



Eye-guided video games improve reading in healthy older adults

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ABSTRACT

In aging, some visual and attentional skills can decrease, affecting reading performance. This study investigates the feasibility and potential efficacy of a custom-built eye-guided video game to train visuo-motor, visual and attentional skills involved in reading on healthy older adults. For this purpose, 40 healthy participants, over 65 years old, were enrolled. The experimental group ($N = 21$) completed a series of cognitive, visual, attentional, and reading tests to assess the initial general cognitive performance and evaluate changes after the training period. The training consisted of 45-min sessions twice weekly for 5 weeks. The control group ($N = 19$) underwent the same assessment before and after the same temporal interval, but without training. Analyses showed that only participants who underwent the oculomotor training experienced an improvement in reading. Specifically, at the post-training assessment, the experimental group recorded a decrease in reading time, a reduction in the number and duration of fixations, and an increase in the amplitude of saccades. Changes emerged for visual tests, while no change was found concerning attentional parameters. In summary, the study confirmed the potential of eye-guided video game training in improving reading in healthy older people as well as the feasibility of conducting a randomized controlled trial.

1. Introduction

Aging is a natural process of life. A set of progressive physiological changes which differs between individuals occurs over age in a series of physical functions, which begins in early adulthood and usually accelerates when getting older (Boss and Seegmiller, 1981; Nigam et al., 2012; Whitbourne, 2012). Over and above physical decline, the changes also involve specific cognitive abilities such as attention, memory, processing speed, and executive functions. Consequently, they directly impact daily life (Deary et al., 2009; Harada et al., 2013; Hasher and Zacks, 1988; Salthouse, 1992). Aging can pose financial and social challenges as a result of physical and cognitive deterioration, as well as the financial burden on the public health system, which can be associated with age-related diseases, disabilities, and dependency (Hertzog et al., 2008). Individuals (and society) benefit from maintaining

cognitive functioning as they live longer, can live independently for extended periods, and incur fewer long-term care costs (Coughlin and Liu, 1989).

Considering the advancement of the elderly population and life expectancy, looking for ways to slow down the decline of these cognitive functions has become an issue of essential importance. Previous studies have shown that engagement in everyday cognitively stimulating leisure activities, such as reading (Sattler et al., 2012; Verghese et al., 2003), doing crosswords puzzle (Pillai et al., 2011), playing board games (Paillard-Borg et al., 2009; Wang et al., 2006), or playing cards (Verghese et al., 2003), correlates with better cognitive functioning (Gow et al., 2014) and a lower risk of developing mild cognitive impairment or dementia (Blacker and Weuve, 2018).

A strategy to prevent elders' deterioration or even improve their cognitive performance is represented by cognitive training (Gates et al.,

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2020; Strenziok et al., 2014; Van Muijden et al., 2012). These are specific stimulations designed to improve mental functioning. It involves the guided practice of structured, validated tasks designed to train relatively well-defined cognitive processes and abilities such as working memory, attention, and problem-solving (Bahar-Fuchs et al., 2019). Over the last decade, in particular, extensive efforts have been made to promote cognitive training to delay cognitive decline (i.e., Park and Bischof, 2013). Specific cognitive training can lead to an improvement of the directly treated skill and a generalized improvement of other skills, although there is not total agreement on the generalization of these effects (i.e., Ball et al., 2002; Kelly et al., 2014).

Among the many cognitive trainings developed for older cognitive functioning stimulation (Thompson and Foth, 2005) there are single- and multi-domain trainings, paper-and-pencil vs more computerized materials, individual vs group sessions. A series of studies have shown that cognitive enrichment is facilitated by computerized training that involves a greater range of activities (Green and Bavelier, 2008; Kueider et al., 2012; Gamito et al., 2020). Different evidence has demonstrated that cognitive functions such as executive functions, reaction times, processing speed, and working memory could be improved by computer-based training (Xu et al., 2020; Sosa and Lagana, 2019; Mansor et al., 2020). Among the many proposals that have recently emerged in cognitive training for aging, video games are increasingly asserting their potential in slowing down cognitive decline and even improving specific abilities (Nguyen et al., 2022). Compared to traditional techniques, video game-based stimulation interventions have the advantage of offering a more personalized and flexible context, providing real-time feedback allowing online correction in the event of an error, and making the activity sufficiently stimulating and adapted to the individual's abilities (Kueider et al., 2012; Gamito et al., 2020). In contrast to monotonous traditional training programs, video games allow one to have fun and maintain motivation to engage in practice for much longer periods. Motivation is a critical factor to training successfully (Melenhorst et al., 2006; Selwyn et al., 2003). Furthermore, adapting the game's difficulty level to each player's performance will ensure that the players are always challenged at their near to maximum ability. Additionally, small increments of difficulty enhance the likelihood of a successful game experience in older adults (Van Muijden et al., 2012; Neri et al., 2021). Playing video games has been shown to improve cognitive abilities in young participants in areas such as visual attention (Feng et al., 2007; Green et al., 2010; Föcker et al., 2018; Qiu et al., 2018) and mental rotation ability (Okagaki and Frensch, 1994; Terlecki et al., 2008). Moreover, the same results were obtained in older adults (Basak et al., 2008). Some studies have used commercial video games, while others have preferred custom video games designed to target specific skills. In both cases, video games have proved to be effective training (Bonnehère et al., 2020; Pallavicini et al., 2018).

There was a specific interest in the relationship between cognitive training and attention, vision, and reading performance in healthy elderly. Attention is fundamental in guiding all other cognitive functions. It refers to a series of cognitive functions such as visuospatial attention that permits us to select relevant information from the environment to orient and focus on. It is essential for learning and memory formation, as well as for decision-making and problem-solving. Attentional processes can inhibit irrelevant or repetitive stimuli by concentrating instead our resources on what is helpful for a specific task. Many attentional components seem to decline during the aging process (Craik, 2016), in particular: processing speed (Salthouse, 1992), inhibition (Hasher and Zacks, 1988), selective attention (Plude and Hoyer, 1986), divided attention (Verhaeghen and Cerella, 2002) and visual search (Facchin et al., 2023; Madden et al., 2004). When attention is impaired all other cognitive processes are compromised and it becomes very difficult to have goal-directed behavior.

However, not only cognitive processes slow down with age. Also, the sensory system, including vision, declines with age. It has been documented in the literature that different visual functions such as visual

acuity, contrast sensitivity, stereopsis, dark adaptation and visual processing speed decline with age (Andersen, 2012; Elliott et al., 1995; Owsley, 2011). Peripherally, presbyopia also occurs (Polat et al., 2012). These modifications can impact the perceptual processing of small object detection and recognition, such as letters, consequently reducing reading abilities (Kavale, 1982). Reading performance, indeed, is affected by aging (Baltes and Lindenberger, 1997; Lindenberger and Baltes, 1994). Nonetheless, reading is a highly complex skill and it is unclear which one of all the different subtasks and numerous visual and cognitive functions involved is more sensitive to aging. In the prelexical phase, vision and attention play an essential role (Coltheart et al., 2001). The role of attention in the reading process permits to extract information from the regions of interest rapidly, and this selection is supported by visuospatial attention in its component of orientation and focus (Rayner and Reichle, 2010). Mainly, focal attention allows the elaboration of each grapheme one by one (Albonico et al., 2016; Castiello and Umiltà, 1990), while the mechanism of orienting attention into space moves attention from one point of fixation to another (Posner, 1980). Visual attention has a fundamental role in analyzing and segmenting letters while reading. As a result, it facilitates the elaboration of sensory information by preventing interference caused by crowding (Bricolo et al., 2015; Yeshurun and Rashal, 2010). A slower and less precise attentional system and a less efficient visual system, can result in slower and less precise reading in older adults (Rayner et al., 2009). Another component that may contribute to reading impairment concerns eye movements. These are, in fact, not immune to the natural decline in functioning due to the aging process; older people make longer fixations and sometimes are less precise in making saccades (Rayner et al., 2009). Indeed, when saccades are performed with low spatial accuracy, correction saccades are required to fixate words properly (e.g., regression movements). This behavior, together with long fixation times result in slow reading speed or lower accuracy (Haegerstrom-Portnoy, 2005; Salthouse, 1992, 1996; Verhaeghen and Cerella, 2002).

Even if reading is affected by aging, in terms of visual and attention skills, it is still possible to benefit from specific training in late adulthood to increase olders' performance (Park and Bischof, 2013). Some studies used perceptual learning training to improve reading performances (Chung, 2011; H.-W. Lee et al., 2010; Yu et al., 2010; Kattner et al., 2017). Perceptual learning refers to the process of long-term improvement in performing perceptual tasks induced by extensive practice (Goldstone, 1998). The processing speed of visual stimuli can also be improved in older adults through training (Ball et al., 2002), and perceptual training can improve reading ability even in adulthood (Ball et al., 2007; Von Bastian et al., 2020). In addition, some authors used oculomotor training to increase reading performance; this consists of a series of exercises (visual tasks like visual search, fixation stability, saccadic and pursuit tracking) by performing explicit eye movements (Bucci et al., 2018; Pijnacker et al., 2011). Oculomotor training has proven effective in young adults, improving reading rates (Pavlidis, 1981; Pirozzolo and Rayner, 1980; Seiple et al., 2005; Shapiro and Raymond, 1989).

In this context, this work investigates the feasibility and potential effects of video game-based training on reading abilities in healthy older adults. Specifically, the aims were 1) to create a video game that trained the functions involved in reading in a fun but also specific way, through an eye movement guidance; 2) to investigate the impact of a training with this tool on reading performance in a sample of older people for a pilot study. To our knowledge, this is the first study that uses an eye-guided modality of interaction in custom-built video games designed for cognitive training. Our hypothesis is that the exercises in the form of video games could improve visual and attentional functions underlying reading and consequently help the elderly to ameliorate reading performance. For this purpose, three custom-built video games were created in which ocular movements controlled the interaction between the participant and the videogame; in particular, to play the games, the participant had to search for stimuli among distractors, perform

saccades, fixations, and pursuit movements. To reach each videogame's specific goal, the participant had to perform accurate eye movements (for example, moving precisely and directly to pick up a target). To offer properly challenging training perfectly adapted to the level of each participant, the three custom built videogames were designed to be adaptable to the participants' performance by changing various parameters (e.g., game speed, number of distractors). To verify the potential effectiveness of the training, a large battery of visual, attentional, and reading tests was administered before and after the training to two groups of healthy elderly people, one experimental and one control (passive).

We expected to find an improvement in reading skills in the experimental group only, associated with an improvement in visual skills and focal attention.

2. Materials and methods

2.1. Participants

A total of 41 participants were initially enrolled in the study. In one case, the second assessment was not completed and the candidate was therefore discarded. Consequently, the final sample included 40 participants (Mean age: 71.4, SD: 6.2, range: 62–84, Education mean: 12.3, SD: 4.1, range: 5–20; 21 females and 19 males). For inclusion in this study, participants had to be Italian, at least 62 years of age, and did not have present or past neurological or psychiatric disorders. Participants were divided into two groups (Experimental and Control). The experimental group consisted of 19 participants (mean age 71.2, SD 5.1; range 64–82; 10F, 9 M), while the control group consisted of 21 participants (mean age 71.7, SD 7.2; range 62–84; 11F, 10 M). All participants were retired. Participants signed an informed consent form before participating in the study. The study was carried out following the guidelines given in the Declaration of Helsinki, and it was approved by the ethical committee of the University of Milano-Bicocca (prot. n. RM-2017–93).

2.2. Tests

All participants completed a first initial screening, to assess general cognitive abilities, and a visual and neuropsychological assessment, pre and post-training to evaluate changes after the training period.

2.2.1. Initial screening tests

To assess the general cognitive level, the Montreal Cognitive Assessment (MoCA) was used (Nasreddine et al., 2005; Santangelo et al., 2015) because MoCA provides the most reliable way to confirm that the cognitive level of participants is normal, excluding in the best way MCI (mild cognitive impairment) (Siqueira, 2019). Cognitive reserve was measured using the Cognitive Reserve Index questionnaire (CRI-q), which assesses formal and non-formal education, occupational activity, and frequency of participation in leisure time activities over an individual's adult life (Nucci et al., 2012).

The presence of normal binocular vision was assessed by evaluating global stereopsis. The TNO test (Lameris Ootech BV, Nieuwegein, Netherlands, 13th edition) was used. To assess global stereopsis, a random dot test is used based on the separation of red and green glasses. A measurement of the minimum stereoacuity (threshold) was taken.

2.2.2. Visual and neuropsychological assessment

Visual and neuropsychological assessments were defined to assess eye movements during reading, visual function and quality of vision together with reading in different forms: text reading, reading without eye movements, sentence reading and focus of attention. Specific tests and procedures were subsequently selected for measuring these parameters. Text reading was performed on the screen while eye movements parameters were recorded (Carter and Luke, 2020). Change in the visual function was evaluated through a contrast sensitivity test (Pelli

and Bex, 2013) and the subjective perception of quality of vision using NAVQ questionnaire (Massof and Rubin 2001). Reading without eye movement was assessed using a rapid serial visual presentation paradigm (Potter, 2018). Sentence reading was assessed using RADNER charts (Radner, 2017) and the focus of attention was measured using a computerized task (Maringelli and Umiltà, 1998). The different visual and cognitive functions selected represent a set in which an eye guided video game used in the training could improve after training. The selected tests or experimental procedures represent validated measures already routinely used in clinical practice and research).

2.2.2.1. Eye tracking in reading. To collect eye movement parameters, the Eye Link 1000 eye tracker (SR Research Ltd., Mississauga, Ontario, Canada) was used. Participants were seated in front of a computer monitor (27-inch, 600 × 340 mm) with a resolution of 1920 × 1080 pixels and a refresh rate of 60 Hz. The participants' heads were stabilized by a chin and forehead rest and the viewing distance was maintained at 60 cm. Although viewing was binocular, only the right eye was tracked at a rate of 500 Hz. A standard nine-point calibration procedure was run before each experiment and training game. The calibration targets were presented randomly in nine different positions on the screen. Immediately following calibration, each experiment was initiated. Eye movement data were preprocessed using EyeLink Data Viewer software (SR Research Ltd., Mississauga, Ontario, Canada).

A reading task was conducted using the eye-tracker to measure the oculomotor performance of participants. Participants had to read 5 texts consecutively on a computer screen (Judica and De Luca, 2005). The length of every text was 27 words divided into 6 lines. All text was presented without punctuation, and each text occupied approximately the entire screen. Each character was presented in a monospaced font Courier New, which has a horizontal dimension of 1.97 degrees. While the participant read the text, the experimenter recorded with a stopwatch the total time of reading. The number of fixations, the duration of the fixations, and the amplitude of the saccades were recorded.

2.2.2.2. Contrast sensitivity. Contrast sensitivity (CS) was assessed using the Pelli-Robson Contrast Sensitivity Chart and expressed as log contrast sensitivity (logCS). The test consists of a table with 8 rows of letters with decreasing contrast. There are 6 letters in each row: the contrast decreases from left to right and between rows. The contrast ranges between 0.00 and 2.25 logCS. The logarithmic value of the contrast sensitivity of the last triplet in which the participant can read at least 2 letters is recorded as a result of the test. Testing was performed at 1 m (Pelli et al., 1988).

2.2.2.3. Near activity vision questionnaire (NAVQ). The Near Activity Vision Questionnaire is a standardized questionnaire aimed to assess the near visual abilities and satisfaction in presbyopic participants (Gupta et al., 2007). Here, the Italian version of the NAVQ questionnaire was used (Zeri et al., 2017). The score represents the level of difficulties encountered during near activity and a higher score represents more difficulties. The analysis did not consider the last question about the overall satisfaction of vision since it represents a separate simple score. The Rasch measure scaled scores were used for the analysis. This score represents a linear measurement transformed score from the Rasch model. The transformation from raw to Rasch scores was performed with a conversion chart provided with the questionnaire.

2.2.2.4. Rapid serial visual presentation. The Rapid Serial Visual Presentation (RSVP) task was performed using a custom script built in the MATLAB environment. Each trial consists of 4 words presented in a serial visual rapid presentation modality on a computer monitor. Each word was presented centrally on the screen, after a fixation cross. Each stimulus has a length of 5 characters using monospaced font Courier New with a size of 24 points on a 13.3 FHD screen. The participant had

to name each of the four words. Immediately afterwards, another screenshot appears in which the same 4 words were presented in a column and the experimenter had to tick only those that the participant misread or was unable to read. The task lasted 20 trials and words were taken from a list of 80 Italian words. The exposure duration varied trial by trial according to an adaptive QUEST procedure, i.e. the presentation rate (starting from 500 ms) increased or decreased following a threshold criterion of 75% correct responses (the same procedure as in [Primativo et al., 2016](#)). The final exposure duration expressed in milliseconds was transformed in reading rate expressed in words/min.

2.2.2.5. Radner test. The Radner reading chart is a sentence optotype, optimized for assessing visual acuity in reading by going over simple visual acuity. Sentence optotypes consist of short sentences that are highly comparable in terms of number of words (14 words), word length, position of words, lexical difficulty and syntactic complexity. The observer has to read aloud each sentence from the biggest to the smallest until reading is feasible. Using a modified script from the R package `mnreadR` ([Calabrese et al., 2017](#)), the reading acuity (ACC), critical print size (CPS) and reading rate (RA) scores were calculated. The Italian version of the Radner test ([Calossi et al., 2014](#)) was used at 40 cm with the best optical correction. In some cases, when the habitual correction of the participant was not adequate, it was provided a specified one.

2.2.2.6. Focal attention test. The focal attention is a component of visuospatial attention that allows us to concentrate our resources selectively on a spatial location while ignoring the rest of the space and to control and adjust the size of that attentional window according to the task's demands; it can be measured with a simple detection or discrimination task in central view by using a pre-cue of different sizes and under different temporal constraints ([Albonico et al., 2016, 2017; Maringelli and Umiltà, 1998](#)). We used a T-detection task with 4 cue conditions and 3 stimulus onset asynchronies (SOAs). The participants were seated in front of a computer monitor (13.3 16:9 inch, 1920 × 1080 resolution). The distance from the screen was 57 cm. The recording of stimulus presentation, timing, and response was carried out using the E-prime 2.0 software (Psychology Software Tools, Pittsburgh, USA, <https://pstnet.com/>).

The target stimulus consisted of a capital letter T (font Sloan, color black) of $1^\circ \times 1^\circ$ of visual angle oriented upright, whereas the cue could be represented by a red dot (0.4° diameter), a small black square (1.2° × 1.2°, 0.1° thickness), a large black square (15° × 15°, 0.1° thickness), or the absence of a cue. All stimuli, either cue or target, were always presented in the center of the screen on a gray background.

Each trial starts with a blank screen followed, 1000 ms later, by one of the possible cues (i.e., a large square, a small square, a dot, or no cue). The cue lasts 100 ms, whereas the target stimulus appears after SOA of 100, 300 or 500 ms. The target stimulus remained on the screen until a response was given (or for a maximum of 2000 ms), after which the target disappeared and the next trial started. A response to the target stimulus was made by pressing the spacebar on the computer keyboard. A baseline condition consisting of the absence of any cues was also included, and in 20% of the trials (i.e., catch trials) no target stimulus was presented.

The participants were instructed to fixate on the center of the screen, and to press the spacebar as quickly as possible in response to the target stimulus (T). The participants completed 120 trials in total. The SOAs and the types of cues were presented at random. At the beginning of the experiment, a practice session consisting of 10 trials was performed in order to allow the participants to familiarize themselves with the task and to practice with response modes (the procedure is the same as Experiment 2 in [Daini et al., 2021](#)).

2.3. The training: eye-guided video games

The eye-guided video games used in this study were custom-built (Neotenia LTD, Cusano Milanino, Italy) in order to achieve the purpose of the study. They were specifically designed so that games could be controlled by the participant's eyes alone, without any other input from him or her.

The three video games used in the training can be modified according to the skills of the participants in order to make them more challenging and prevent boredom.

To allow the interaction between the participant and the videogame by eye movements, a Matlab script was developed to take the information from the eye tracker and translate it into the game. Specifically, it collected participants' eye position and converted it into mouse coordinates, based on the screen size. This allowed participants to play, with eyesight, a video game that uses a mouse's coordinates. To successfully play the games, participants had to perform accurate saccades, fixations and pursuit movements. Direct online feedback was given to participants on their performance in terms of speed, accuracy, by gaining (or losing) game points.

2.3.1. First game "Gamabunta"

The first eye-guided videogame was "Gamabunta" (aimed at training attention, saccades and fixations). There was an avatar, a frog, and the goal was to eat healthy locusts, jump on them, avoiding enemies and unhealthy locusts. The choice of a frog as the avatar was linked to its natural jumping behavior, which resonates with the movement of the eyes during reading. The locust targets differed from the distractors in size (big locusts with the same appearance) or in color (red locusts with the same size). Both kinds of locusts appeared on screen for a limited time, moving their wings before disappearing; this required the player to choose the best strategy to collect as many as possible. In addition, the participants had to avoid two types of enemies, some of which were moving (in the form of scorpions) and others were static (thorns). In order to move the avatar, participants needed to charge a jump, fixing for a proper length of time the frog's body. A longer fixation on the avatar's body resulted in a higher jump; the longest jump possible was $\frac{1}{3}$ of the screen. Participants were required to move their eyes to a particular location on the screen in order to direct a jump towards that location. The scene containing thorns and scorpions is larger than the screen and can be explored by moving the frog to the edge, while the locusts are generated within the screen space.

This game did not have a priori performance adjustments (game level) because the level was regulated based on participant skills. As a result, several parameters can be subsequently adjusted, such as: the avatar charging time for the jump, the duration of the targets before they disappear, the frequency of appearance of the distractor and their ratio, the number of enemies, how fast they move and how enlightened were the thorns. The screenshot in [Fig. 1a](#) illustrates the game.

2.3.2. Second game "No remora"

The second eye-guided videogame was "No Remora" (aimed at training attention and pursuit). In this game, the avatar was a butterfly fish required to clean dirty sharks. We chose this scenario because cleaning up and completion are naturally rewarding patterns. The participant's task was to follow the shark's movements with an eye. The avatar moved at the same speed as the shark but the shark also occasionally swerves sharply. The butterfly fish followed participants' eyesight so following the shark's movements was an efficient way to perform pursuit eye movements and consequently to clean the shark (the goal of the game).

Butterfly fish had to clean the shark piece by piece, shown by the shark changing color little by little, towards clearer skin. The shark doesn't simply become lighter; it appears to be scrubbed, making it clear when it is still slightly dirty due to the patches. Additionally, the cleaning speed increases over time with a ramp, eventually reaching a

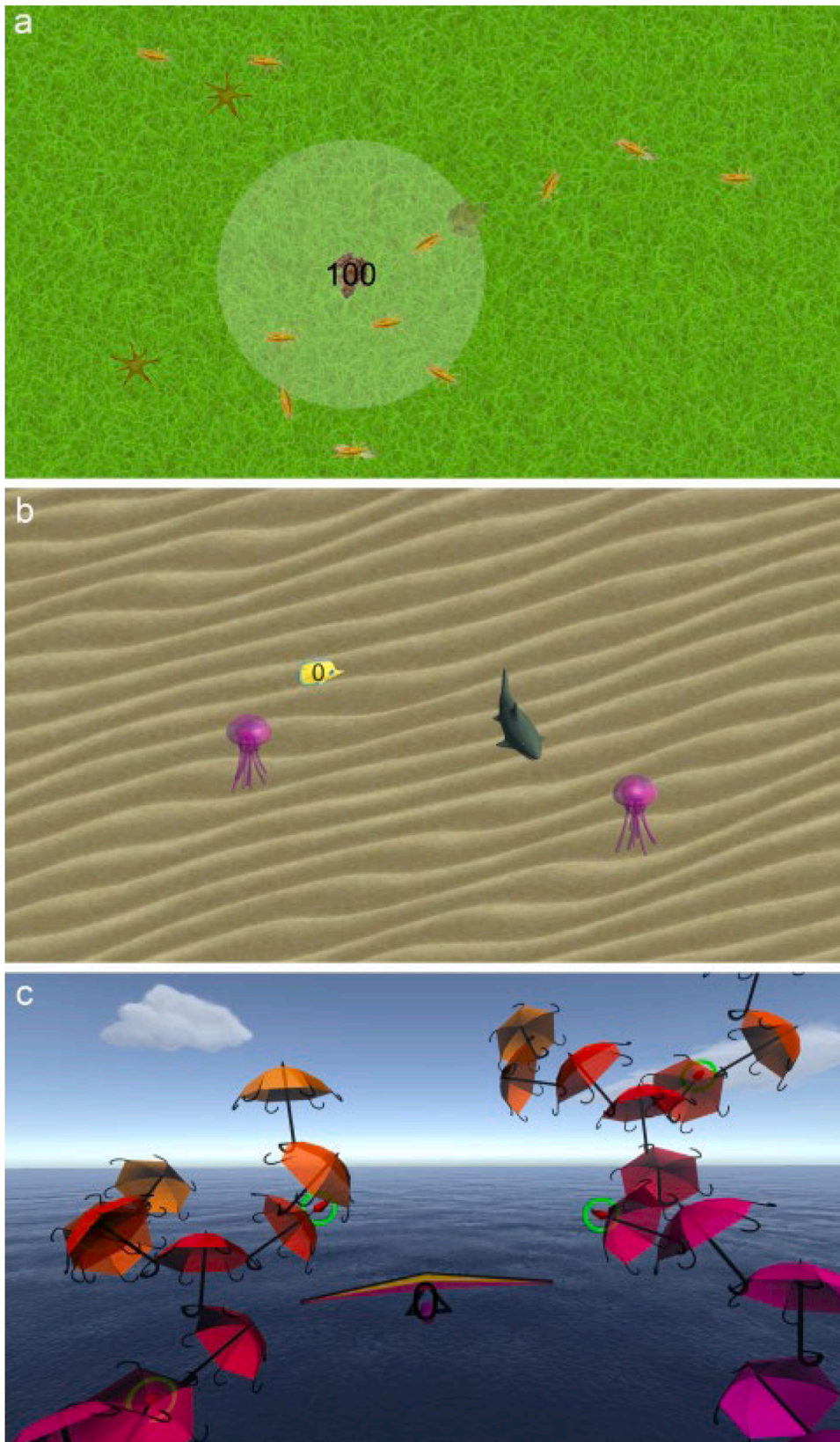


Fig. 1. Screenshots of the three eye guided video games used: a) Gamabunta; b) No Remora; c) Umbrella.

maximum speed, rewarding particularly continuous and fluid fixations. Once the shark is fully cleaned, it leaves the screen, and a new target takes its place. Good participants' performance was rewarded by earning points (feedback). Distractors were present in the form of other butterfly fish (NPC following the shark) and jellyfish, which could be static or moving. If the butterfly fish touched a jellyfish negative feedback was given (loss of points). Since participants had to keep their eyes fixed on the shark, jellyfish needed to be detected with peripheral vision.

Game parameters that could be adjusted through training, with participants' improvement, were: shark speed, jellyfish number and speed. In Fig. 1b, a screenshot from the game can be seen.

2.3.3. Third game "Umbrella"

A third eye-guided videogame was "Umbrella", which was performed in a 3D environment to train attention, fixations, saccades, and pursuit. This game is more similar to commercial games in terms of graphic quality and overall experience. Specifically, the avatar was a hang glider, and participants had to maneuver it through the branches of a giant tree made of umbrellas emerging from the ocean under a blue sky, trying to reach its buds (targets) at the tips of the branches, which appear as closed umbrellas, while dodging the tree's branches (stationary) and origami cranes (moving) flying around the branches. When a bud is collected, it disappears and can regenerate if the game continues for a certain period.

To reach a target or avoid a collision, participants had to direct their gaze to the destination, thereby creating a new trajectory toward the new location. The game also featured distractors in the form of origami cranes that interfered with the player's flight path and had to be avoided. While regular origami cranes flew randomly through the scene, a special crane was occasionally generated to intercept the player's path when they focused on a target. Another type of distractor was a deceptive bud that transforms into an enemy upon close approach. This enemy bud is a type of camouflaged predator that disguises itself as a bud, when players approach, it suddenly opens like an umbrella, resembling a mouth.

The difficulty level can be adjusted by modifying various factors, including the hang glider's speed and maneuverability, the number and velocity of origami cranes, the frequency of special origami cranes, the color of distractors, and the presence of visual cues (for example, a green circle can highlight target buds, while a red circle can mark enemy blossoms once revealed). Fig. 1c shows a screenshot of the game.

2.4. Procedures

Participants were assigned to the training (experimental) or the control group, depending on their availability. Indeed, participants who could perform 10 sessions, two times a week, were included in the experimental group. In contrast, participants who were only available for the initial and final sessions were included in the control group. The training was conducted over a period of five weeks. An evaluation was conducted before and after eye-guided video game training for all participants in the experimental group. As for the control group, the same two sessions of visual and neuropsychological assessment were conducted pre- and post-a five-week period.

The experiment and its timing were explained to the participants. They signed an informed consent form, and initial screening tests (MoCA, Cri-q, Stereopsis) were performed, lasting up to 45 min. Afterwards, the participants underwent visual and neuropsychological assessments, which included: a reading task, Pelli-Robson Contrast Sensitivity, NAVQ, RSVP, Radner Test, and a Focus Attention Test (see paragraph 2.2.2). These tests were presented in a random order and the assessment lasted up to 45 min.

The results from the initial screening tests and the visual and neuropsychological assessment were used to set the parameters for starting the training, in terms of difficulty values. The experimental group performed eye-guided video game training for ten training sessions twice a

week. Each training session lasted 45 min; each game lasted 15 min. In the control group, no training was conducted. After 5 weeks, all participants underwent a 45-minute neuropsychological and visual assessment.

2.5. Statistical analyses

Firstly, a power analysis was not run since no reference studies were available. On the other hand this pilot study will become the reference for estimating the effect size and computing a power analysis in a randomized controlled trial (RCT). A sensitivity analysis was conducted to determine the detectable effect size of the sample collected. To verify the equivalence of the two groups, a Wilcoxon rank-sum test for age, MoCA scores, Cognitive Reserve Index scores and stereopsis values was performed. Statistical analyses were aimed primarily at assessing the effectiveness of eye-guided video game training. For this reason, a linear mixed model ANOVA using the between fixed factor Group with two levels (Experimental, Control), the within fixed factor Session with two levels (Pre- and Post) and the random factor ID. Separate analyses were performed for each test. A post-hoc test with Holm correction was also performed to compare specific conditions. Specifically, we were interested in comparing the Session Pre between Groups for assessing the same baseline, and, within the experimental group, the Pre and Post Sessions. Effect sizes are reported with partial eta squared or Cohen's d . In order to assess the relationship between the performance in reading tasks and visual tests, before and after the training, the correlation among reading and visual tests among all the participants in the pre-training was analyzed, and the correlation between the difference Post-training minus Pre-training performances in the two groups separately.

3. Results

A sensitivity analysis was performed using the following parameters: alpha = 0.05, power = 0.80, a correlation among repeated measures of 0.6, and a sample size of 19 and 21 participants for the experimental and control groups, respectively. A detectable small to medium effect size of $f = 0.20$ could be achieved.

In the comparison between two groups (experimental and control ones), the age of participants did not differ significantly ($W = 196$ $p = 0.93$), as much as the cognitive level at MoCA ($W = 214$ $p = 0.70$), the Cognitive Reserve Index ($W = 220$ $p = 0.59$) and stereopsis ($W = 164.5$ $p = 0.83$).

3.1. Reading time performance and eye tracking measures in text reading

Firstly, the reading time (in seconds) of text presented on screen during eye tracking recording was compared. The results of the ANOVA indicated a significant interaction between the factors Group and Session [$F_{(1,37,14)} = 11.14$ $p < 0.005$, $\eta_p^2 = 0.23$]. The main factor group and the main factor session were not significant. Results are depicted in Fig. 2. Post hoc comparisons showed no significant difference between groups for the Pre session. For the experimental group, the comparison between Sessions showed a significant difference [$t_{(18)} = 3.59$, $p < 0.01$, $d = 0.33$]. No significant difference was found between sessions for the control group. Reading time, therefore, improved only in the experimental group, which however started slower.

With regard to the number of fixations executed during text reading, the results of ANOVA showed a significant interaction between the factor Group and Session [$F_{(1,353,94)} = 10.34$, $p < 0.005$, $\eta_p^2 = 0.09$] and the significant main factor Session [$F_{(1,353,94)} = 6.91$, $p < 0.05$, $\eta_p^2 = 0.07$]. The main factor Group was not significant. Post-hoc comparisons showed only a significant difference between pre and post session values for the experimental group [$t_{(353,1)} = 4.08$, $p < 0.001$, $d = 0.43$]. Results are depicted in Fig. 3. Interestingly, the two groups had the same number of fixations at pre-training but only the experimental group

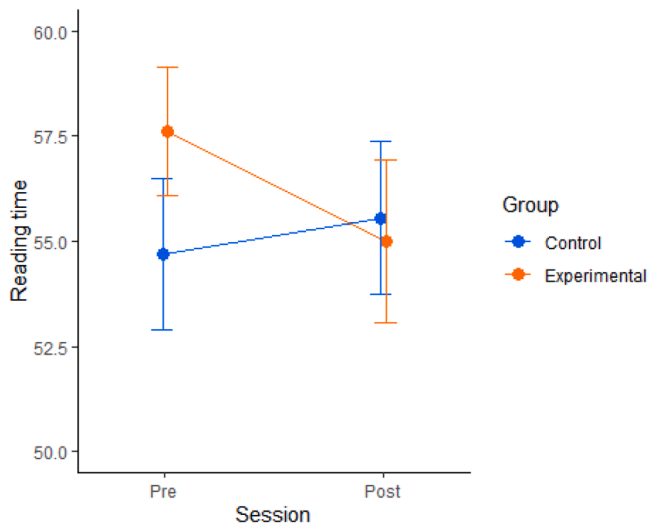


Fig. 2. Reading time (in seconds) for group (Experimental and Control) and session (pre- and post-training). Bars represent ± 1 Standard Error of the mean.

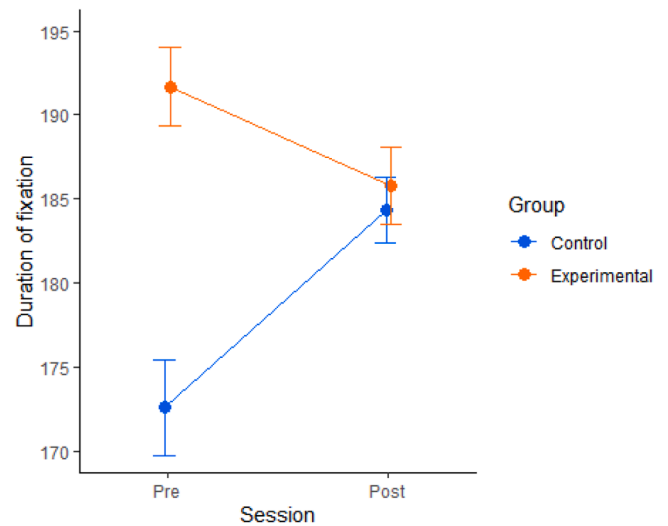


Fig. 4. Duration of fixations for group (Experimental and Control) and session (pre- and post-training). Bars represent ± 1 Standard Error of the mean.

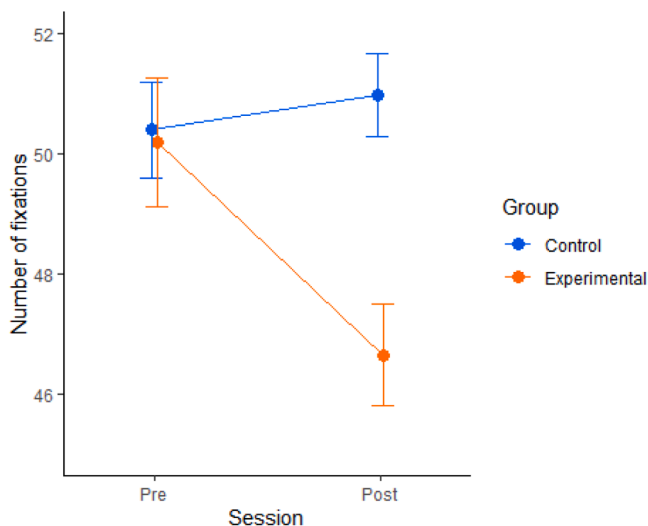


Fig. 3. Number of fixations for group (Experimental and Control) and session (pre- and post-training). Bars represent ± 1 Standard Error of the mean.

showed a reduction at post-training.

Concerning the duration of fixation in reading, the results of ANOVA showed a significant interaction between the factor Group and Session [$F_{(1,38)} = 30.61, p < 0.001, \eta^2p = 0.19$] and the significant main factor Session [$F_{(1,38)} = 5.05, p < 0.05, \eta^2p = 0.03$]. The main factor Group was not significant. In post hoc analyses, there was a significant difference in the pre conditions between the experimental and control groups [$t_{(42.1)} = 2.54, p < 0.05, d = 0.78$], between pre and post session in the experimental group [$t_{(349.6)} = 2.26, p < 0.05, d = 0.24$] and between pre and post session in the control group [$t_{(349.5)} = 5.65, p < 0.001, d = 0.60$]. Fig. 4 depicts the results. The results on fixation duration confirm the improvement of the experimental group in reading performance, even if they started from a different baseline.

For the amplitude of saccades expressed in degrees during reading, ANOVA results indicated a significant interaction between the factors Group and Session [$F_{(1,345.64)} = 24.59, p < 0.001, \eta^2p = 0.14$] and the significant main factor Session [$F_{(1,345.64)} = 4.02, p < 0.05, \eta^2p = 0.03$]. There was no significant effect of the main factor Group. Post-hoc comparisons showed a significant difference in the pre-condition between Groups [$t_{(43.5)} = 2.17, p < 0.05, d = 0.66$], between pre and post

session in the experimental group [$t_{(346.6)} = 4.74, p < 0.05, d = 0.51$] and between pre and post session in the control group [$t_{(344.5)} = 2.18, p < 0.001, d = 0.24$]. The results are depicted in Fig. 5. Coherently with the results of fewer fixations, the amplitude of saccades increased only in the experimental group. As with the previous case, the experimental group started with different baseline values.

3.2. Visual and neuropsychological evaluation

In the analysis of contrast sensitivity, measured with the Pelli-Robson Contrast Sensitivity Chart, the ANOVA revealed a significant interaction between the factors Group and Session [$F_{(1,38)} = 10.27, p < 0.005, \eta^2p = 0.21$] as well as a significant main factor Session [$F_{(1,38)} = 15.74, p < 0.001, \eta^2p = 0.29$]. The main factor group was not significant. The results are depicted in Fig. 6. Post hoc comparisons showed a significant difference between groups for the Pre session [$t_{(38)} = 3.2, p < 0.01, d = 1.01$]. For the experimental group, the comparison between the two sessions showed a significant difference [$t_{(18)} = 4.95, p < 0.001, d = 1.02$]. No significant difference was found between sessions for the control group. Contrast sensitivity, therefore, improved only in the

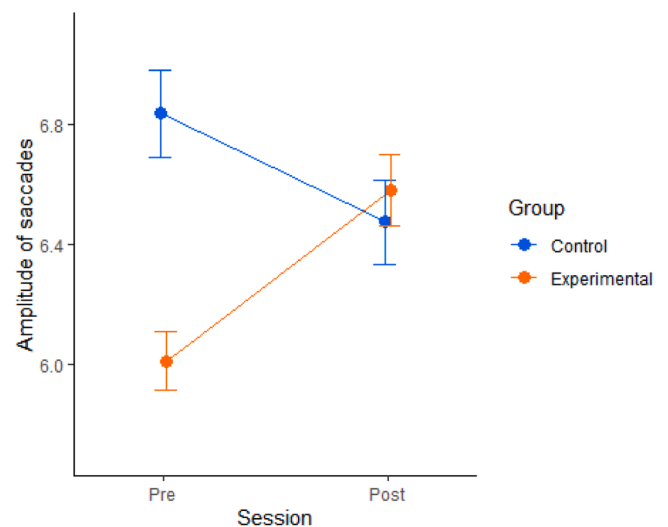


Fig. 5. Amplitude of saccades (degrees) for group (Experimental and Control) and session (pre- and post-training). Bars represent ± 1 Standard Error of the mean.

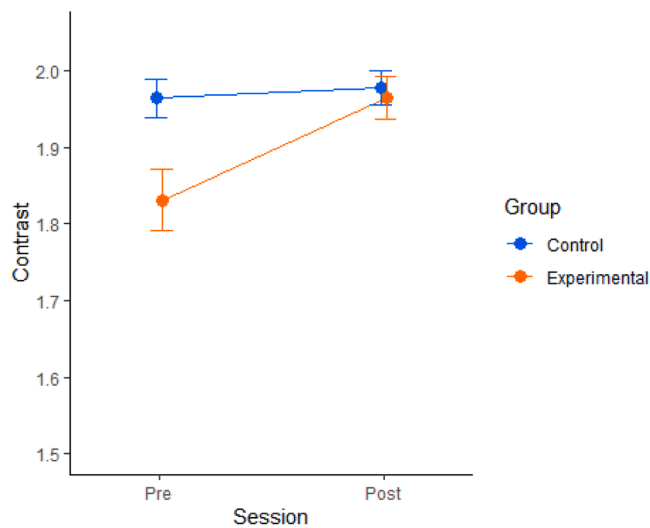


Fig. 6. Contrast sensitivity (higher is better) for group (Experimental and Control) and session (pre- and post-training). Bars represent ± 1 Standard Error of the mean.

experimental group, which however started lower (higher values represent better contrast sensitivity).

The results of the Near Activity Vision Questionnaire (NAVQ) analysed using an ANOVA revealed only a significant interaction between the factors Group and Session [$F_{(1,38)} = 4.92, p < 0.05, \eta^2p = 0.12$]. Fig. 7 illustrates the results. Post hoc comparisons showed no significant difference between groups for the Post session. No significant differences were found between sessions for the experimental group and for the control group. From the figure it emerges that the two groups presented more extreme values at the first administration and values that were more flattened towards the average at the second administration. A lower score indicates fewer symptoms. Nevertheless, in the experimental group the trend of discomfort shows a decrease while in the control group the trend is the opposite.

With regard to Rapid Serial Visual Presentation (RSVP) and the Radner test, the results of ANOVA showed no significant results.

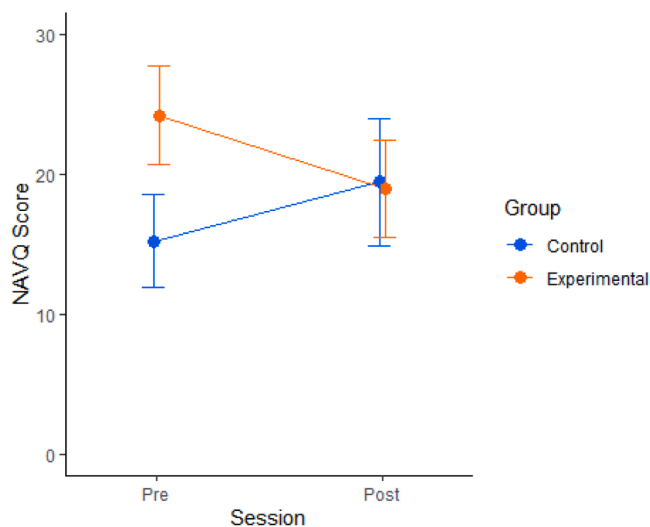


Fig. 7. Near Activity Vision Questionnaire scores for group (Experimental and Control) and session (pre- and post-training). A lower score indicates fewer symptoms. Bars represent ± 1 Standard Error of the mean.

3.3. Focus attention test

The focus of attention was measured using a computerised task, in which the results (reaction times) were reported in milliseconds. In order to assess the presence of a cue effect on all participants, 3 separate ANOVAs were performed separately for each SOA (100, 300 and 500 ms) in the pre-training condition. Only SOA = 100 showed a significant effect of Cue [$F_{(3117)} = 10.33, p < 0.0001$] (Fig. 8). In particular, post-hoc comparisons showed a difference between the optimal cue for focal attention (small Cue) versus all the other cues (all $ps < 0.005$).

These results confirm the validity of the paradigm and the presence of an exogenous effect of focal attention in an elderly population as much as the one in younger participants found by Albonico et al. (2016).

In order to assess the effect of training on focal attention, 3 separate ANOVAs were performed separately for each SOA (100, 300 and 500 ms).

Considering the SOA = 100, the results of ANOVA showed significant results for the main factor Cue [$F_{(3266)} = 4.42, p < 0.005$] and the interaction Session x Group [$F_{(1266)} = 18.89, p < 0.001$]. The interaction Cue x Session x Group did not reach significance, suggesting that training did not improve focal attention. The same conclusion about the triple interaction can be drawn for the other two SOAs.

Regarding the SOA = 300, indeed, the ANOVA showed only a significant result for the main factor Session [$F_{(1266)} = 4.24, p < 0.05$].

Instead, concerning the SOA = 500 of the control group, the results of ANOVA showed significant results for the main factor Session [$F_{(1266)} = 7.70, p < 0.01$] and the interaction Session x Group [$F_{(1266)} = 6.13, p < 0.05$].

Both groups showed preserved exogenous focal attention at baseline, as the small cue was the condition with faster reaction times at 100 msec. Nonetheless, no improvement of such an effect was found after training in the experimental group.

3.4. Correlations

Considering only the correlations among reading, eye movements and visual measures, in the pre-training (Fig. 9) we found the following results: reading time was negatively correlated with the Radner MRS, ($r = -0.72, p < 0.001$) and contrast ($r = -0.44, p < 0.01$); the number of fixations was negatively correlated with the Radner MRS, ($r = -0.41, p < 0.05$) and positively correlated with reading time ($r = 0.45, p < 0.01$); saccades amplitude was positively correlated with the RSVP ($r = 0.52, p$

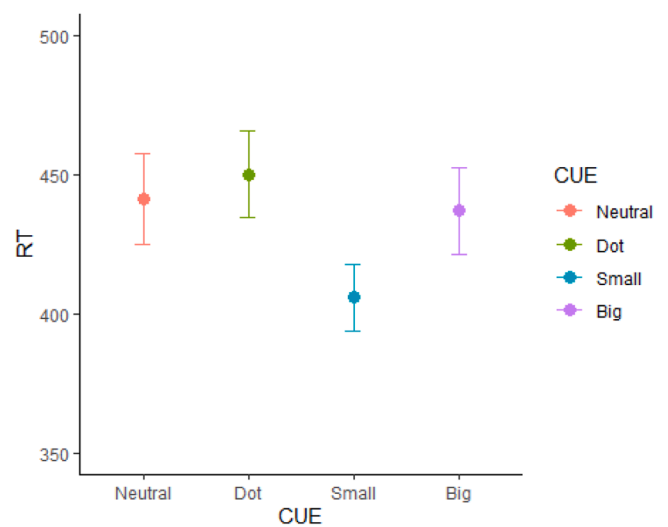


Fig. 8. Results on pre-training response times of all individuals concerning at the focus of attention paradigm, at different cue conditions. Bars represent ± 1 Standard Error of the Mean.

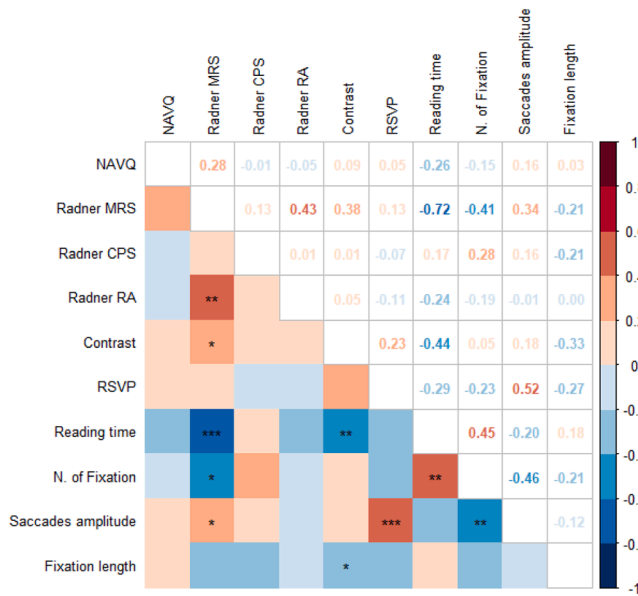


Fig. 9. Correlation matrix of visual and reading variables at Pre-training condition, within all participants. * = $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

< 0.001).

The difference between the two assessments in the Control Group (Fig. 10) highlighted a positive correlation between the number of fixations and contrast ($r = 0.77, p < 0.001$); a negative correlation between saccades amplitude and RSVP ($r = -0.49, p < 0.05$); a positive correlation between saccades amplitude and reading time ($r = 0.53, p < 0.05$).

The highest and most interesting correlation considering the difference between the two assessments in the Experimental Group (Fig. 11) concerned the negative correlation between NAVQ and, respectively, the reading time ($r = -0.51, p < 0.005$) and the Radner CPS ($r = -0.52, p < 0.05$).

In order to further illustrate the two more interesting correlations of the experimental group, two regression analyses were performed using NAVQ as a dependent variable and reading time ($\beta = -0.51, p < 0.05$) and Radner CPS ($\beta = -0.52, p < 0.05$) as independent variable (Fig. 12).

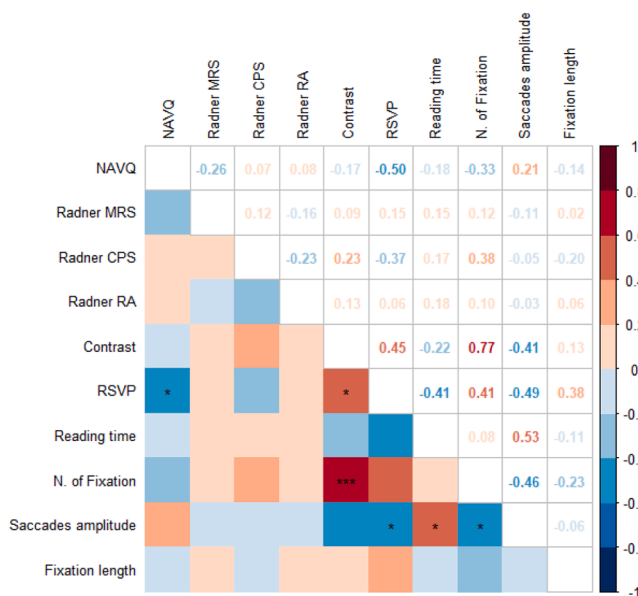


Fig. 10. Correlation matrix of the difference among Post minus Pre-training performances in the Control group. * = $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.



Fig. 11. Correlation matrix of the difference among Post minus Pre-training performances in the Experimental group. * = $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Results show that higher negative differences in scores at NAVQ, i.e., increase of perceived comfort, were associated with a higher positive difference in reading time, as much as a higher positive difference in critical print size (Radner CPS).

4. Discussion

This study aimed to investigate the effectiveness of a new training developed as eye-guided video games on improving reading performance in older adults. Eye tracking is a non-invasive technology that allows participants to proceed naturally on their task, while detailed accurate and quantifiable data are recorded (Duchowski, 2007). With eye-tracking methods, researchers can track an individual's eye movements in order to measure both where their gaze is located at any given time, as well as the sequence in which they move their gaze from one location to another (Poole and Ball, 2004). Additionally, cognitive load is strongly correlated with eye movements, such as the duration and frequency of fixations (Duchowski, 2007). Finally, fixation duration appears to be related with the resolution of the attentional window (Bricolo et al., 2015). Here eye movements were used not only as a measure but also as a modality to control and respond to visual tasks. Visual abilities, eye movements, and attention are closely related to each other and their role is not easily disentangled in reading.

The training was expected to result in improved reading performance as well as significant improvements in attentional tasks, visual abilities, and oculomotor precision. The primary result obtained from our study is that reading improved specifically in the experimental group as a result of eye-guided video game training. Following the training, indeed, the experimental group showed a decrease in reading time; the control group, on the other hand, did not show any significant difference in reading time.

Furthermore, in the post-training condition, only the experimental group showed a reduction in the number of fixations, a reduction in fixation duration, and an increase in saccade amplitude. In summary, all eye movement parameters linked to reading improved after training. Vice versa, a mirror pattern was recorded in the control group at post-condition, with an increase in the number of fixations, an increase in fixation duration, and a decrease in the saccade's amplitude.

Unexpectedly, the performance at baseline differed between the two groups, with the experimental group exhibiting longer fixations, shorter

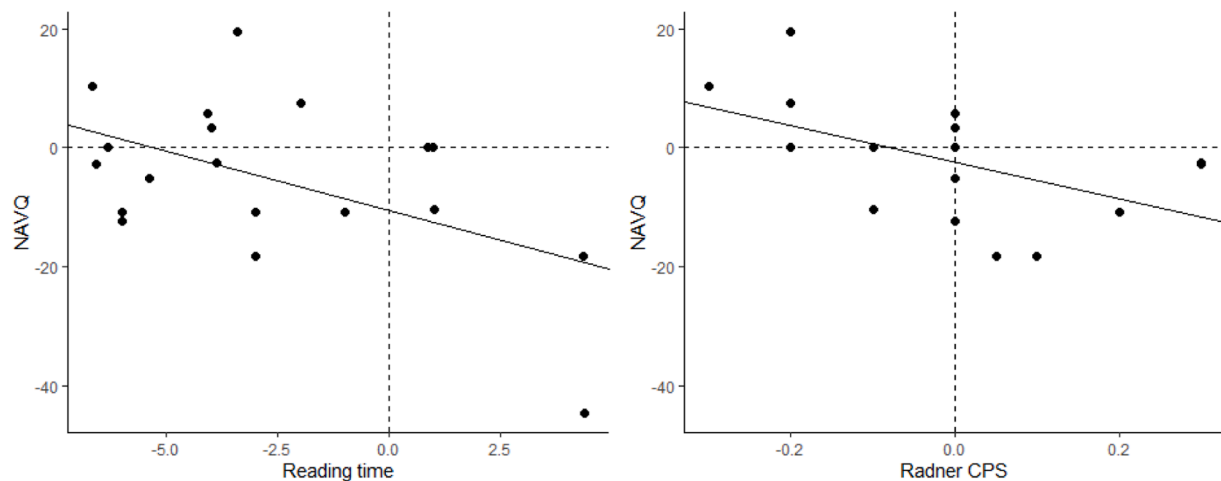


Fig. 12. . Scatterplot of relationship between reading time and NAVQ (left) and between NAVQ and Radner CPS.

saccades, and longer reading times. The two groups have similar age, cognitive level, and cognitive reserve, but the selection of participants may be biased because those with more difficulties may have given their consent to participate at the training. In any case the experimental group showed significant improvements over these characteristics, but also in others with no baseline difference (i.e., number of fixations).

A reduced number of fixations may reflect participants' ability to control their eye movements more consciously and accurately after the training as a result of improving eye control.

A few studies have measured saccadic eye movements in action games in order to investigate visual attention changes. These studies include oculomotor capture tasks, saccadic trajectory paradigms, pro-saccades, and antisaccades in young adults (e.g. [Chisholm and Kingstone, 2012](#); [Mack and Ilg, 2014](#); [West et al., 2013](#)) and found an improvement in all variables.

Using a series of visual search tasks, [Azizi et al. \(2017\)](#) in a group of young adult participants (range: 17–35 years old) examined whether action video game training altered eye movement patterns and didn't find any change in duration of fixations or saccade amplitude between sessions (pre- and post-training) and groups (non-gamers and experienced action gamers). Researchers observed, however, that the action-game-trained group changed their search strategy by reducing the vertical distribution of fixations.

Our study showed an improvement in reading and eye-movement measures during reading after video game training in an older population.

A second result concerns the visual abilities, where we found significant and specific improvements in contrast sensitivity were observed after training. This result is in line with a study that shows that intensive training with action video games enhances contrast sensitivity in video game players in young adults ([Li et al., 2009](#)).

In addition to contrast sensitivity, the perception of near vision quality (NAVQ questionnaire) also improved specifically in the experimental group after training. According to our knowledge, this is the first time that behavioral training has been found to improve the perceived quality of near vision in healthy adults. We also found a significant negative correlation between the changes in NAVQ questionnaire with the changes in reading time: higher the improvement in reading time (negative values), higher the decrease in visual discomfort (positive values). Given that only the experimental group showed this correlation, we suggest that the training improving the prerequisites for reading, made reading objectively more effective and subjectively less tiring.

In contrast to expectations, the experimental group did not show a significant improvement in the paradigm of focal attention.

Although all participants showed an improvement of target detection after the optimal focal cue (small squares) compared to the other cue

conditions, no improvement was observed in the comparison between pre and post training sessions.

Our results can be read as a sign that focal attention does not decrease with aging, and also as a reason why no improvement has been found.

On the other side we found a correlation between changes in fixation duration and critical print size of the RADNER that suggests that training has resulted in an improvement of the attentional window. Other paradigms are probably needed to verify the effect of attentional skills in reading of older adults and, specifically, about the possible relationship between the effectiveness of an eye-guided cognitive training and focal attention.

Little research has focused on the use of video game-based cognitive intervention, in particular for reading, in healthy people with the primary objective solely of strengthening attention and visual skills or to prevent their decay. Among these, the work of [Pasqualotto et al. \(2022\)](#) stands out, who sought to improve reading skills through a custom-made video game that mixes action mechanics and cognitive training in a group of children. The study showed that training with a game designed to address the different cognitive challenges that reading poses and to train one's attention and eye movements not only improved attentional control and reading skills, but also other fundamental components of the executive system. Possibly such an improvement in attention, executive functions, as well as reading, could also be obtained in an elderly population in future studies.

Using an existing real-time strategy video game to train executive functions in the elderly, [Basak et al. \(2008\)](#) have demonstrated a significant improvement in the measures of performance and a subset of cognitive tasks. These include task switching, working memory, short-term visual memory, and mental rotation.

Previous studies (for a review see [Pallavicini et al., 2018](#)) showed that both commercial- and ad-hoc non-commercial video games can train cognitive and emotional capacities in the healthy adult population (range: 18–59 years old), especially processing speed and reaction times. Specifically, regarding non-commercial video games, research has shown that short-term and visual working memory ([H. Lee et al., 2012](#); [Looi et al., 2016](#); [Nikolaidis et al., 2014](#)) and cognitive task-switching ([Montani et al., 2014](#); [Parong et al., 2017](#)) improved after video game training.

In accordance with the results of our study, it would therefore seem that when the tools used are created specifically on the basis of neuropsychological characteristics to be trained, they allow to obtain concrete results tailored to the objectives.

4.1. Limitations

The sample size was small and the assignment to the experimental and control groups was not made randomly. The study required participants to remain present at the University laboratories continuously for a period of time in order to conduct training using technological devices, during a period when Sars-CoV-2 was still present. Therefore, participants were assigned to either an experimental or control group based on their availability and willingness. A future randomized controlled trial should be run to prevent selection bias, which includes more participants, as well as a follow-up session. In this study, the effective effect size has been calculated for each task, making it possible to plan the proper sample size for a RCT. Also participants' prior familiarity with video games should be measured in a future study.

Another potential limitation of eye-guided video games is the possibility of experiencing annoyances due to the dynamic movement of certain commands (e.g., cybersickness, headache, and fatigue). This study strictly observed pauses between video games in order to prevent fatigue and unpleasant effects from occurring.

Future studies could take different directions. It may be possible to overcome the aforementioned limitations by expanding the sample acquired and improving the methodology used by implementing a complete RCT study. A different approach might be to consider newer technologies like virtual reality environments (VR headsets) with a built-in eye tracking system to improve reading in aging.

5. Conclusions

In summary, this study proposed video games and eye-tracking technology to improve reading for older people. We explored the feasibility and potential effectiveness of the training, and whether there were any statistical relationships between the improvement in reading performance and the improvement in visual, oculomotor, and attentional abilities. Taken together all our findings suggest that eye-guided video game training can improve reading performance and that this could be due to the improvement of oculomotor and some visual abilities, but not to focal attention.

In line with the literature (Kueider et al., 2012; Nguyen et al., 2022), our study, therefore, supports that cognitive training using video games, guided by eye movements and adapted to the participant's characteristics, can facilitate activity involvement and leads to cognitive enrichment. This result is even more impressive when one considers that reading has improved without having been trained with reading exercises themselves, since the video games did not anticipate their involvement.

The achievement of this result in the elderly population demonstrates the potential effectiveness of the training used and, in general, illustrates how video games designed with specific purposes are increasingly regarded as an effective method of improving various cognitive functions among the elderly.

This kind of video game can easily be made accessible for clinical use with the availability of more affordable and commercial eye trackers, as opposed to the custom built implementation performed using a research oriented eye tracker.

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CRediT authorship contribution statement

Ramon Pedrini: Writing – review & editing, Writing – original draft,

Software, Methodology, Investigation, Data curation, Conceptualization. **Cristina Costantini:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Sara Polato:** Writing – original draft, Investigation, Data curation. **Claudio Lira:** Software, Methodology. **Alessio Facchin:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Roberta Daini:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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