance seems to be better following caffeine intake than after the placebo drink (M=9291.55, SD=4539 and M=11534, SD=6317, respectively). See Figure 48.

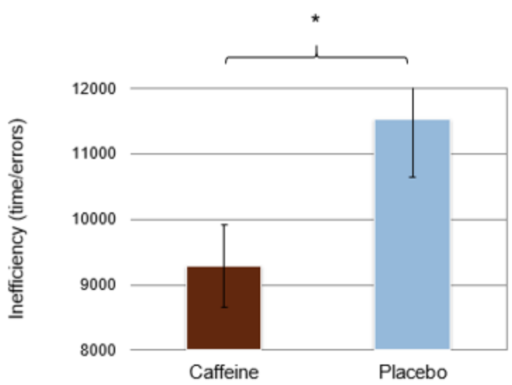

Figure 48. Inefficiency (speed of response/accuracy) of participants at the RAT (adaption from Salvi et al., 2016) after the assumption of caffeine (brown bars) and placebo drink (sky blue bars). Data are reported as means ± standard errors. The asterisks indicate the significant differences.

Text Reading

To evaluate the effects of a single caffeine intake, two t-tests for paired samples were conducted on reading speed (syll/sec) and accuracy. The results show a significant increase in reading speed in the post-caffeine intake condition compared with the post-placebo ones (M=5.92syll/sec, SD=0.67 and M=5.80, SD=0.66, respectively; $t_{(51)}=2.053$, p=0.045). Notably, a gain of 0.12 more syllables per second are read in caffeine than in the placebo condition (see Figure 49, panel A). However, the number of errors made does not appear to differ between the caffeine and placebo conditions (M=3.06, SD=2.55 and M=3.00, SD=2.89, respectively; $t_{(51)}=0.151$, p=0.881; see Figure 49, panel B).

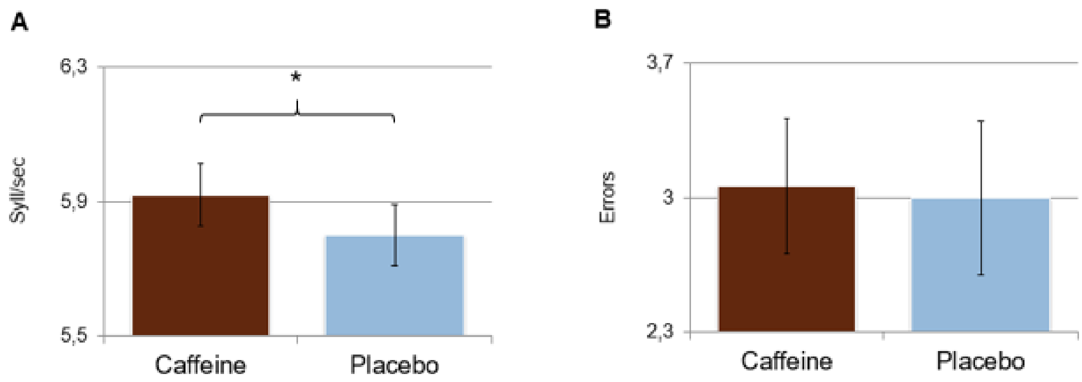

Figure 49. Reading speed (syllable per second; A) and accuracy (number of errors; B) of participants at the text reading text (Judica & De Luca, 1993) after the assumption of caffeine (brown bars) and placebo drink (sky blue bars). Data are reported as means ± standard errors. The asterisks indicate the significant differences.

Sleeping Hours

In order to rule out possible cognitive outcomes from the different times spent sleeping before the two experimental sessions, a paired samples t-test on sleep hours was conducted. The results show that there were no statistically significant differences between the hours spent sleeping the day before the session with caffeine rather than placebo (M=6.98hours, SD=0.90 and M=6.96, SD=1.07, respectively; $t_{(51)}=0.19$, p=0.914).

4.3 Discussion

The study investigated the impact of moderate caffeine intake (200 mg) on contextual reading abilities, emphasizing reading speed, executive functions mediated by semantic abilities and emotions. The results report interesting and some unexpected data compared to the initial expectations.

Regarding the STAI, the mixed analysis of variance was crucial for the emergence of a statistically significant significance not entirely anticipated. The main variable of the experimental research, namely the comparison between caffeine and placebo, did not yield any discrepancies, and therefore, there was no increase in the percentile score of anxiety levels following substance administration. Reflecting one of the previously cited studies, Smith (2002) did not report an increase in anxiety symptoms following moderate doses of caffeine. Therefore, this current research aligns with this result, confirming that caffeine at a dosage of 200 mg is not an incremental factor in anxiety levels. Presumably, with a higher quantity of the substance, effects reminiscent of those typically seen in abuse behaviour would have been evident (see Broderick & Benjamin, 2004 for a review and symptoms of "caffeine-induced anxiety disorder" in DSM-5, APA, 2013). However, a more interesting and unexpected finding from the analysis of the STAI-Y is the discrepancy observed in the completion times of the questionnaire. At the beginning of the experiment, subjects declared less anxiety compared to the end of the session, regardless of the type of experimental condition. This data suggests that the increased agitation of participants was likely since they had been subjected to a series of tests evaluating their abilities. Therefore, even though the administration environment was relaxed, and efforts were made to put everyone at ease, the effect of performance anxiety remained present and emerged in this questionnaire.

Furthermore, the responses to the questionnaire (Franceschini et al., 2022) on emotions experienced during the gaming session showed the absence of a general increase in tension in favour of a statistically significant increase in the perception of fun after the caffeine assumption. Specifically, participants rated the same game experience as more enjoyable in the session characterized by caffeine intake, without rating the difficulty of the game and their level of happiness, energy, and agitation differently. This shows that caffeine does not interact with the self-assessment of the perceived emotional state during the activity (tense, happy, energetic) but only on the evaluation of the just-performed activity and how it was perceived (fun). Given the literature analyzed regarding emotional activation, this result is surprising and innovative, as a generic increase in emotional excitement (Barry et al., 2005; Brunyé et al., 2012) was expected but not observed. The result obtained on the perception of fun could be associated with and determined by the increased transmission of monoamine neurotransmitters caused by the interaction of caffeine with certain adenosine receptors (Fredholm et al., 1999) and increased global processing (Franceschini et al., 2020; Brunyé et al., 2012), which probably helps to focus on features of the activity perceived as fun. This hypothesis would be consistent with the study by Franceschini and colleagues (2022) on the effects of video games, where it was found that only the most fun perceived video game increases cognitive processes associated with global processing.

Moreover, the results obtained in the RAT also show that caffeine is associated with lower inefficiency values compared to the placebo condition. Considering that the goal of the test is to find words linked by synonymy or semantic association, it can be assumed that the RAT is a good tool for exploring associative functioning and reflects the degree of activation of the neural mechanisms theorized by associative network models (Collins & Loftus, 1975), distributed semantic models (Harris, 1970), and feature models (see Kumar, 2021 for a review) and, more in general, activation of the CEN. Additionally, our results in this test confirm the improvement associated with caffeine intake in creative problem-solving tasks found by Zabelina and Silvia (2020), probably associated with improved attentional focus (Rao et al., 2005) and faster insight problem-solving processes (Kamimori et al., 2015).

In addition, the study results revealed that contextual reading speed and semantic association significantly increased after administering 200 mg of caffeine, further supporting the hypothesis that caffeine enhances these abilities. Our study replicated the results of Franceschini and colleagues (2020), the first evidence in the literature of increased contextual reading speed following caffeine intake. Both studies followed the same design and experimental procedure and were conducted on similar but different participant samples, increasing the validity of the effect found. However, reading accuracy did not affect caffeine intake; participants obtained a similar reading error score in caffeine and placebo conditions. This could be because the experimental sample consisted mostly of university students, who are assumed to have high reading accuracy already. Obtaining a variation due to the intake of any substance might be difficult, given the already optimal starting conditions.

Instead, the results obtained in text reading speed could depend on improvement in all other abilities underlying contextual reading, namely an increase in text comprehension and, thus, the ability to make inferences about the meaning of what is read through greater context processing and involvement of broader and more widespread semantic fields. This data aligns with studies that have found improved performance in verbal comprehension tasks following caffeine intake (Haskell et al., 2005; Warburton et al., 2001).

Another possible explanation is that caffeine improves text reading speed and semantic association by enhancing global perception and salience processing skills. In fact, in addition to the description of the implications of global processes during reading, it has been described how children with DD have been found to have a causal connection between the lack of precedence of global perception over local perception and some reading deficits (Franceschini et al., 2017; 2021), and specific training to improve global perception has also improved reading skills (Franceschini et al., 2017; Marsicano et al., 2021). It has also been described how caffeine improves some global processes (Brunyé et al., 2012; Franceschini et al., 2020; Giles et al., 2013; Mahoney et al., 2011). This data could be supported by the results obtained in the study by Franceschini and colleagues (2020), in which the same improvement in the text reading test was associated with an improvement in global perception (Navon task) following caffeine intake. At the same time, previous studies in this thesis have demonstrated the role of the SN in automatic reading and phonetic skills in children and adults. Specifically, the enhancement following the caffeine intake confirmed the improvement associated with the major psychophysiological activation of fun in the speed of the same text reading in a different sample of young university adults (Study 6). Moreover, note that the improvement we found in text reading, considered the most ecological and automatized test, is in line with children's data in reading-related tasks that less than the others involve executive control (i.e. word reading and phonemic perception in school and preschool children, respectively; Study 4 and Study 5).

Another interpretation provided for the found effect is the possible right lateralization common to processes underlying contextual reading, global processing and perception, and neural and cerebral effects resulting from caffeine intake. Regarding contextual reading, linguistic context seems to be processed more in the right fronto-parietal areas (Bastiaansen et al., 2010; Lam et al., 2016; Roman et al., 1987). In the right hemisphere, there are also broader and more widespread semantic fields than those present in the left hemisphere (Jung-Beeman, 2005), so there is a greater chance that many different concepts could be active for a longer time semantically overlap, explaining the role in context processing. The right hemisphere could therefore have a greater capacity for integrating the global meaning to be attributed to the text read (St George et al., 1999). This is possible through the use of inferences, of which an important role of the right hemisphere has been recognized (Beeman, 1994; Jung-Beeman et al., 2000; Powers et al., 2012). Reading comprehension is linked to all the processes mentioned, and evidence related to it has typically been associated with the right hemisphere (Horowitz-Kraus et al., 2015; Horowitz-Kraus et al., 2014a; Horowitz-Kraus et al., 2014b). In the same studies, a right-lateralized circuit has been hypothesized that predicts greater activation of the right hemisphere's fronto-temporo-parietal areas (inferior longitudinal fasciculus, inferior frontal-occipital fasciculus, uncinate fasciculus, extreme capsule, middle longitudinal fasciculus, superior longitudinal fasciculus, arcuate fasciculus, and frontal aslant tract) during tasks related to contextual reading (see Shekari & Nozari, 2023 for a recent narrative review). Furthermore, it is possible that the aforementioned areas that have been hypothesized to be more activated by caffeine coincide or partially overlap with the areas of the right ventral fronto-temporo-parietal circuit hypothesized and described by the Corbetta and Shulman model (2002). In their model, researchers postulate that visual attention is controlled by two partially segregated networks. One network is bilateral and located dorsally, underlying endogenous orienting, and thus voluntary attention processes guided by goals and internal stimuli through top-down processes (DAN). The other network is located ventrally and lateralized to the right, underlying exogenous orienting and thus the automatic capture of attention guided by sensory stimuli through bottom-up processes (VAN). Therefore, it is possible that caffeine, through its stimulating effects on the right hemisphere, has caused greater activation of this latter network, rebalancing the action of the two attentional systems.

In addition to skills closely related to contextual reading, many studies have found right lateralization for global perception and processing skills (Bardi et al., 2010; Gable et al., 2013; Lamb et al., 1990; Lux et al., 2004; Robertson et al., 1988; Volberg & Hübner, 2004). Finally, it seems that some of the processes that are most increased by caffeine also exhibit greater right lateralization (Koppelstaetter et al., 2008; Lorist & Snel, 1997), such as general arousal (not related to caffeine) (Heller et al., 1995; Kheirkhah et al., 2021; Morrow et al., 1981; Zoccolotti et al., 1986) and the activity of the neurotransmitter systems of NA, 5-HT and DA (Arato et al., 1991; Larisch et al., 1998; Oke et al., 1978).

In summary, the study, utilizing a double-blind, repeated-measures design, confirmed the positive impact of caffeine on reading speed and provided insights into potential cognitive and neural mechanisms. The discussion included hypotheses about the right lateralization of caffeine effects and the SN-CEN and/or VAN-DAN interplay, emphasizing the importance of neuroimaging techniques for validation. Additionally, the study addressed the influence of caffeine on emotions, highlighting an increase in tension during the session and a positive effect on the perceived enjoyment of a game. These findings contribute to a more comprehensive understanding of how caffeine affects both cognitive and emotional aspects, providing valuable insights for future research in this domain.

Chapter 5. Effect of Lexilens ® Glasses on Reading Enhancement Modulation

Introduction

Developmental dyslexia (DD) is the more frequent specific learning disorder in which a severely invalidating learning disability affects literacy acquisition despite normal intelligence and adequate instruction (APA, 2013).

Although reading skills are normally distributed as a continuum, the different cut-offs established in different countries lead to estimates that about 5-10% of children are diagnosed with DD. This means that in a typical school class composed of 20-25 children, at least one-two children will show difficulties in the development of reading skills and need intervention. Thus, the identification of training useful for reading improvement in people with DD is compulsory. At a clinical level, it is necessary to improve the quality of life of children with DD, using the most effective and least expensive tools in terms of time and money. To do that, it is necessary to identify all the factors that can make the treatment more effective and efficient.

Moreover, intervention studies are considered the strongest test of causation (Goswami, 2015). To demonstrate causality driven by the cognitive and sensory process, an active control group receiving a matched training, specifically omitting the key variable, must show smaller or no beneficial effects from the training.

Galuschka and colleagues conducted a comprehensive review and meta-analysis about the effectiveness of multiple interventions for DD remediation (Galuschka et al., 2014). Data were collected for treatments targeted to train phonemic awareness, phonics instruction, reading fluency and comprehension, and auditory processing, as well as medical treatments and coloured overlays. Overall, the meta-analysis demonstrates that, among those examined, none but one training appeared effective. Although most of them showed similar effect size, only phonic instruction demonstrated a small but statistically significant clinical effect (g=0.322; 95% CI: 0.177-0.467; Galushka et al., 2014). This evidence has confirmed phonic instruction treatment as the gold standard (but Bowers, 2020). Specifically, direct and intensive phonological training about letter-to-speech-sound correspondence or larger sub-syllabic units (Lowett et al.,1994; 2000) could induce beneficial effects on reading skills if compared to the effect of training with identical duration (e.g., 35 hours) that mixed instruction on classroom etiquette, life skills, organizational strategies and self-help techniques, or compared to training in mathematics and general academic survival (Lowett et al.,1994; 2000), or also compared to the effects of remaining in the classrooms and receiving the as usual reading instruction provided by the school (Bhattacharya & Ehri, 2004). Nevertheless, if remediation treatments that involve different experimental reading techniques, i.e. phonics instruction vs. word identification strategy training, are compared together, differences are negligible (Lowett et al.,1994; 2000; see Bowers 2020 for a review). It may be interesting to note that by the definition of DD in DSM-5, a training based on phonology must not be too beneficial, otherwise, it would prove to have done a wrong diagnosis (criterion A DSM-5: "difficulties in … despite targeted help"; APA, 2013 pag. 77).

These results at clinical level indicate that DD could be partially ameliorated, but do not allow us to understand the key cognitive variable that generated the observed result. As described by Simons and colleagues (Simons et al., 2016; Boot et al., 2013) in psychological interventions, participants typically know which treatment they are receiving. In the case of training for DD - especially if reading strategies are supposed to be the key for reading remediation - participants undergoing experimental training are aware that they are receiving reading treatment and are likely to expect - at least in the first period of interventions (Gaab & Petscher, 2022) - to improve as a result. These positive expectancies could be probably larger than those originated by receiving classroom etiquette and life skills instructions, math training or nothing.

Discussing the null results of coloured overlays, Galuschka and colleagues (2014) defined the importance of expectancy in reading training. These lenses seem to show a significant effect if the experimental group's performance were compared to an untreated-passive control group. However, the effect became negligible when compared to those of a group that used placebo lenses. Importantly, these data could suggest that at a clinical level, DD could be ameliorated on the fly by manipulating expectancy, and allows us to hypothesize - at the experimental level - that reading improvements could be obtained by manipulating emotional and motivational aspects in participants. Accordingly, recent studies have shown that psychophysiological activation linked to positive emotion can significantly change reading performance in children with and without DD (Franceschini et al., 2022; Johann & Karbach, 2020). In addition, changes in positive emotions correlated with contextual reading enhancement also in healthy young adults (Franceschini et al., 2022; see Anguera & Gazzaley, 2015 for a review).

Placebo effect in cognitive interventions

The placebo effect is recognized as a powerful determinant of health across many different diseases and encounters (see Wager & Atlas, 2015 for a review). The placebo effect can be conceptualized as the product of a general positive expectancy learning mechanism in which verbal and social conditioned cues are centrally integrated, producing changes in behaviours and outcomes (Petrie, 2019; Colagiuri et al., 2015). Previous experiences of the participant with (real or supposed) elements of the environment in which the effect of a substance/training/tool induced modification in the interaction between the participant and the substance/training/tool, altering the behavioural outcome.

In sports and academic contexts, and especially in clinical treatments, from pain to immunosuppression and also in the presence of neurodevelopmental disorders like attention deficit hyperactivity disorder, the induction of positive expectations seems to improve the outcomes of participants (Schwarz, et al., 2016; Weimer et al., 2013; Benedetti, 2014; Colagiuri et al., 2015). Age of participants seems to influence the induction of placebo effect: despite little is known about placebo effect in children (see Weimer et al., 2013 for a review), training expectation appears to produce larger effects in children younger than 12 years as compared with children older than 12 years (Bridge et al., 2009) or adults (Weimer et al., 2013). However, as indicated by multiple studies, positive expectations induce modification in perception and behaviour also in adulthood, demonstrating that a wide range of situational and personal factors, and not only age, could drive the appearance of the effects (see Colagiuri et al., 2015; Petrie & Rief, 2019; Schwarz et al., 2016; Wager & Atlas, 2015 for a summary of perspectives on the topic).

Few studies investigated the effects of placebo on complex cognitive abilities. Foroughi and colleagues (2016) designed a procedure to intentionally induce a placebo effect in order to evaluate the role of placebo effects in fluid intelligence gains induced by cognitive training. Individuals who self-selected into the placebo group showed improvements after a single session of cognitive training, whereas controls showed no improvement. Parong and colleagues (2022) showed that positive expectations of training can induce beneficial effects on multiple cognitive abilities, regardless of whether having participated in an effective working memory or a control training. They confirmed that independently from expectancy, the working memory training improved working memory skills (see also Tsai et al., 2019). Amazingly, training associated with positive expectations, regardless of their content, produced improvements in a broader set of cognitive skills than the working memory training designed to improve cognitive skills. In particular, the improvements were observed in measures of fluid intelligence, cognitive flexibility and working memory. Most of the effects disappeared when participants were fully debriefed regarding the study's true purpose. Cognitive functions like spatial cognition and visual selective attention were not influenced by positive expectations associated with working memory training (Parong et al., 2022; Vodyanyk et al.,2021). However, in these studies, no direct or indirect manipulation of positive expectations about spatial cognition and visual selective attention was applied, not excluding that, for example, the use of special glasses can also affect these domains. Indeed, recent research, including a single case study, showed that by the use of flickering glasses for DD, the participant showed a placebo effect in reading skills, paving the way to demonstrate a role of positive expectation on reading outcomes (Lubineau et al., 2023). Flickering glasses for DD remediation, created to manipulate users' visual perception by periodically refreshing bottom-up visual inputs, if tested using double-blind research design, could allow us to measure both the effects of glasses themselves. The empirical demonstration of the effects of expectancy on reading performance should be crucial as a yardstick for the efficacy and efficiency of reading training programs.

Flickering glasses for DD

Multiple causal factors, such as visual perception and attention, could be at the basis of reading difficulties in children and adults with DD (see Hari & Renvall, 2001; Shaywitz & Shaywitz, 2008); Vidyasagar & Pammer, 2010; Gori & Facoetti, 2014; Stein & Walsh, 1997; Grainger et al., 2016; Laycock & Crewther, 2008; Peters et al., 2019 for reviews).

An alternative, even if debated (Lubineau et al., 2023), visuo-perceptually based theory sustains that many of the reading difficulties observable in children and adults with DD could be due to the peculiar structure of the foveal Maxwell spot centroids (Le Floch & Ropars, 2017). In particular, an eye dominance disorder in people with reading difficulties can produce a cascade noise effect in the perception of mirror-image letters along the vertical line, such as the "b" and the "d". Nevertheless, as the authors note, the neurological basis of reversal shape/letter perception remains unknown (Le Floch & Roapars, 2017; but see Priftis et al.Rusconi & Priftis, 2003). In response to this hypothesized visuo-perceptual deficit in individuals with DD, commercial glasses that should neutralize the mirror image by the use of flickering lenses have been developed (https://abeye.tech/lexilens/). The wearer of the glasses - observing a text - has to tune the frequency (60-120Hz range) with which the lenses flicker and its luminance level.

Although low-frequency light flickering at about 10Hz results in an improvement in some perceptual diseases in single case studies (see Lubieneau et al., 2023 for a recent review), in two different experiments, Lubieneau et al. (2023) showed that 10 and 15 Hz computer screen flickering compared to the no flicker condition impaired lexical decision response time for written words in healthy adults and did not modify the performance of children with DD. Unfortunately, the commercial flickering glasses for DD do not include 10 and 15 Hz frequencies.

For the evaluation of the effects of flickering lenses in children with DD, despite the possibility to regulate the Hz rate, Lubieneau et al. (2023) imposed for all the participants a frequency of 80 Hz. Compared to daylight conditions, neither in case of glasses turned off, nor turned on, word and text reading skills, as well as sentence comprehension, resulted to be different (Lubieneau et al., 2023). These results largely contradict the evidence obtained by interviewing users of these expensive glasses for DD, of which 86% indicated having academic improvements (https://abeye.tech/lexilens/ 16/6/2023). Based on these data, people who wear glasses in the most suitable tuning condition for them could improve their performance and discrimination of shapes, mainly of mirror-image letters, producing improved performance in reading and text comprehension.

Overall Aim and Study

The first aim was to investigate the presence of the placebo effect on reading skills, while the second one was to evaluate the possible reading effectiveness of glasses for DD remediation, manipulating the frequency of flickering lenses.

The positive expectations regarding the glasses for DD should enhance attentional processing resources, improving reading performance. In particular, the positive expectations could facilitate the processing of the noisy letter-string sensory information, inducing a goal-directed attentional bias towards orthographic visuo-perceptual information stored in the specialized ventral occipitotemporal network, i.e. the visual word form area (VWFA; see Dehaene & Cohen, 2011 for a review). Accordingly, a recent study has shown that words evoke much larger VWFA responses when the task is relevant than when it is ignored, suggesting that reading effort evokes communication between language areas and the VWFA by targeted frontal and parietal excitatory feedback (White et al., 2023). Indeed, several studies have investigated the functional connectivity of the VWFA and found that it is highly correlated with frontal language regions (Koyama et al., 2010, 2011; Li et al., 2017, 2020), parietal goal-directed attention regions (Vogel et al., 2012) or both (Wang et al., 2014; Zhou et al., 2015; Chen et al., 2019). Recent findings suggest that this word-selective cortex includes two distinct subregions: the more posterior VWFA-1 is sensitive to visual features, while the more anterior VWFA-2 processes higher-level language information. Interestingly, VWFA-1 is more strongly correlated with bilateral visual regions including ventral occipitotemporal cortex and posterior parietal cortex (Yablonski et al., 2023). In contrast, VWFA-2 is more strongly correlated with language regions in the frontal and lateral parietal lobes (Yablonski et al., 2023). Thus, the top-down expectations could impact both the phonological pseudoword decoding and lexical-word reading because the VWFA stores both visual features and language representations of the letter strings.

In the first experiment, the effect of positive expectation on reading performance was tested in primary and secondary school children with a diagnosis of DD. In the second replication experiment, the hypothesis was tested on typical and poor readers young adults.

Regarding the second aim, in the first experiment, we tested the hypothesis that glasses for DD, individually tuned in frequency and luminance as indicated by each child with DD, could ameliorate their perceptual reading abilities. In the second experiment, we tested if tuned glasses for DD at the extreme lowest and highest of the flickering frequency could modify reading performance.

Study 8. Expectation-Driven Placebo Effect Enhances Reading Performance

Abstract

The more frequent neurodevelopmental disorder is the specific learning disorder of reading or developmental dyslexia (DD). Traditional remediation programs for DD are rarely controlled for the placebo effect, suggesting that positive expectations might explain their efficacy. Indeed, the users of expensive flickering lenses for DD report extraordinary reading findings. The effectiveness of these glasses and their possible placebo effect on reading performance were tested in a double-blind within-subject experimental design in children with DD (n=49) and young adults (N=48). The flickering frequency of individually tuned glasses predicted phonological decoding speed and tuned lenses showed a mild effect on pseudoword decoding speed in children with DD. Expectancy improved word reading accuracy in younger children with DD, with a larger effect size than the gold-standard training programs. This improvement was replicated in adult poor readers, whereas typical readers improved in pseudoword decoding speed. Placebo-driven reading enhancements could support the effective behavioural, pharmacological and neuromodulation training for DD.

5.1 Experiment 1: The effect of flickering glasses in children with DD.

5.1.1 Materials and Methods

Participants

The study involved 49 children (34 males and 15 females) native Italian speakers with DD diagnosis. Twenty-nine children attended primary school (M=9.49 years old; SD=0.92 years), 20 the secondary school (M=12.67y.o.; SD=1.03); all participants received DD diagnosis by the Italian National Health Service according to APA's inclusion and exclusion criteria (i.e. DSM-5; 2013). No sensory deficit (auditory, visual, or motor) or cognitive impairments (such as language disorders, neurological disability, ADHD or autism spectrum disorders) were reported.

Participation in the study was voluntary after both parents or those who had parental control over the child signed. The procedure and the goals for data collection were made explicit on the form that was given to adults.

The University of Padua's Ethics Committee approved the study, which was written per the European Union Standards of Good Clinical Practice (research protocol number: 4963).

Procedure

The study included a single evaluation time characterized by 3 experimental sessions of about 20 minutes; therefore, each child was involved in an hour. The order of presentation of the 3 experimental sessions was counterbalanced and assigned to each participant by a computerized generator. Laboratory illumination was provided with light bulbs (100 watts) near the table and a PC without a polarized screen to ensure excellent illumination that did not interfere with flickering lenses and to avoid external noise that could create clues to identify the conditions.

Before each meeting all children were informed in the same way by reading the following text: "We will test three times, one of which should absolutely work, and the other two of which you must tell me if one works better than the others. I'll combine the times; just know that when we test the condition, it should work. The other two conditions will be referred to as "Blue" and "Green", which are fictitious names. At the end of the experiment, I'll ask you to rate which of these two situations you thought was the best. All right? Remember that there is no judgment on your tests; at the moment, it is just important to analyze whether these glasses can assist children reading and how; as a result, I will record your performance times and errors."

Specifically, the "Blue" session delineated the child's baseline cognitive functioning and represented the control condition; the "Green" session was the experimental condition and allowed us to evaluate the real effectiveness of the Lexilens® glasses. Facts, in this specific condition, the glasses were felt according to what the child's preferences were, as suggested by the manufacturer. Finally, in the Placebo session, the glasses were off, as well as in the Blue session, but participants were told that that was the calibration that would surely work, so as to induce high expectations in participants.

The study was conducted in double-blind: the experimenter who manipulated the glasses to the child was not the same one who then evaluated the cognitive effects of the Lexilens®. "Blue" and "Green" labels thus made it possible not to bias the experimenter who administered and corrected the tests or even the experimenter who then analyzed the data: in fact, even the analysis phase was conducted blind.

Each child was associated with an alphanumeric code consisting of a sequential number from 1 to 47 and the initials of the name.

The phases of experimental data collection were the following:

1) Flickering Frequency and Brightness Glasses Calibration: the speed (or "Vitesse"; 60-120Hrz range, represented as -20+40 values on the box screen) and "Balance" (-5;+5 range) parameters that could be changed by the external box knobs were governed by two staircases in order to define the better calibration of glasses flickering frequency and brightness respectively. The child was handed a text-filled paper sheet, and the experimenter then provided a detailed explanation of customized glasses calibration. The regulation was managed by the researcher who was not blinded to the experimental condition (see "Instruction for Glasses Calibration" for more details).

2) Setting of the experimental condition (Green, Blue or Placebo) by the experimenter manipulating the glasses

3) Reading abilities assessment (word list reading; pseudoword list reading; text reading - only in the experimental and control sessions-) and letter discrimination assessment in specular and/or not specular stimuli (computerized task). Immediately after the neuropsychological assessment, the

experimenter who tested the child proposed the self-assessment questionnaire on reading performance.

Phase 2) and 3) repeated and succeeded each other 3 times (See Figure 50 for a graphical description of the experimental timeline).

Figure 50. Schematic representation of the timeline of Study 8.

Neuropsychological battery

Reading Abilities

1. Word List Reading (adaptation from Batteria De.Co.Ne. per la lettura, Franceschini et al., 2016)

The word reading task assesses the participant's lexical skills by administering lists of words from the spoken language. The child is specifically requested to read aloud a list of words that are longer, shorter, and more or less common in everyday language (and hence familiar to the participants) as rapidly and precisely as they can. Each of the three lists included 53 words, for a total of 119 syllables each, which were balanced for difficulty and usage frequency. The amount of time spent reading and the mistakes committed were then measured for each list: a mistake was recorded for every word misread without spontaneous self-correction.

Three different versions of the test can be found in the Appendix Section.

1. Pseudoword List Reading (adaptation from Batteria De.Co.Ne. per la lettura, Franceschini et al., 2016)

The nonsense word lists used in the pseudoword reading test are used to assess the participant's sub-lexical skills. The child is instructed to read aloud a list of pseudowords of varying lengths as quickly and precisely as possible. Each of the three lists contained 34 pseudowords, with 100 syllables per list.

The time spent reading and the errors made were then calculated for each list: each pseudoword read incorrectly without spontaneous self-correction was counted as one error.
Three different versions of the test can be found in the Appendix Section.

2. Text Reading (Judica & De Luca, 1993)

The passage reading test assesses lexical, sub-lexical, semantic, and comprehension skills, assessing every day reading difficulties. Participants read two texts with 218 syllables each, recording reading speed and errors. A misread word was counted as one error regardless of the number of incorrect letters or syllables pronounced; spontaneous self-correction was counted as a 0.5 error. (See the Material Section of Study 3 for more details).

Letter Discrimination Task

This computerized task is used to evaluate specular or not specular letter discrimination abilities in the 3 different experimental conditions (glasses on, glasses off, Placebo condition).
The experiment and task data were collected with E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA), running on a 13-inch laptop (1024x768). In this task, participants were seated at 60cm from the screen and presented with an initial central fixation point on a grey screen (300 milliseconds). Then fixation vanished, and two letters (font: Calibri, size: 0.5x0.5°) appeared on the screen's horizontal axis in foveal or parafoveal (0.5° and 5° of visual angle, respectively). In the Specular state, letters could be a couple of "b" and/or "d" and a couple of "i" and/or "o" in the Non-specular condition. Participants were required to identify whether letters were identical or not using keyboard keys ("N" and "P" correspondingly). For 1000 milliseconds following the response, a green (for correct response) or red (for incorrect response) fixation point appears. A total of 96 experiments were conducted. Ten trials were provided prior to the start of the experimental session to familiarize the children with the task. Mean response time and accuracy were analyzed for a total of 96 trials (See Figure 51 for the task timeline).

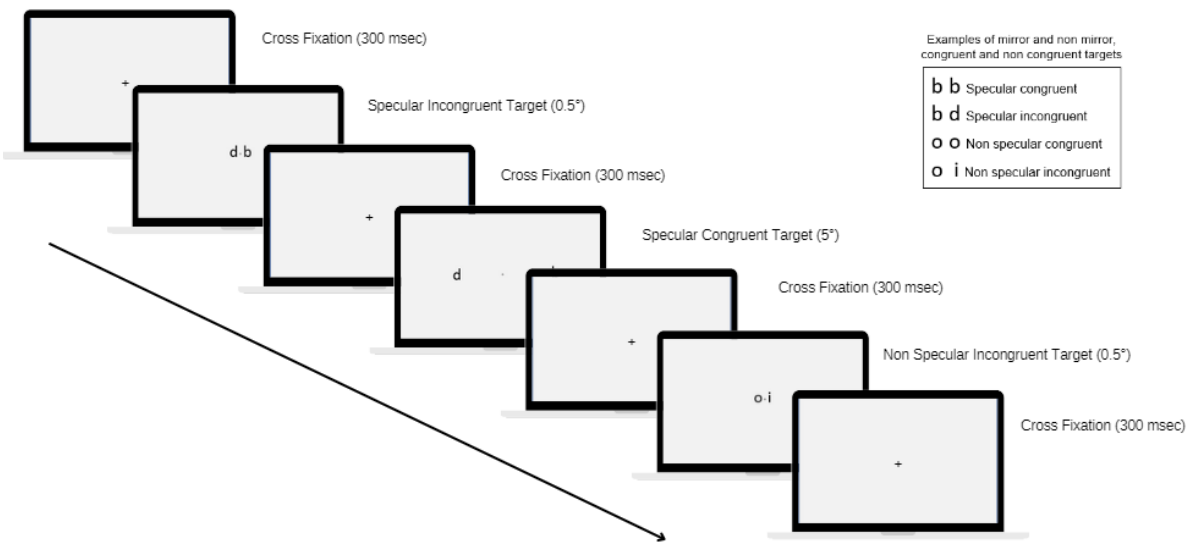

Figure 51. Representation of the letter discrimination task used. Specular and non specular letters alternated within the trial in a randomized pattern. The space of the letter could be small (0.5°, first and third examples representation) or large (5°, second example representation).

Self-Evaluation Questionnaire

Four questions were given to the participants at the end of the experiment. It was stated to them that they needed to assess their performance in the experimental (glasses on) and control (glasses off) conditions. The administrator then answered these four questions in the following order:

1. Which of the two reading sessions with the experimental glasses did you believe you read better?
2. Which of the two reading sessions with the experimental glasses did you believe you comprehended the passage's text better?
3. Which of the two glasses conditions did you think the computer task to be easier?
4. Which of the two moments do you believe the glasses were set in the most appropriate way for you?

Possible responses were only Green or Blue conditions.

Lexilens ® Glasses

According to the manufacturer's website, “Lexilens® looks like an ordinary eyewear with embedded electronics and battery. These control the active filters that enable a smoother reading with less effort. Lexilens® filters out the parasite images and instantly makes the reading easier. While doing so, the cognitive load once allocated to deciphering is now allocated back to comprehension. All Lexilens users confirm: the text appears clearer and is instantly meaningful. This enables them to not only read with less effort but also to memorize better with strong impact on reading performance and overall self-confidence" ("How does Lexilens® work?" Section on https://lexilens.com/sciences/).

Glasses appear as normal dark-lensed sunglasses, adjustable in brightness and flickering frequency (see "Instruction for Glasses Calibration" for more details). The two models used in the present research were identical to each other, except for the presence of a cable connecting to the external box. Specifically, the experimenter calibrated the glasses with the cable according to the child's requests (as suggested by the manufacturer) in the Experimental condition and the Control condition (glasses off). On the other hand, the second pair of glasses had no external cables and was always off (Placebo condition). See the procedure section for a detailed description of the experimental design.

Instruction for Glasses Tuning

The flickering speed (or "Vitesse") was controlled by a staircase with sixteen levels (+/- 20; 15; 10; 8; 6; 4; 2; 1) on the box scale. In this scenario, the experimenter let the children choose the beginning flickering value after explaining how the spectacles worked as described in the box's handbook and then applied the staircase from there. At each staircase step, the children had to pick between the previous value and the new calibration value. The picked one became the new beginning point for the following stairwell step.

The brightness (or "Balance") was controlled by a four-step staircase (+/ 2;-1). In that case, a child began by selecting either 0 or -3 as the starting point for the staircase application.

5.1.2 Results

First aim: Placebo effect (placebo vs. glasses off conditions)

Word and Pseudowod Reading Performance

Both reading accuracy (number of errors) and reading speed (time in seconds) were analyzed by using a mixed ANOVA with a 2 x 2 x 2 design. The within-subject factors were the Task (word and pseudoword) and Condition (placebo and control), while the between-subject factor was the School grade (primary and secondary school children).

Reading Accuracy

The results of the ANOVA on errors show the significant main effects of Task ($F_{(1.47)}$=125.692, p<.001) and School grade ($F_{(1,47)}$=11.821, p=.001). Interestingly, Task x Condition x School grade interaction was significant ($F_{(1,47)}$=9.303, p=.004). Two separate ANOVAs were executed on word and pseudoword errors.

The ANOVA on the word errors showed a significant effect of School grade ($F_{(1,47)}$=9.551, p=.003) and a significant Condition x School grade interaction ($F_{(1,47)}$=8.107, p=.007). Planned comparisons showed that primary school children in the placebo condition committed fewer errors (M=4.00, SD=3.56) compared to the control condition (M=5.50, SD=4.27, p=0.013, Cohen's d=-0.610, 95%CI=-1.082/-.124). In contrast, in secondary school children, the difference between the two conditions was not significant (p=0.375, Cohen's d=.168, 95%CI=-.200/.533). Interestingly, whereas the difference between primary and secondary school children was significant in the control condition (p<0.001 Cohen's d=1.123, 95%CI=0.505/1.731), the two groups were not significantly different in the placebo condition (p=0.071 Cohen's d=0.536, 95%CI=-0.046/1.113; see Figure 52 and Table 12 for more details).

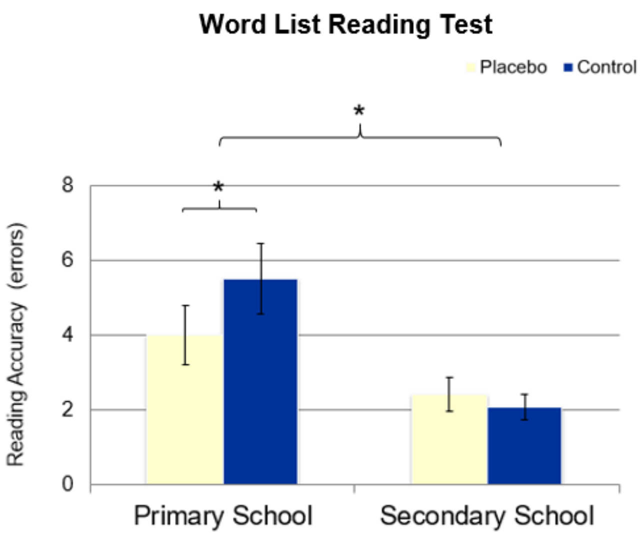

Figure 52. Performance of children attending the primary (left side) and the secondary school (right side) in word reading list accuracy. Data are reported as means ± standard errors. The asterisks indicate significant differences.

In the ANOVA on the pseudoword errors, only the main effect of Age was significant ($F_{(1,47)}$=9.277, p=0.004). No other main effect or interaction was significant (all ps>0.063).

Reading Time

The same ANOVA with a 2 x 2 x 2 carried out on reading time (in seconds) shows the main effects of Task ($F_{(1.47)}$=34.344, p<0.001), School grade ($F_{(1,47)}$=26.128, p<0.001) and their significant interaction ($F_{(1,47)}$=20.609, p<0.001). Specifically, planned comparisons showed that in primary school children, there was no difference between word and pseudowords reading times (M=101.18sec, SD=26.42 and M=104.38, SD=21.14, respectively; p=0.481; Cohens'd=0.161, 95%CI=-0.600/0.283), whereas a significant difference was found in secondary school children between words and pseudowords (p<0.001; Cohens'd=-1.794, 95%CI=-2.380/-1.195): as expected, reading times for words are significantly shorter than those for pseudowords (M=58.54 sec, SD=20.56 and M=83.74 sec, SD=23.58, respectively). No other main effect or interaction was significant (all ps>0.632).

	Primary school (n=20)			Secondary school (n=29)		
	Placebo	Control	Tuned glasses	Placebo	Control	Tuned glasses
Word reading errors (number)	***4.00 (3.55)**	**5.50 (4.27)**	5.65 (3.94)	2.41 (2.47)	2.07 (1.81)	1.45 (1.40)
Pseudoword reading errors (number)	11.20 (3.94)	9.85 (4.57)	11.00 (4.91)	6.79 (3.94)	7.31 (4.58)	6.52 (3.75)
Word reading time (seconds)	100.33 (29.10)	102.03 (25.33)	105.25 (26.13)	58.75 (21.35)	58.34 (20.70)	59.26 (19.54)
Pseudoword reading time (seconds)	103.68 (19.32)	105.08 (23.13)	96.86 (25.55)	82.44 (23.97)	85.04 (26.18)	83.19 (21.83)

Table 12. For the three conditions, the mean and standard deviation of accuracy (number of errors) and speed (time in seconds) for word and pseudoword reading lists in primary and secondary school children. The asterisk indicates a significant difference between the placebo and control (glasses off) conditions.

Letter Discrimination Task

The accuracy (rate) and response time (msec) of the computerized letter discrimination task were analyzed by using two mixed ANOVA with a 2 x 2 x 2 x 2 design. The within-subject factors were the Letter type (specular and non-specular), Letter location (foveal and parafoveal position) and Condition (placebo and control). In contrast, the between-subject factor was the School grade (primary and secondary school children).

Accuracy

The main effect of Letter location ($F_{(1,47)}$=4.588, p=.037), Letter type, ($F_{(1,47)}$=61.581, p<0.001), their interaction ($F_{(1,47)}$=6.090, p=0.017), as well the main effect of School grade ($F_{(1,47)}$=11.265, p=0.002) were significant. The main effect of the Condition or other interactions were not significant (all ps >0.151; see Figure 53, panel A).

Response time

The main effect of Letter location ($F_{(1,47)}$=26.123, p<0.001) and Letter type ($F_{(1,47)}$=30.989, p<0.001) were significant. The main effect of the Condition or other interactions were not significant (all ps>0.094; see Figure 53, panel B).

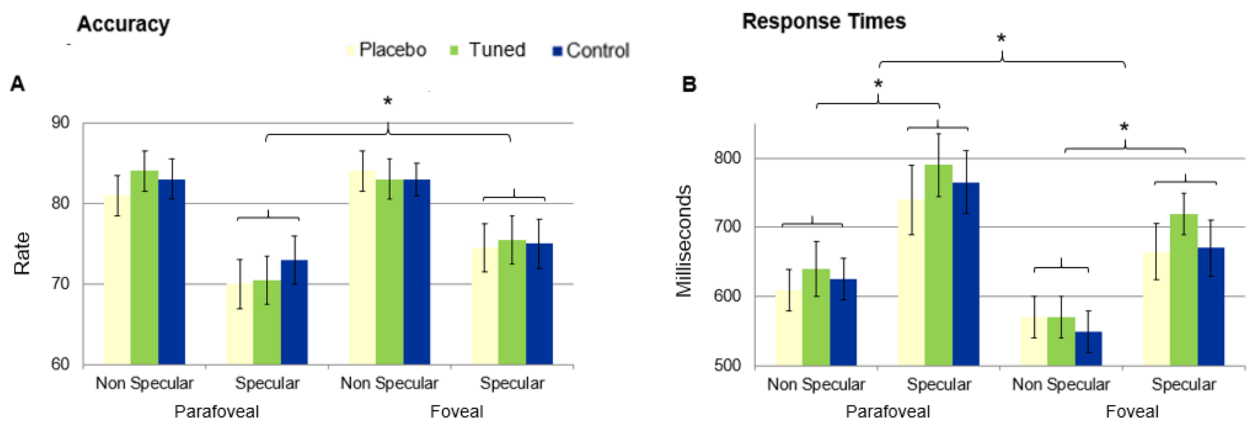

Figure 53. Accuracy (A) and response times (B) of children in the letter discrimination task in the three conditions (placebo, glasses tuned and control) in foveal and parafoveal position and in specular and non-specular stimuli. Data are reported as means ± standard errors. The asterisk indicates a significant difference.

Second aim: Glasses effect (glasses on vs. glasses off)

Word and Pseudoword Reading Performance

Reading accuracy (number of errors) and reading time (in seconds) were analyzed by using two mixed ANOVAs with a 2 x 2 x 2 design. The within-subject factors were the Task (word and pseudoword) and Condition (tuned and control), while the between-subject factor was the School grade (primary and secondary school children).

Reading Accuracy

The main effects of Task ($F_{(1.47)}$=129.482, p<0.001) and School grade ($F_{(1,47)}$=18.190, p<0.001) were significant. No other main effect or interaction was significant (all ps>0.086, see Table 12).

Reading Time

The main effects of Task ($F_{(1.47)}$=15.997, p<.001), School grade ($F_{(1,47)}$=25.056, p<.001) and their interaction ($F_{(1,47)}$=24.421, p<.001) were significant. Interestingly, the Condition x Task interaction ($F_{(1,47)}$=5.534, p<0.023) was also significant. Specifically, the planned comparison showed that no significant differences were found neither in word reading time (tuned M=78.03seconds, SD=31.22 and control M=76.18, SD=31.22; p=0.419; Cohen's d=-0.116, 95% CI=-0.397/0.165) nor in pseudoword (tuned M=88.77seconds, SD=22.92 and control M=93.22, SD=27.73; p=0.066; Cohen's d=0.269 95% CI=-0.017/553). Comparing the reading time spent in word vs pseudoword reading (i.e., lexicality effect), we found that the differences were both significantly different, but effect size in the control condition (p<0.001, Cohen's d=-0.755 95% CI=-1.070/-.434) was more than double compared to tuned condition (p=0.013, Cohen's d=-0.371 95% CI=-0.658/-0.079; see Figure 55), showing that in the tuning of flickering lenses induced a tendency toward a faster phonological decoding and slower lexical access. No other main effect or interaction was significant (all ps>0.158; see Table 12).

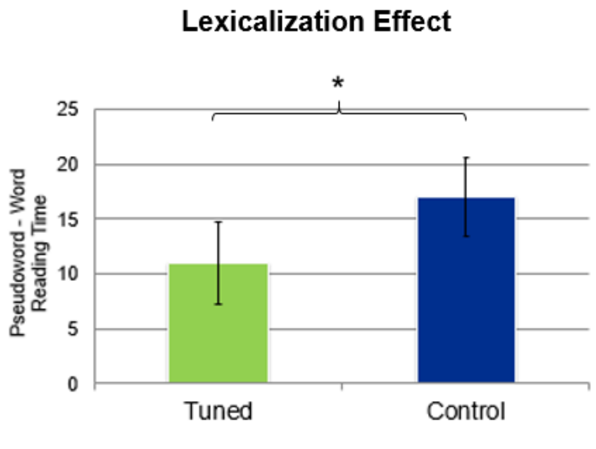

Figure 55. Delta score between pseudoword and word list reading time (in seconds). Data are reported as means ± standard errors. The asterisk indicates a significant difference.

Text Reading Performance

Two mixed ANOVAs with a 2 x 2 design were executed using the reading accuracy (number of errors) and reading time (seconds) as dependent variables. The within-subject factor was the Condition (tuned and control), while the between-subject factor was the School grade (primary and secondary school children).

Reading Accuracy

The main effect of School grade was significant ($F_{(1.47)}$=20.799, p<0.001). Also, the main effect of the Condition was significant ($F_{(1,47)}$=4.803, p=0.033), showing that in the tuned condition, children with DD committed more errors compared to the control ones (M=9.25; SD=4.30 and M=8.10 SD=4.82, respectively; Cohen's d=-0.257 95% CI=-0.497/-0.017; see Figure 56). However, School grade x Condition interaction was not significant (p=0.116; see Table 13).

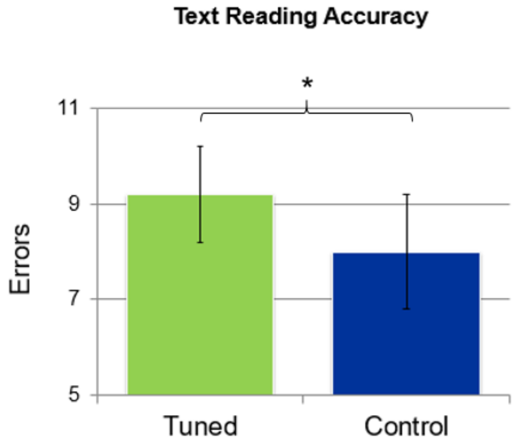

Figure 56. Accuracy of children (number of errors) in word text reading in tuned and control conditions. Data are reported as means ± standard errors. The asterisk indicates a significant difference.

Reading Time

The ANOVA show only a significant main effect of School grade ($F_{(1,47)}$=41.917, p<0.001). No other main effect or interaction was significant (all ps>0.477).

	Primary school (n=20)		Secondary school (n=29)	
	Tuned	Control	Tuned	Control
Text reading errors (number)	12.40 (4.99)	10.40 (6.45)	6.10 (3.61)	5.79 (3.08)
Text reading time (seconds)	182.74 (57.57)	180.53 (45.23)	104.02 (29.57)	105.76 (37.04)

Table 13. Mean and standard deviation of accuracy (number of errors) and speed (time in seconds) in word text reading divided for primary and secondary school children.

Letter Discrimination Task

The accuracy (rate) and response time (msec) of the computerized letter discrimination task were analyzed by using two mixed ANOVA with a 2 x 2 x 2 x 2 design. The within-subject factors were the Letter types (specular and non-specular), Letter location (foveal and parafoveal) and Condition (tuned and control), whereas the between-subject factor was the School grade (primary and secondary school children).

Accuracy

The main effect of Letter location ($F_{(1,47)}=4.762$, $p=0.034$), Letter types, ($F_{(1,47)}=63.358$, $p<0.001$), their interaction ($F_{(1,47)}=10.788$, $p=.002$), as well the main effect of School grade ($F_{(1,47)}=14.732$, $p<.001$) were significant. The main effect of Condition and interactions were not significant (all ps>0.133; see Figure 53, panel B).

Response Time

The main effect of Letter location ($F_{(1,47)}=23.501$, $p<0.001$) and Letter types ($F_{(1,47)}=42.376$, $p<0.001$) were significant. No other main effect or interaction was significant (all ps>0.152).

Self Evaluation Questionnaire

For each of the four questions, a series of binomial analyses separately for primary and secondary school students were conducted. The expected response distribution between Tuned (glasses on) and Control conditions (glasses off) was set to 0.50 (chance level). Binomial analyses revealed that neither primary nor secondary school students had a significant preference between the two conditions. See Table 14 for more details.

	Primary school children (n=20)		Binomial P-value	Secondary school children (n=29)		Binomial P-value
	Tuned	Control		Tuned	Control	
Question 1: Read better	8	12	0.503	15	14	1.000
Question 2: Passage better	13	7	0.263	16	13	0.711
Question 3: Computer easier	9	11	0.824	14	15	1.000
Question 4: Most suitable	7	13	0.263	15	14	1.000

Table 14. Separately for each school grade, the number of participants who indicated a preference for the tuned (glasses on) or control (glasses off) condition and the result (p-values of the binomial analysis) are indicated.

Relationship between the individual tuning of flickering lenses and reading performance

In order to investigate the possible link between optimally tuned refreshing bottom-up visual inputs and reading skills, we analyzed the correlation between the individual data of the thresholds of flickering lenses and reading performance in children with DD.

Partial correlations were performed for Frequency and Luminance thresholds with word, pseudoword and text reading (time and errors) performance, controlling for chronological age. Interestingly, the frequency thresholds of the tuned glasses were related to pseudoword reading time in all three reading conditions: tuned glasses ($r=-0.31$ $p=0.036$), glasses off ($r=-0.31$, $p=0.034$) and placebo ($r=-0.32$ $p=0.028$; See Figure 54). No other correlation was significant (all $ps>0.093$).

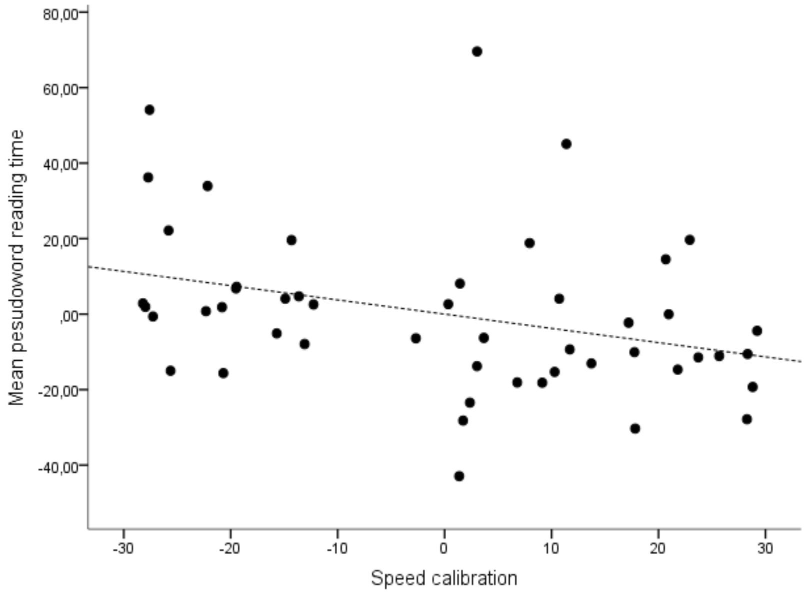

Figure 54. Partial correlation: scatterplot of pseudoword reading time (residual mean between tuned, glasses off and placebo conditions) and flickering frequency of lenses psychophysically tuned by each participant.

5.2 Experiment 2: The Effect of Placebo, Low (60Hz) and High (120Hz) Flickering Spectacles on Reading Skills in Healthy Adults

5.2.1 Materials and Methods

Participants

The experiment involved 48 university students (9 males and 8% left-handed; M age=21.31y.o., SD=2.57) from the Department of General Psychology (Padua) without a diagnosis of DD. Participants were mainly recruited through advertisements during lessons and flyers on social media. The sample was categorized into poor readers (PR; reading performance less than -1DS) and typical readers (TR; reading performance greater than -1SD) based on the z scores (average between speed and accuracy) obtained in text reading in the condition closest to ecological reading (i.e. 120 Hz).

The procedure and the goals for data collection were made explicit on the form that was given to participants. The study was written in compliance with the European Union Standards of Good Clinical Practice and authorized by the University of Padua's Ethics Committee (Protocol number: 122-b).

Procedure

The experimental procedure is the same as described in Experiment 1 with the children with DD; all participants were evaluated simultaneously by two experimenters in a well-lit and quiet laboratory of the Department of General Psychology (University of Padua; see characteristics of the illumination in the Experiment One procedure section).

As for experiment one, a double-blind, repeated-measures design was used in a single-session experiment: the data collection and the analysis process were conducted in double-blind using two fictitious labels. The glasses used to evaluate the placebo and the two experimental conditions (60 vs 120Hz conditions) were the same used in experiment one. The three conditions were administered in a counterbalanced order between participants and assigned to each participant by a computerized generator. The three tasks (word, pseudoword, and text reading) were always administered in the same order and were the same used and described with the children.

Differently from Study 1, in this experiment, the glasses were not calibrated on the basis of participant preference: only 60 and 120Hz flickering frequencies were used, and the brightness was maintained at the default value of zero. In the Placebo condition, 120 Hz frequency (plus positive verbal expectation) was used.

5.2.2 Results

First aim: Placebo effect (120 Hz glass flickering with positive expectations) vs. glasses 120 Hz flickering

Reading Performance

Two mixed ANOVA with a 2 x 2 x 2 design were used to analyze reading accuracy (number of errors) and reading time (in seconds). The within-subject factors were the Task (word and pseudoword) and Condition (placebo and control), whereas the between-subject factor was the Group (TR and PR).

Reading Accuracy

Results on reading errors show the main effects of Task ($F_{(1.46)}$=67.664, p<0.001), Group ($F_{(1,46)}$=22.289, p0<.001), their interaction ($F_{(1.46)}$=11.088, p=0.002) and the Task x Group x Condition interaction ($F_{(1.46)}$=6.039, p=0.018).

Two separate ANOVAs were executed on word and pseudoword errors to better understand the triple interaction. Specifically, the ANOVA on the word list reading errors showed a significant effect of Condition ($F_{(1,46)}$=7.787, p=0.008), Group ($F_{(1,46)}$=23.866, p<0.001) and their significant interaction ($F_{(1,46)}$=15.422, p<0.001). Planned comparisons showed that in the TR group, no significant difference was found between placebo and control conditions (p=.068, Cohen's d=0.286 95% CI=-0.040/0.609; see Table 12). Crucially, in the PR group, a reduction of errors was found in placebo compared to the control condition in word reading (one tail t-test p=0.034, Cohen's d=-0.668 95% CI=-1.231). Due to the low number of errors in this task, we repeated the analysis using the non-parametric Wilcoxon signed rank analysis that confirmed the presence of a significant difference in the number of errors in the PR group (Z=-2.028, p=0.049, matched rank biserial correlation=0.399, 95% CI=-0.971/-0.425) and the previous observed no significant difference in the other comparison.

Interestingly, whereas a significant difference was present between the two groups in the control condition (p<0.001, Cohen's d=-1.778 95% CI=-2.556/-0.986; Mann-Whitney p<0.001 rank biserial correlation=0.632, 95% CI=-0.818/-0.325), in the Placebo condition the difference between groups was not significant (p=0.123, Cohen's d=-0.558 95% CI=-1.261/0.151; Mann-Whitney p=0.051 rank biserial correlation=0.355, 95% CI=-0.651/0.035; see Figure 57).

The ANOVA on the pseudoword errors showed that only a significant effect of Group ($F_{(1,46)}$=17.966, p<0.001) was present (all other ps>0.252).

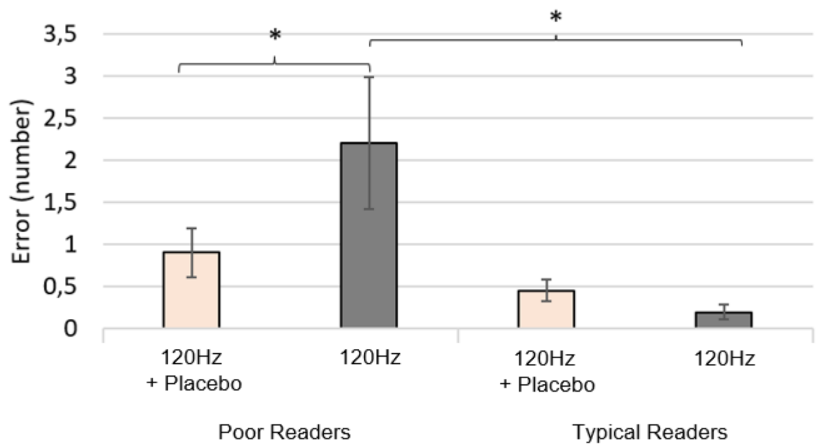

Figure 57. The performance of poor readers (PR) and typical readers (TR) in the placebo (120Hz+positive verbal expectation) and control condition (120Hz) in word list reading accuracy (number of errors). Data are reported as means ± standard errors. The asterisks indicate the significant differences.

Reading Time

The same ANOVA on reading time shows the main effects of Task ($F_{(1.46)}$=72.269, p<0.001), Group ($F_{(1,46)}$=15.469, p<0.001), and the Task x Group x Condition interaction ($F_{(1,46)}$=8.590, p=0.005). Two separate ANOVAs were executed on word and pseudoword errors to better understand the triple interaction.

In particular, in the ANOVA on word list reading time, only the main effect of the Group was significant ($F_{(1,46)}$=8.853, p=0.005). No other significant difference was found (all ps>0.343).

On the other hand, in the ANOVA on pseudoword list reading time, the main effect of Group ($F_{(1,46)}$=14.934, p<0.001) and the Group x Condition interaction were significant ($F_{(1,46)}$=6.327, p=0.015). The planned comparison showed no significant difference between placebo and control conditions in the PR group (p=0.229 Cohen's d=0.408 95% CI=-0.249/1.045). In contrast, a significant difference was found in the TR group: in the placebo condition, participants read pseudoword faster compared to the control condition (p=0.034, Cohen's d=-0.357 95% CI=-0.683/-0.027; see Figure 58 and Table 15).

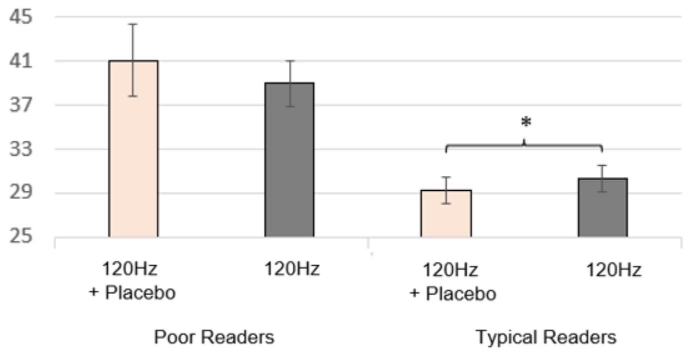

Figure 58. The performance of poor readers (PR) and typical readers (TR) in the placebo (120Hz+positive verbal expectation) and control condition (120Hz) in pseudoword list reading speed (time in seconds). Data are reported as means ± standard errors. The asterisks indicate the significant differences.

Second aim: Frequency effect (120 Hz vs. 60 Hz flickering comparisons)

Word and Pseudoword Reading Performance

In order to compare the glasses flickering (120Hz vs 60Hz), two mixed ANOVA with a 2x2x2 design were run on reading accuracy (number of errors) and reading speed (time in seconds). Again, the within-subject factors were the Task (word and pseudoword) and Condition (60 and 120Hz), whereas the between-subject factor was the Group (TR and PR).

The ANOVA on reading accuracy shows the main effects of Task ($F_{(1.46)}$=44.169, p<0.001) and Group ($F_{(1,46)}$=19.242, p<0.001). No other main effect or interaction was significant (all ps>0.053; see Table 15 for descriptive statistics).

Due to the low number of errors, we performed comparisons using the Wilcoxon signed-rank non-parametric test. In the PR group, no significant difference was found between word or pseudoword reading errors within the two conditions (ps>0.588). In particular, in the TR group, a significant difference was found between the number of errors in word list reading accuracy (Z=2.260, p=0.020 051 rank biserial correlation=0.686). Instead, no significant difference was found in the pseudoword reading errors (Z=0.314, p=0.758; rank biserial correlation=0.067).

The main effects of Task ($F_{(1.46)}$=64.270, p<0.001) and Group ($F_{(1,46)}$=15.957, p<0.001) were significant. No other main effect or interaction was significant (all ps>0.227; see Table 15 for descriptive statistics).

	Poor Readers (n=10)			Typical Readers (n=38)		
	Placebo	120Hz	60Hz	Placebo	120Hz	60Hz
Word reading errors (number)	* 0.90 (0.88)	2.20 (2.35)	1.70 (1.77)	0.45 (0.80)	0.16 (0.55)	*0.50 (1.70)
Pseudoword reading errors (number)	7.10 (4.63)	6.00 (5.83)	6.00 (3.65)	2.42 (2.09)	2.42 (2.08)	2.61 (2.82)
Word reading time (seconds)	27.49 (4.01)	28.38 (3.85)	28.87 (4.73)	23.65 (4.29)	23.62 (4.44)	23.44 (3.81)
Pseudoword reading time (seconds)	41.00 (9.78)	38.96 (6.23)	40.27 (8.20)	*29.20 (7.55)	30.27 (7.49)	30.18 (7.92)

Table 15. Reading time and error number (mean and SD) for word and pseudoword reading lists divided for Typical and Poor readers in the three conditions. The asterisks indicate a significant difference from the Control (120Hz) condition.

Text Reading Task Performance

The effects of glasses on reading accuracy (number of errors) z score and reading speed (time in seconds) z score were analyzed using two mixed ANOVA with a 2x2 design. The within-subject factor was the Condition (60 and 120Hz), whereas the between-subject factor was the Group (TR and PR).

Specifically, in the ANOVA on reading accuracy, only the main effect of the Group was significant ($F_{(1,46)}$=74.995, p<0.001); no other main effect or interaction was significant (all ps>0.088; see Table 16).

Similarly, the ANOVA on reading speed show the only main effect of the Group ($F_{(1,46)}$=65.381, p<0.001); no other main effect or interaction was significant (all ps>0.083 see Table 16).

	Typical Readers (n=38)		Poor Readers (n=10)	
	60Hz	120Hz	60Hz	120Hz
Text reading accuracy (Z-score)	0.73 (1.78)	0.97 (1.43)	-1.83 (2.15)	-3.28 (2.33)
Text reading speed (Z-score)	0.65 (1.06)	0.62 (0.93)	-1.24 (1.28)	-1.56 (1.45)

Table 16. Reading speed (z score mean and SD) and accuracy (z score mean and SD) for text reading task in typical readers (TR) and poor readers (PR).

Overall Discussion and Conclusions

The aims of this study were to investigate the possible expectation-driven placebo effect as well as the effectiveness of the flickering glasses for DD on reading performance. A consistent expectation-driven placebo effect was shown both in children with DD and adult readers. In addition, the flickering frequency of psychophysically tuned glasses predicted phonological decoding speed in children with DD. Finally, tuned refreshing bottom-up visual inputs impact the fluency of the sub-lexical route for learning to read.

In the first experiment, we observed that positive expectation improves word reading accuracy in primary school children with DD. This effect was not found in secondary school children. These results confirm that the placebo effect could be observable in young, but not in older children (see Bridge et al., 2009 and Weimer et al., 2013 for reviews). Testing the induction of an expectation-driven placebo in young adults (experiment 2), the placebo effect was again demonstrated both in poor and typical readers. Adults' poor readers replicate exactly what was observed in primary school children with DD, showing a significant improvement in word reading accuracy. The absence of placebo effects in secondary school and its reappearance in adult poor readers could be interpreted as a consequence of decline conditioning. In particular, the expectations towards the environment, the experimenter, and the tools used to improve their difficulties could be decreased in older children with DD by previous negative school and/or training experiences with the consequence of vanishing of improvements (Parong et al., 2022; Hartmann et al., 2023). In contrast, adults who have never had negative experiences with reading and young DD children with no or little experience with reading treatments can still show a placebo effect conveyed by the multiple elements of the treatment context (Wager & Atlas, 2015).

To estimate the clinical impact of an expectation-driven placebo, it should be noted that the induced improvement in word reading accuracy in primary school children with DD allows them to read like secondary school children with DD. Similarly, the induced improvement in word reading accuracy in adults with reading difficulties allows them to read like typical readers. These results demonstrate that reading difficulties can be partly improved through the manipulation of expectancy and hypothesize that improvements in reading can be achieved by manipulating participants' emotions. Indeed, neurophysiological studies have shown that placebo treatments increase opioid (Wager et al., 2007) and DA release (de la Fuente-Fernández et al., 2001), reducing the activation in brain regions related to negative emotions (Rutherford et al., 2017).

The improvements could be present only in word reading accuracy because the expectation-driven placebo drives the goal-directed attentional facilitation on the lexical information stored in the VWFA (Dehaene & Cohen, 2011).

Our results in children with DD and poor reading adults appear to confirm this explanation. Despite the difficulty of interpreting a null result, the absence of a placebo effect in the letter discrimination task could constitute a further element to hypothesize that the placebo, like goal-directed attention, acts facilitating recognition by a top-down attentional mechanism, lowering the criterion level of evidence necessary for a decision to be made but leaving perception unchanged (Summerfield & Egner, 2009). In this direction, in the placebo condition, in no case is obtained a speed/accuracy trade off. Rather, together with the improvement in word accuracy, there is an observable tendency to worsen performance in pseudoword reading tasks, which could be attributed to the slowdown linked to the induction of a prediction strategy of a possible target, that results useful in word reading but detrimental in pseudoword reading, because no one of possible lexical access could match with the perceptual target, making the task slower and more difficult.

Nevertheless, the placebo effect is observed in typical reading adults in pseudoword reading time. We think that this unexpected result could be explained by two factors. First of all, there was a lack of sensitivity in our word reading task. We used only high-frequency words, because our primary aim was to maximize the effects of automatization. Although suitable for assessing children's abilities, these words were probably too easy to test university adults, leading to a ceiling effect. In fact, it can be noted that the adults who are good readers in the three conditions make very few errors. This did not allow us to observe significant differences. Secondly, the small positive effect observed in pseudowords reading is probably an effect linked to the strong phonological decoding automatization obtainable in a transparent language like Italian. Further study is necessary to explain our results.

At the clinical level, improvements in word reading appear comparable, if not larger (Cohen's d=-.610), to those observed applying the gold-standard phonic instruction (Galuschka et al., 2014). Given the absence of the expectation control in many rehabilitation studies in children with DD, whether these effects could influence the efficacy obtained in phonics training for reading remediation remains to be clarified.

The most intriguing data we obtained testing flickering lenses is the relation between pseudoword reading skills and the Hz rate children selected as more suitable. Children adjusted the frequency with which letter string information was made available based on their phonological decoding skills, confirming a direct connection between sub-lexical route of reading and button-up mechanisms of visual perception. Multiple not tested ophthalmologic (Buzzelli, 1991; Kvarnström et al., 2001), perceptual (Stein, 2018; Gori et al., 2014, 2016; Stein & Walsh, 1997; Livingstone et al., Rosen, Drislane, & Galaburda, 1991) and visual-attentional mechanisms (Goswami, Power, Lallier, & Facoetti, 2014; Franceschini et al., 2012; Vidyasagar & Pammer, 2010; Gori & Facoetti, 2015; Ruffino et al., 2014; 2010), could be hypothesized to be at the basis of this relationship. In the same direction, comparing word and pseudoword reading performance in toned glasses and glasses turned off conditions showed that tuned lenses slightly affected the reading modality, facilitating the phonological decoding hampering the lexical access. This result partially overlaps with those of Lubineau et al (2023), who demonstrated that extremely low frequency (10-15 Hz) slowed down word recognition facilitating response to pseudowords. Difficulties in lexical access could be the cause of worsening text reading errors.

All these effects could be observed only in the case of tuned lenses and in the presence of reading impairment. In the adult sample, using the two extreme conditions (i.e., 60 and 120Hz flickering) did not influence word, pseudoword and text reading performance. This data indicates that only using extremely low frequencies outside the range of the glasses can affect the reading performance of typical readers (Lubineau et al., 2023), whereas using flickering lenses at their extreme value did not affect their reading performance.

The letter discrimination tasks seem to exclude that glasses modify specular letter discrimination. Neither specular nor non-specular letters, neither in foveal nor parafoveal presentation, resulted in easier recognition with tuned lenses in children with DD. The sum of these data led to a hypothesis that it is not the structure of the central part of the fovea (Le Floch & Roapars, 2017), but rather other visuo-perceptual mechanisms that influence the selection of flickering frequency. A plausible explanation could be linked to a mild dysfunction in the magnocellular-dorsal stream associated with DD (Stein & Walsh, 1997; Gori & Facoetti, 2014). It is possible that the reduction of refreshing button-up visual information could facilitate the necessary serial attentional mechanisms for an efficient grapheme parsing engaged in the phonological decoding, impairing the fast and automatic orthographic processing from specialized ventral occipito-temporal area (VWFA). Further studies are necessary to test this possible explanation.

Overall these data led to exclude that the tuning lenses, at least on the fly, could be the primary cause of reading amelioration perceived by glasses users. Also, when evaluating subjective sensations collected in the self-evaluation questionnaires, the children did not show different feelings when wearing or taking off glasses. However, this data is important for our research because it indirectly demonstrates that the children did not perceive any manipulation of turning the lenses on or off.

To conclude, the beneficial effect of expectations appears to be a pervasive effect that could be used to improve treatment outcomes. Maintaining during training that a person is in the best condition to do a task well is not a deceit, as the declaration seems to induce this condition without creating negative effects. The presence of this effect also in reading performance led to the evaluation of all the interventions from a different perspective: the presence of a positive effect of training in comparison with a condition of absence of intervention or in comparison with an intervention that does not induce expectations does not help to understand which variable produced the beneficial effect (see Bowers, 2020).

Glasses to improve reading, through a short-term placebo effect, seem to be able to induce a real effect on reading skills, and it cannot be excluded that over time the small facilitation effect in the use of the sublexical route and the difficulty in lexical access could result in a form of training. In any case, we cannot exclude that combining the action of the placebo effect, mainly on orthographic recognition, with that of relative acceleration of phonological decoding, at the expense of orthographic recognition, can create a significant effect in remediating reading difficulties in participants with DD. Speculatively, this potential effect would once again find a possible explanation in the reshaping of the two main attentional networks extensively discussed in this doctoral thesis.

General Conclusions

In conclusion, this dissertation has comprehensively explored attention, investigating its various dimensions, from definition and models to the neural substrates involved. The research has extended its focus to understanding the intricate relationship between attentional control mechanisms and interventions to enhance cognitive functions. Through the examination of action video game (AVG) training, emotional modulation through gaming, caffeine consumption, and the innovative use of Lexilens® glasses and the manipulation of the placebo effect.

In particular, the first 3 studies in the second chapter highlight the cognitive effects and in particular, the outcomes of long-term manipulation of attention by training with AVG combined, in adults, with transcranial electrical stimulation. In general, the results show stable and cross-sectional improvement in executive functions and cognitive control in children as well as in adults. On the other hand, the chapter on short-term effects, through 3 different studies, highlighted some peculiarities and dissociations in the effects of play and emotions, highlighting even more the role of the Salience Network (SN) and Central Executive Network (CEN) and their mutual interaction in manipulating attention. In particular, results on children show how positive stress induced by play and fun temporarily activates the SN, producing improvements in cognitive tasks that require more stimulus-driven processing while inhibiting the CEN and thus worsening performance in goal-directed tasks. However, the same effects in adults seem to be attenuated and driven by an improvement in the SN but not at the expense of the CEN. Therefore, it is possible to hypothesize that these differences are due to the different degrees of maturation of the prefrontal cortex in children and adults and to more general neurocognitive differences. With the study on caffeine, we wanted to balance the mutual and asymmetric interaction between the SN and the CEN through the administration of a psychostimulant substance which, based on our results, seems to determine improvements in attentional processes and the positive emotions experienced. Finally, the attentional manipulation induced through the different frequencies of flickering and the induction of positive expectations (placebo) highlighted once again the role of the expectation-driven placebo in the goal-directed attentional facilitation of lexical information, especially in children with developmental dyslexia (DD).

In conclusion, the dissertation has provided valuable insights into the potential avenues for improving cognitive abilities, specifically in individuals with DD and reading difficulties. However, the dissertation acknowledges its limitations and calls for continued research in this evolving domain.

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Link

- GetData Graph Digitizer. http://getdata- graph- digitizer.com/index.php
- https://www.theesa.com/resource/2021-essential-facts-about-the-video-game-industry/
- https://abeye.tech/lexilens/

Appendix

Discrimination of Minimal Pairs (adaptation from CMF; Marotta et al., 2008)

List A		List B		List C	
CAPA	CABA	PACA	BACA	CEPE	CEBE
TABA	TAPA	BATA	PATA	BOTO	POTO
SEPA	SEPA	PASE	PASE	PASO	PASO
MIFA	MIVA	FAMI	VAMI	MIFO	MIVO
TAVA	TAVA	VALA	VALA	FALA	FALA
LATE	LADE	LETA	LEDA	TALO	DALO
COTO	CODO	TOCO	DOCO	TACA	DACA
LACI	LAGI	CILA	GILA	LECI	LEGI
PIGA	PIGA	GIPI	GIPI	PIGO	PIGO
NOMU	NONU	MUNO	NUNO	MENE	NENE
NOCA	NOGA	CANO	CAMO	GAMO	GANO
TACO	PACO	LACO	RACO	LACE	RACE
LUSA	LUSA	SALU	SALU	SULO	SULO
BESA	BEZA	SEBA	ZEBA	SABE	ZABE
VARE	VASE	RAVE	SAVE	REVA	SEVA

Short-Term Memory Test of Pseudowords

Task A

2	sed – gam
2	tul – sid
3	fib - nup – gan
3	rag - bil – sut
4	tol - vus - rab – dig
4	cal - ner - dig – bov
5	tuf - sev - gal - cid – fom
5	bes - rad - niv - cot – puc
6	saz - vum - tob - nic - rel – fup
6	lem - gor - vus - rab - tin – fad
7	sat - mid - bog - tur - dab - fip – zal
7	nir - cov - pef - ghip - das - lon – tif
8	bor - cit - vem - fal - saf - cub - nid - pog
8	teb - pid - mac - nor - ked - faz - sel - vup

Task B

2	bog – lem
2	cit – rab
3	das – lon – tif
3	cub – nid – pog
4	saz – cot – nup – bor
4	gal – rad – vum – pid
5	mid – gor – tob – fip – zal
5	fad – tin – rab – dab – tur
6	vup – faz – ked – cit – vem – sut
6	tul – sid – nor – sel – mac – cid
7	teb – ner – dig – teb – vus – rab - cot
7	cal – sev – dig – bov – tol – gan – fib
8	tuf – nar – fal – cid – fom – vus – gor – bog
8	bes – ghi- niv – saf – puc – lem – rel – gam

Task C

2	mid – vem
2	teb – niv
3	faz – ked – bor
3	pid – nar – cov
4	saf – vup – nor – rel
4	das – bog – sel – tin
5	tol – vum – rag – sid – pef
5	gal – lem – nid – fom – tur
6	puc – tob – fip – bes – fal – cub
6	mac – tif – sev – cot – sut – fal
7	sat – bad - zal- nir- ghip – lon - cit
7	pog – dim – met – vot –deb – ler - gob
8	din – mev – sir – nig – cut – rul – pol - pur
8	zut – vir – ner – mut – tum – ber – foc - fre

Word List Reading

(adaptation from Batteria De.Co.Ne. per la lettura, Franceschini et al., 2016)

List A		List B		List C	
casa	burro	anno	torre	uomo	preda
nome	prato	mano	barba	sera	genio
aria	fetta	tipo	furia	voce	miele
arte	brodo	zona	vasca	mare	torta
lato	litro	fase	ladro	vino	palma
neve	rissa	luna	razzo	aula	targa
cane	drago	lago	capra	fame	ragno
erba	volpe	naso	tosse	riva	verme
pepe	belva	seta	fieno	fama	trota
toro	lepre	lupo	perla	coro	rospo
dose	cervo	tela	corvo	mago	talpa
noia	guerra	agio	strada	vaso	gruppo
orso	nebbia	lana	sabbia	vela	febbre
lite	scimmia	nodo	freccia	nido	guancia
seme	ghiaccio	palo	specchio	topo	spiaggia
tana	natura	faro	estate	cera	parola
sugo	divano	rana	fucile	fata	farina
lode	sapone	diga	mulino	pala	carota
orma	canzone	mulo	albergo	elmo	cavallo
fune	pigiama	gufo	canguro	foca	zanzara
notte	prigione	madre	fastidio	gente	faccenda
cielo	sentiero	bocca	chitarra	vento	gabbiano
turno	serpente	gioia	coniglio	clima	minestra
sonno	alluvione	ritmo	labirinto	treno	tartaruga
frase	anatra	folla	bibita	ponte	vipera
gatto	fulmine	bomba	pentola	nonno	raffica
	pettine		valvola		bussola
Tempo= 46/tempo= parole errate=	Tempo= 73/tempo= parole errate=	Tempo= 46/tempo= parole errate=	Tempo= 73/tempo= parole errate=	Tempo= 46/tempo= parole errate=	Tempo= 73/tempo= parole errate=

Pseudoword List Reading

(adaptation from Batteria De.Co.Ne. per la lettura, Franceschini et al., 2016)

List A		List B		List C	
bafeda	fretto	dalefa	chieso	faceda	cilore
chemme	struda	chette	guirra	cheffe	fuglio
noseto	daccio	pomeso	volene	soteno	stuata
puge	sobbia	cuge	vopare	vuge	nobbia
zulecu	dagano	vufebu	ciprai	bulecu	fenala
lacento	polata	cebanto	cameto	camento	ortaci
vurocaio	vacinde	zurolaio	fudicia	burobaio	ramonzo
gnete	serolla	gnese	momeria	gneme	iffucio
bufapo	matolle	pucato	osfalta	zulapo	bolcane
ghesotte	teppota	ghenomme	petenta	gherolle	ostinti
zufalero	tiraffa	budafeto	sacchio	pudaseto	gorenia
vucanose	cetrema	zufapole	cretare	pucatofe	garaffi
fedabuto	compogna	tebacuro	fenistra	lefacuno	corvelle
mepola	cerriara	senoca	giordina	tesoba	frotella
sobapucu	fimaglia	solavupu	prebloma	bolazuvu	monistri
lostrobe	menistra	bostrole	sontiere	postrose	cinoglio
	profette		centiera		vandette
	ginastre		cenfotto		gronchia
Tempo= 50/tempo= parole errate=	Tempo= 50/tempo= parole errate=	Tempo= 50/tempo= parole errate=	Tempo= 50/tempo= parole errate=	Tempo= 50/tempo= parole errate=	Tempo= 50/tempo= parole errate=

Glasses Calibration Staircase

Flickering Speed or “Vitesse”

	-20	-19	-18	-17	-16	-15	-14	-13	-12	-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
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Brightness or “Balance”

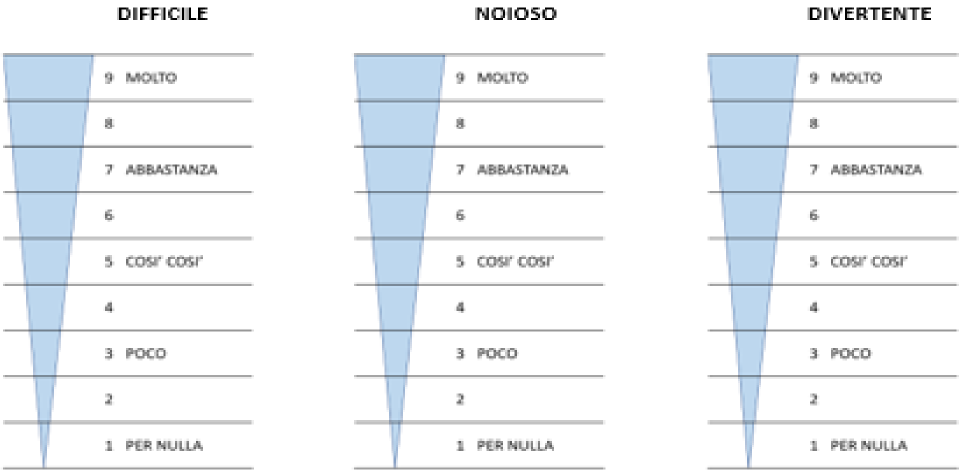
	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10
2DX																					
2SX																					
1DX																					
1SX																					
fine																					

Games and Self-Evaluation Questionnaire- Italian Version

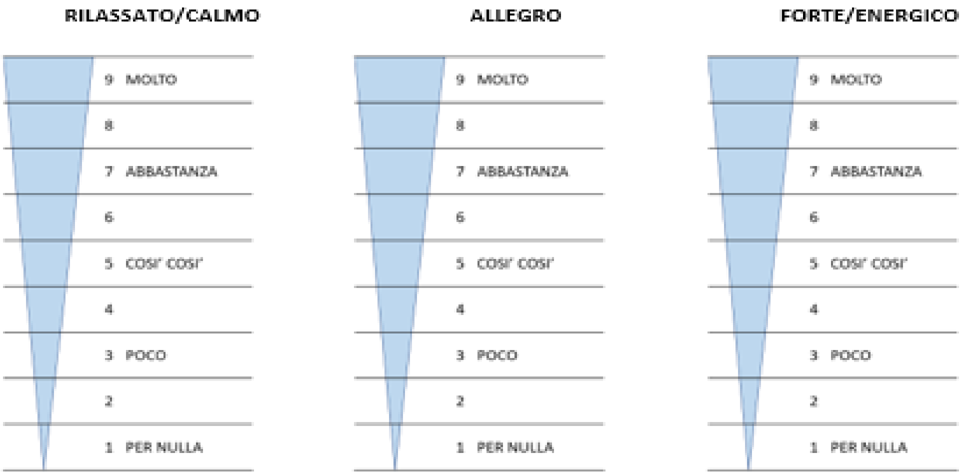
(adaptation from Franceschini et al., 2022)

Prova ad immaginare che tu debba riempire di una quantità di parola un bicchiere:

INDICA QUI SOTTO QUANTO L'ATTIVITA' APPENA SVOLTA ERA:



INDICA QUI SOTTO QUANTO TU ADESSO TI SENTI:



Remote Association Task- Italian Version

(adaptation from Salvi et al., 2016)

LUCE	COMPLEANNO	MOTORE	**candela**	LEGNA	GAS	PATATE	**forno**
SANGUE	TURCO	PUBBLICO	**bagno**	PICCHE	PUNTI	RUOTE	**due**
SCOMMESSE	ANGOLO	MERCATO	**calcio**	CIGLIO	MAESTRA	BATTUTA	**strada**
DO	DOPPIO	POLLO	**petto**	LONDRA	OCCHI	ARROSTO	**fumo**
BELLA	INCOLLA	CARBONE	**copia**	PIEDE	BOTTIGLIA	BAR	**collo**
SPARO	LATTE	STELLE	**polvere**	VIOLINO	CASA	PAROLA	**chiave**
SANGUE	CIELO	OCCHIO	**blu**	VENTI	DESERTO	MAGLIA	**rosa**
IMPERFETTO	LIBERO	REALE	**tempo**	NERO	BUE	COLPO	**occhio**
ESPRESSO	REGIONALE	CAPO	**treno**	CAPRA	SVIZZERO	BUCHI	**formaggio**
CAPITALE	MORTE	SOFFERENZA	**pena**	VIA	VECCHIO	BATTUTO	**ferro**
MECCANICO	FERRO	MORTE	**braccio**	ULTIMO	ZERO	LUCE	**anno**
FORTUNA	TRASPORTO	COMUNICAZIONE	**mezzo**	TRATTENERE	TROMBA	COLLO	**fiato**
AFRODITE	BOTTICELLI	STRABISMO	**Venere**	GIUDIZIO	MAL	PASTA	**dente**
FRATELLO	DITTATORE	PUFFO	**grande**	TAPPETO	POMODORO	PESCE	**rosso**
LINGUA	LINEA	PERLA	**madre**	AGO	PESO	COSTELLAZIONE	**bilancia**
PARCO	SALA	CARTE	**gioco**	VIAGGIO	INVITO	LISTA	**nozze**
ERBA	SPINATO	DIRETTO	**filo**	BIANCA	CREDITO	IDENTITÀ	**carta**
POSIZIONE	ALLENTARE	GIRO	**presa**	ARRESTO	PARTENZA	PASSO	**falso**
PSICHE	PRIMO	PROPRIO	**amore**	OSSA	CREPA	OCA	**pelle**
BERLINO	PIANTO	PORTANTE	**muro**	PEPE	MINIERA	GROSSO	**sale**
MOBILE	MUSICALE	EMERGENZA	**scala**	PRESA	BIRRA	ROSA	**spina**
PETROLIO	SCIENZA	DESIDERI	**pozzo**	GIUDA	FRANCESE	DAMA	**bacio**
CONTROLLO	SCACCHI	AVORIO	**torre**	GOVERNO	GENTILUOMO	APPARTAMENT O	**ladro**
TAGLIARE	MALTESE	CIRCUITO	**corto**	CATTIVA	IRONIA	ESTRAZIONE	**sorte**
PENTOLE	MUSICA	CARICA	**batteria**	NERO	COLLETTO	CONIGLIO	**bianco**