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ORIGINAL RESEARCH

Short-Term Effects of Video-Games on Cognitive Enhancement: the Role of Positive Emotions

Sandro Franceschini[1,2] · Sara Bertoni[1,3] · Matteo Lulli[4] · Telmo Pievani[5] · Andrea Facoetti[1]

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Abstract
According to established background knowledge, playing is essential in human development and a power remediation tool in clinical populations. In clinical interventions, the beneficial roles of playing have often been sought and investigated in the specific features of the game, rather than in the positive emotions generated by playing. However, regardless of game specifications, cognitive enhancement could be driven by the emotions linked to play. Establishing the causal connections between play and cognitive enhancement should allow us to determine how to involve play in therapy, prevention and educational programmes. Today, video-gaming is one of the most diffused forms of play. In the first crossover randomized controlled trial, we compared the short-term effects induced by shooting and puzzle video-games in visual perception, sensorimotor and reading skills in children with developmental coordination disorder and dyslexia. The funnier and more activating game enhanced breadth of visual perception and reduced sensorimotor and reading disorders. Visual perception, sensorimotor and reading improvements correlated with fun. In the second crossover randomized controlled trial, comparing the effects of the same shooting with a fighting video-game in healthy young adults, we show that regardless of game characteristics, changes in positive emotions correlated with contextual reading enhancement, while play-driven biochemical activation boosted single word and pseudoword reading. The short-term effects induced by play could be a useful clinical tool for the prevention and treatment of multiple cognitive disorders.

Keywords Emotion and cognition · Reading disorder · Sensorimotor disorder · Game therapy · Alpha-amylase

Introduction

In healthy people, play is part of the life milestone experiences. Play is present in humans from early childhood. Nevertheless today, through the use of technology, the gaming experience is daily available for adults and children both in clinical and non-clinical contexts (Horne-moyer et al., 2014; Pine et al., 2020; Primack et al., 2012; Zhonggen, 2019). Gamification of everyday activities, serious games and also commercial video-games appear to be effective tools, also for therapeutic setting, to facilitate the (re)habilitation of multiple behavioural and cognitive skills (Pine et al., 2020; Primack et al., 2012). Thus, a research question about the causal connection between video-game play and cognitive enhancement arises (Pavlas et al., 2010).

The Possible Role of Play

Most young and large parts of adults in primates, but also in rodents, carnivores, ungulates, elephants and cetaceans, devote a significant amount of time and energy playing. There are hundreds of play forms, social or solitary with and without the use of objects (Graham & Burghardt, 2010).

However, the evolutionary adaptive significance of play remains largely speculative. Play behaviour has been linked

✉ Sandro Franceschini
sandro.franceschini@unipd.it

1 Developmental and Cognitive Neuroscience Lab, Department of General Psychology, University of Padua, Via Venezia 8, 35131 Padua, Italy

2 Child Neuropsychiatry Unit, School of Medicine, University of Insubria, Varese, Italy

3 Department of Human and Social Sciences, University of Bergamo, Bergamo, Italy

4 Department of Experimental and Clinical Biomedical Sciences "Mario Serio", University of Florence, Florence, Italy

5 Department of Biology, University of Padua, Padua, Italy

to the presence of surplus of energy, instinct practice, recapitulation, training for unexpected events and simulation of behavioural patterns, as well as socialization (Graham & Burghardt, 2010). Nevertheless, play has large costs in terms of energy consumed, parental and social care needed and risks of predation. Seemingly, playing fighting seems not to enhance later fighting success, and social play does not reduce aggression and does not improve social cohesion (Sharpe, 2005). Thus, it seems that playing is different from a kind of exercise.

Play engages young mammals in vigorous complex actions, and this activation state partially modifies their perceptual and sensorimotor systems, allowing the development of new cognitive skills (Graham & Burghardt, 2010). In humans, it has been shown that play co-occurs with some other fitness-enhancing capacity, like the ability to use and combine symbols. Children play with an object "as if" it is something else, creating semantic links between objects' representations. "As if" playing appears related not only to emotion regulation, but also to language development, logical reasoning and visual object recognition (Lillard, 2017; Smith & Jones, 2011). However, attempts to find a causal link between the play and specific cognitive enhancements were inconsistent so far (Lillard, 2017).

It has been hypothesized that play facilitates the development of social competence, self-regulation, creativity and problem solving (Nijhof et al., 2018), as well as physical and psychological resilience (Pellis & Pellis, 2017). Like anxiety, that changing the level of arousal could prepare for fight or flight response, play could prepare to interact with the environment, activating a specific emotional state, functional during and immediately after the play (Fredrickson, 2004; Fredrickson & Branigan, 2005). Play is an activity practiced to obtain fun in free time (Garvey & Lloyd, 1990). Joy sparks the urge to play (Fredrickson, 2001) and vice versa. Play is also a highly rewarding activity, meaning that its costs have been balanced by significant evolutionary advantages.

Positive Emotions and Cognitive Enhancements

Fredrickson (2001, 2013) showed that positive emotions, such as fun, seem able to increase not only the size of perceptual span, but also cognitive integration of multiple sources of information. A meta-analysis on hedonic tone effects confirms that happiness and fun experiences promote fluency and lexico-semantic abilities, inducing a positive and active state (Baas et al., 2008; Rowe et al., 2007). Positive emotions facilitate the global extraction of visual stimuli in the Navon task (Basso & Lowery, 2004; Fredrickson, 2004; Fredrickson & Branigan, 2005; Johnson et al., 2010; see Fig. 4 A for an example), as well as the thought-action fluency (Fredrickson & Branigan, 2005). A connection between global visual perception and lexico-semantic abilities has been observed also in studies on caffeine effects. In particular, global perception of Navon figures (Navon, 1977), lexico-semantic abilities and contextual reading fluency were selectively enhanced by caffeine (Brunyé et al., 2012; Franceschini et al., 2020), without any effect on local perception.

The effects of positive emotions – commonly induced with evocative film clips, self-generated stories or bags of candy – are relatively small (r = .15) (Baas et al., 2008). Nevertheless, positive images, food or music could be enjoyable, but that does not necessarily entail a feeling of fun (Posner et al., 2005). Thus, play – strictly linked with fun and fulfilment – could be the best tool to observe more relevant effects (Posner et al., 2005). Longitudinal studies on kindergarten children confirm that an increase of fun engagement in academic tasks was related to a higher level of academic achievement (Lillard et al., 2017).

Considering that mammals play despite the great diversity in brain size, habitat, home range size, body size, locomotor pattern, social organization, life history and diet (Graham & Burghardt, 2010), and that many other animals (such as birds, and especially corvids) play a lot throughout their life, it is likely that play, regardless of the game characteristics and contexts, generates a positive and active state. This activation state could be ruled by a network acting as a scaffold to simultaneously integrate multiple information that facilitate broader thought and actions.

Video-Games and Learning

In the last century, one of the most appreciated forms of play in humans is video-gaming. About 2 billion people across the world, belonging to the most diverse cultures, spent part of their free time playing video-games (Entertainment Software Association, 2019). Recent research on the benefits of video-games in rehabilitation settings indicates that video-games are often equivalent to more traditional treatments and may be more enjoyable or acceptable. Patients enjoy and benefit from interventions that use video-games in health care and psychological health settings, with a variety of diagnoses and therapeutic goals (see Horne-Moyer et al., 2014 for review). Although methodological concerns include the lack of randomized controlled trials for many applications, multiple evidence highlights that video-game use in clinical and educational settings could improve therapy outcomes (Primack et al., 2012; Pine et al., 2020 for reviews). Thus, video-games appear a good trans-cultural candidate to evaluate the effect of fun induced by play on behavioural and cognitive skills of children and adults, with and without neurodevelopmental disorders.

A debate about the long-term effects of training with video-game is still open in many fields, for example, aggression (Bensley & Van Eenwyk, 2001) or prosocial behaviours (Gentile et al., 2009). The possible effects of video-game on behavioural and cognitive skills have been described mainly by studying the effects of the action video-games (AVG). AVG are characterized by specific features including extraordinary speed (both in terms of very transient events and in terms of the velocity of moving objects), a high degree of perceptual, cognitive and motor load in the service of an accurate motor plan (multiple items that need to be tracked and/or kept in memory, multiple action plans that need to be considered and quickly executed typically through precise and timely aiming at a target), unpredictability (both temporal and spatial) and an emphasis on peripheral processing (Green et al., 2010). It has been shown that training with AVG – mainly shooting games – should have beneficial effects on attentional control, working memory (Dale et al., 2020; Bavelier & Green, 2019; but see Hilgard et al., 2019), sensorimotor (Granek et al., 2010) and in higher cognitive functions, such as reading (Franceschini et al., 2013). Nevertheless, long-term effects should be obtained only after 10–50 h of repetitive exercises training.

The short-term effect on behavioural and cognitive enhancement of video-game play per se, and its connection with emotional changes, is less studied and understood (Granic et al., 2014). Similarly to fighting games in rats (Pellis & Pellis, 2013, 2017), video-games play in humans facilitate immediate anxiety management and could improve engagement in intervention programmes (Pine et al., 2020).

Skosnik et al. (2000) showed that the stress provoked by 15 min of a shooting game – measured through the quantification of salivary cortisol and a-amylase – was related to greater cognitive performance in a computerized global perception task. Nevertheless, it must be noted that children and adults playing do not simply become more activated, but they are also having fun (Palagi et al., 2004). De Lisi and Cammarano (1996) showed that men and women's mental rotation abilities improved after 20 min of a Tetris-like game, whereas women – but not men – improved performance also using a solitaire card game. However, fun and difficulty of video-games, happiness, stress and perceived activation after playing AVG, puzzle or Tetris were not measured. Consequently, it could not be distinguished if participants were playing or simply performing an exercise.

The impact of fun on cognitive enhancements in video-game play could be grasped in Kozhevnikov et al. (2018). They showed that in AVG players, about 20 min of AVG induced a state of well-being. Immediately after AVG, players improved their performance in visual perception and memory tasks compared to baseline performance (pre video-gaming) and compared to performance of video-game players that simply watched other video-game players playing. Improvements were observed in specific visuo-spatial attentional abilities, whereas other components of attention, like alerting, turned out to be unaffected. After enjoying their preferred game genre, people obtained a selective transient cognitive enhancement lasting for about 30 min. Interestingly, the observed positive attentional effects were similar to those obtained with the use of meditation techniques that are already part of mindfulness therapy (Obana & Kozhevnikov, 2012).

The Present Study

As suggested by literature on play in animals and humans (Berghänel et al., 2015; Graham & Burghardt, 2010; Pellis & Pellis, 2013, 2017), and on positive emotions and video-games (Fredrickson, 2004; Fredrickson & Branigan, 2005; Kozhevnikov et al., 2018), we suppose that play could facilitate the execution of tasks that involve multiple information processing, regardless of game features. As shown in studies on animals, we supposed that improvements could also be observed in sensorimotor tasks (Berghänel et al., 2015; Graham & Burghardt, 2010; Pellis & Pellis, 2013), in addition to unique human skills, such as reading.

The principal aim of our study was to use play as a powerful evolutionary selected behaviour capable of exerting a large, consistent and domain-general effect of positive emotions on cognitive functioning, ranging from children with complex neurodevelopmental disorder to healthy adults.

Cognitive enhancement had already been demonstrated in healthy adults (e.g. Kozhevnikov et al., 2018; Obana & Kozhevnikov, 2012). However, in Kozhevnikov et al. (2018), the characteristics and genre of the game were not manipulated, being studied only the short-term effect of playing AVGs in expert action video-gamers. More importantly, the effects of emotions induced by the game itself were not controlled (Kozhevnikov et al., 2018; Obana & Kozhevnikov, 2012). Thus, the aim of Experiment 1 was to verify whether the short-term effect of video-games on cognitive enhancement was also present in a population of children with neurodevelopmental disorders, measuring also the emotional state induced by video-games. However, the findings of Experiment 1 were compatible with two possible explanations: (i) the sensorimotor, perceptual and cognitive enhancements could be linked to the specific characteristics involved in AVG; (ii) the sensorimotor, perceptual and cognitive enhancements could be linked to positive emotions induced by funny video-game. In Experiment 2, we tested our hypotheses in a large group of healthy young adults. In a sample of adult typical readers, we compared the effects of the same shooting AVG with a fighting game (a non-action video-game NAVG). If the effects were only present after the AVG, we could conclude that the short-term effects

– similarly to the long-term effect observed after hours of training – correlate with the specific characteristics of the game. In contrast, if reading enhancements were only found after the emotionally preferred game, we can prove that the short-term cognitive enhancements are induced by play-driven positive emotions.

In the two experiments, we used crossover randomized controlled trials (Green et al., 2019). In the first experiment, we tested the short-term effects on cognitive enhancements of fun induced by playing a shooting AVG and a puzzle video-game (a typical NAVG) in a sample of children with developmental coordination disorder (DCD) and dyslexia (DD). The dependent variables were visual perception, sensorimotor and reading performance.

Material and Methods

The entire investigation process was conducted according to the principles expressed in the Declaration of Helsinki. Written informed consent was obtained from the parents of the children participating in Experiment 1 and from the adults participating in Experiment 2. All procedures were jointly approved by the Ethics Committee of the University of Padova. For both experiments, analyses were conducted by a researcher blind to the characteristics of the games. Bonferroni and Greenhouse-Geisser corrections were used in analysis of variance (ANOVA) statistics.

Experiment 1: Children with DCD and DD

Participants

Nineteen children (4 females and 15 right-handed) from 2nd to 5th grade primary school participated in the experiment. Children were recruited from specialized clinical centres. Children received a diagnosis of DCD and DD by the Italian National Health Service, based on standard exclusion criteria [APA, 2013; DCD a total score in the Movement Assessment Battery for Children (Henderson & Sugden, 1992) equal or below the 16° percentile; DD at least one performance in pseudoword and word reading or text comprehension below-1.5 standard deviations; see Table 1]. All the children have a full IQ equal or above 85 (mean full IQ of the sample = 98 and SD = 8). Although the video-games experience – measured by the questionnaire on video-game experience (Franceschini et al., 2013) – was greatly variable across the selected participants (range from less than 15 min up to more than 14 h per week; mean= 5.58 hs, SD=4.3), all children were able to play with video-games. All participants stated that they had never played the two types of video-games selected in the present study.

Sample size was established based on previous literature (Bavelier & Green, 2019). A power analysis using the Gpower computer programme (Faul et al., 2009) indicated that a total sample of 15 participants would be needed to detect small effects (d = .35) with 80% power using an F test for a repeated measure, within factors analysis of variance (ANOVA) with alpha at .05.

Procedure

A single-blind crossover randomized controlled trial was used. All the children were evaluated three times, 1 week apart each time: a pre-test evaluation (baseline) and two experimental sessions. In baseline were collected reading, sensorimotor and visual perception skills (see Fig. 1 A). In both experimental sessions, in counterbalanced order, children played for 60 min one of two video-games: "Bust-a-move" (puzzleG; Pan European game association evaluation, PEGI=3 years) or "Geometry Wars: Galaxies" (shootingG; PEGI=3 years). Both games were played on a Nintendo DS. In Bust-a-move, the aim is to clear each board of bubbles by using the special bubble launcher. Shoot the coloured bubbles to link 3 or more of the same colour, thus eliminating them from play. In Geometry Wars, the gamer is a geometric ship trapped in a grid world, facing off against waves of multiple geometric enemies. The aim is to shoot them down for points and to survive long enough to set a high score. The duration of video-games administration was chosen to allow children to become familiar not only with the sensorimotor requests of the device, but also with the rules of the video-game itself. The two video-games were selected because both were: (i) used on the same portable device (i.e. Nintendo DS); (ii) free of complex game rules; (iii) easily playable even by children with sensorimotor coordination difficulties; (iv) characterized by oculo-motor coordination; (v) characterized by an increase in the level of challenges; and (vi) theoretically comparable in terms of engagements for children. Although the two video-games involved visual and auditory stimulation, they were largely different in terms of the presence/absence of AVG characteristics (i.e. an extraordinary speed, a high degree of perceptual, cognitive and motor load, temporal and spatial unpredictability and an emphasis on peripheral processing). Finally, the specific third-person shooting AVG was selected because the same video-game could be also played – using a different device – by healthy adults (see Experiment 2). Children in both games were instructed to do their best to reach the maximum score. The questionnaire concerning the self-evaluation of game and emotions was administered after each video-game. The questionnaire was developed to measure the basic emotional states induced by video-games. Then, word and pseudoword reading, as well as sensorimotor and visual perception skills, were measured.

Table 1 Individual data (gender, chronological age, reading and sensorimotor skills, video-games experience and comorbid diagnosis) of the 19 children with developmental coordination disorder and dyslexia

N	Gender*	Age (years)	Word list time	Word list errors	Pseudword list time	Pseudword list errors	Pseudword text time	Pseudword text errors	Reading comprehension	Mov. ABC Tot	Hours of video-game playing per week	Comorbid diagnosis**
1	M	8.8	−3.72	−1	−3.39	−1.60	−3.41	−5.58	−1.03	5°	0.1	dysg, dysor, dysc
2	M	10	0.32	0.67	0.73	−0.50	−0.42	−0.76	−1.85	3°	7	dysor dysc
3	M	11	−4.69	−1.67	−2.6	−2.25	−1.44	−2.25	−2.4	< 1°	1	dysor, dysc
4	M	10.3	−7.88	−5	−5.54	−4.75	−9.47	−12.64		4°	7	dysor
5	M	8	−4.63	−1.29	−6.12	0.20	−5.16	−1.73	−1.5	2°	7	dysc
6	M	9.4	−3.55	−2	−1.83	0.00	−4.03	−0.25	−2.86	5°	7	dysg, dysc
7	M	9.8	−0.29	−1	−0.21	−0.50	−0.83	−1.78	0.34	< 1°	3	dysg, dysor, dysc
8	M	10.9	−1.22	−1	−0.11	0.00	−0.91	−10.05		8°	14	
9	M	8.6	−0.91	−2	−0.61	−0.80	−3.54	−0.77	−1.94	15°	7	dysg, dysor
10	M	10.3	−2.87	−3.67	−2.87	−3.50	−0.98	−10.41	−0.12	< 1°	10	dysg, dysor, dysc
11	M	10.2	0.39	0.67	0.66	0.25	0.39	−1.60	−1.49	15°	2	dysc
12	M	10.0	−2.53	−0.33	−2.07	0.25	−2.52	−1.60	−1.94	11°	14	dysor
13	M	9.1	−3.8	−4	−1.71	−2.25	−3.69	−6.35	0.79	1°	7	dysg, dysor, dysc
14	M	10.3	−5.84	−3	−2.05	−2.00	−2.46	−20.44	−0.7	13°	7	dysg, dysor
15	F	9.46	−14.9	−4	−8.36	−3	−11.02	−5.33		< 1°	0.5	dysg, dysor
16	F	8.95	−6.2	−4.25	−1.13	−3.8	−6.71	−9.42		9°	5	
17	F	8.18	−2.49	−2.5	−1.52	−1.4	−2.76	−4.62		16°	0.25	Dysg, ADHD
18	M	8.13	−0.06	−0.04	0.32	0.2	−0.17	−1.73		1°	6	dysg, dysor
19	F	9.01	−2.29	−1.75	−1.87	−0.8	−3.41	−3.65		5°	0.5	dysg, dysor

*Gender: *M* male, *F* female. ***Dysg* dysgraphia; *Dysor* dysorthographia; *Dysc* dyscalculia; *ADHD* attention deficit and hyperactivity disorder. Reading abilities are reported in Z scores. Sensorimotor abilities are indicated in percentiles. Video-games experience is reported in hours per week

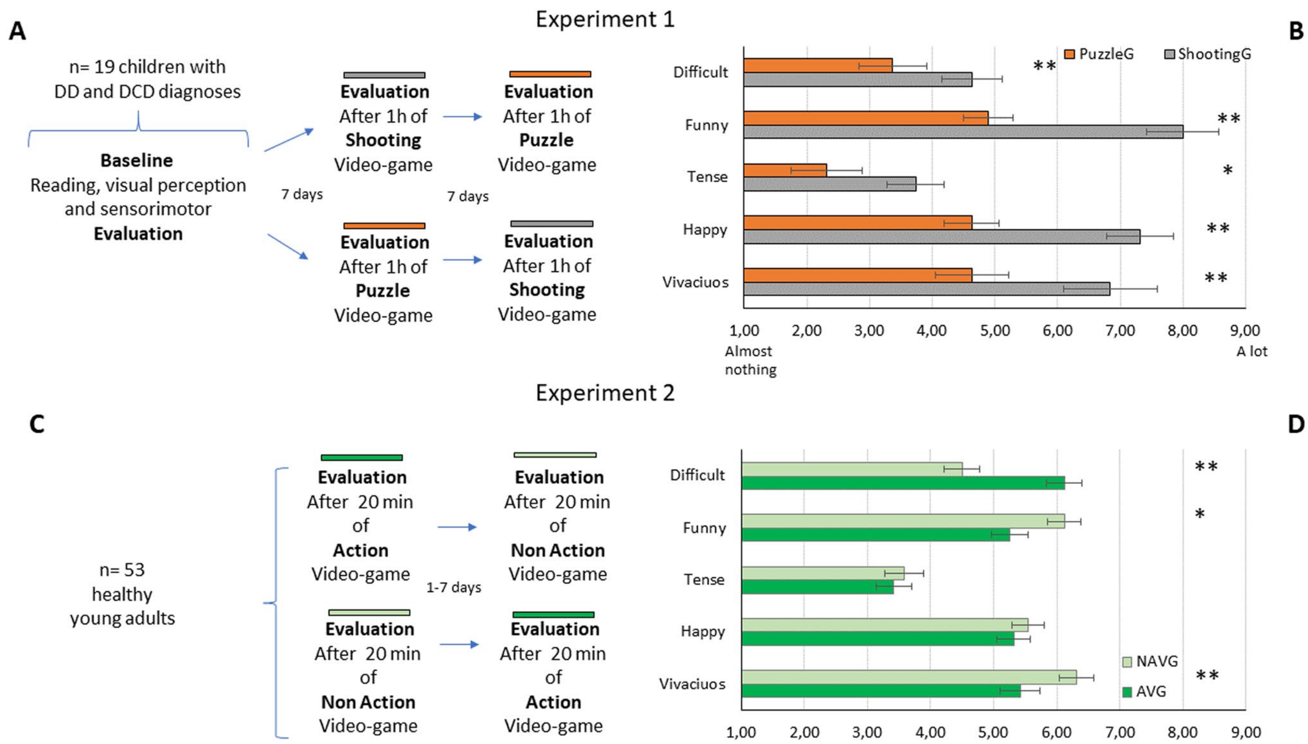

Fig. 1 **A** Design description of Experiment 1. **B** Item ratings of children in video-games and self-evaluation questionnaire administered after the video-game sessions. For each item of the questionnaire, participants were invited to indicate on a 9-point scale (from "almost nothing" to "a lot"), the video-game characteristics (first 2 items) and their feelings (least 3 items). **C** Design description of Experiment 2. **D** Item ratings of adult typical readers in video-games and self-evaluation questionnaire administered after the video-game sessions. Data are reported as means ± standard error means (SEMs). Asterisks indicate a significant difference (*< .05; **< .01)

At the beginning of any clinical evaluation, the administrator is advised to put the child at ease, based on the characteristics of the child. Thus, the emotional tone at each phase of the study was controlled, reducing children's potential nervousness and making children more comfortable.

Baseline Evaluation Tasks

Reading skills We measured the reading abilities using clinical standardised word and pseudoword lists reading test (Sartori et al., 1995) and pseudoword text (Franceschini et al., 2016). Comprehension data were provided by clinical centres.

Sensorimotor skills Four tasks selected from the Movement ABC (Henderson & Sugden, 1992) were administered. The same tasks were administered independently from the age of the children. The four tasks were administered each time following the standard instructions, except for the different indications below. Tasks were administered in the following order.

1. Placing pegs: Children have to rotate 12 pegs in the holes of a board. Each hand was tested two times, dominant hand first. Time and errors were measured. In order to obtain a single coefficient, the inefficiency index score was calculated dividing the execution time (in seconds) for the accuracy rate.
2. Catching with one hand: Children have to throw a tennis ball on a wall and catch it with the same hand. Each hand was tested two times (10 + 10 trials), dominant hand first. A number of catches were measured, and the mean was analysed.
3. Standing on a leg: Children have to maintain balance on a leg on a balance board. Each leg was evaluated two times, dominant leg first. The number of seconds was measured (max 20 seconds in each trial). Mean number of seconds was analysed.
4. Throw a beans bag into a box: In this task the preferred hand was tested two times (10 + 10 trials). Mean number of hits was analysed.

Visual perception Navon tasks The rapid naming of global and local tasks, both congruent and incongruent figures, was administered. In the global task, children were invited to name aloud the larger figures represented on a paper sheet, independently from the local figures. In contrast, in the local task, children were invited to name aloud the smaller figures, independently from the global figures. Global and local figures could be congruent (for example a square composed by squares) or incongruent (a square composed by triangles; for details see Franceschini et al., 2017; see Fig. 4). Execution times and accuracy were measured. Because accuracy was at ceiling, only execution times (in seconds) were analysed.

Experimental Session Tasks

Video-games and self-evaluation questionnaire A 5-item questionnaire was administered. Children have to indicate on a 9-point scale how much the game just played was "difficult" and "funny". They have to indicate how much they evaluate themselves: "tense", "happy" and "vivacious".

Reading skills The word and pseudoword experimental lists and the pseudoword text were administered in counterbalanced order in the two sessions.

Word Reading Abilities

Two lists of 72 words, paired for number of letters (6–9) and frequency (list 1 mean = 123, standard deviation, SD = 183; list 2 mean = 123.5, SD = 178), were used (Franceschini et al., 2020). The two lists were administered in counterbalanced order in the two sessions between participants. Words that were wrongly read were counted as one error independently from the quantity of wrong letters or syllables pronounced. Speed (in syllable for second) and errors were recorded. Self-correction was not classified as an error.

Pseudoword Reading Abilities

Pseudoword lists: Two lists of 36 pseudowords, paired for letters number (6–9), were used. Pseudowords were made up starting from the word reading task lists, inverting syllables and in some cases changing syllables between the two lists. Speed and errors were evaluated as in the word reading task.

Pseudoword text reading: Phonological decoding ability was measured using three texts, each of 46 pseudowords composed of 1–3 syllables (same syllables in different order for each text) for a total of 100 syllables for each text (Franceschini et al., 2016). Texts were administered in counterbalanced order in the different sessions between participants. All participants were invited to read each text aloud as quickly and as accurately as possible. Speed and errors were evaluated as in the word reading task.

Sensorimotor skills and visual perception Navon task: The same sensorimotor and Navon tasks used in the baseline evaluation were used after the shooting and puzzle video-games.

Results

Video-games and self-evaluation questionnaire

Paired sample *t* tests show that evaluations in the questionnaire differed in each item. The shootingG was largely preferred. Despite it being evaluated more difficult, it was largely funnier than the puzzleG, and after playing the shootingG children were happier, more tense and more vivacious (all ps $< .04$; see Fig. 1 B and supplementary information (SI) Table A2).

Reading Skills

Word Reading

Word list reading speed (syll/sec) and errors after shootingG and puzzleG were compared. Reading speed was significantly increased after shootingG (mean = 1.43, SD = .86) compared to puzzleG (mean = 1.33, SD = .83; $t_{(18)} = 2.611$, $p = .018$ Cohen's d = .599, 95% confidence interval (CI) = .102/1.082). Fifteen of the nineteen children (about 80%) improved their reading speed. In the same direction, a significative effect was observed also in number of errors (shootingG mean = 6.79, SD = 5.03, puzzleG mean = 9.05, SD = 4.86; $t(18) = 4.689$, $p < .001$ Cohen's d = 1.076, 95% CI = .497/1.635; see Fig. 2 A, C). Fourteen of the nineteen children (about 75%) improved their accuracy (see SI Fig. A1 panel A).

Pseudoword Reading

Pseudoword text reading: Repeated measures analysis of variance (ANOVA) on reading speed (syll/sec) in baseline, shootingG and puzzleG conditions was significant ($F_{(2,36)} = 5.849$, $p = .008$, $\eta^2 = .245$). Post-hoc comparisons showed a significant difference between baseline (mean = 1.15, SD = .43) and shootingG (mean = 1.29, SD = .49, p = .008, Cohen's d = .796), and between baseline and puzzleG (mean = 1.27, SD = .50, p = .034, Cohen's d = .647), but not between shootingG and puzzleG (p = .99, Cohen's d = .107) condition, indicating an effect of familiarization in the phonological decoding task.

Repeated measures ANOVA on errors was also significant ($F_{(2,36)} = 4.712$, $p = .021$, $\eta^2 = .207$; Fig. 2B and D). Post-hoc comparisons showed no significant differences (all ps $> .062$). Only direct comparisons showed a significant difference between the number of errors in baseline (mean = 11.73, SD = 8.39) and shootingG (mean = 9.58, SD =

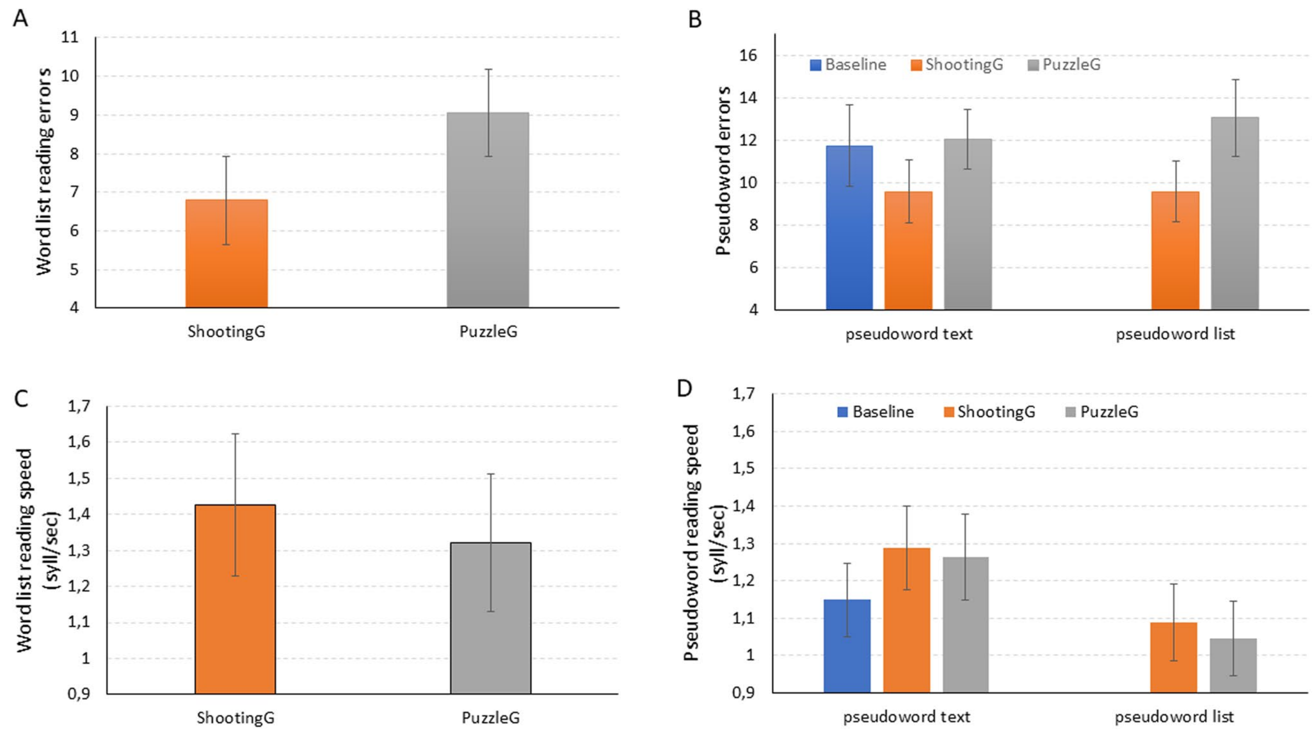

Fig. 2 Mean performance (errors and speed) of children with DCD and DD after the shooting and the puzzle games in word reading list (**A** and **C**) and in the pseudoword text and pseudoword list (**B** and **D**). Data are reported as means ± SEMs

6.47, $t_{(18)} = 2.265$, p = .036, Cohen's d = .52, 95% CI = − .03/.993) and between shootingG and puzzleG (mean = 12.05, SD = 7.84, $t_{(18)} = 2.531$, p = .021, Cohen's d = .581, 95% CI = .086/1.061), but not between baseline and puzzleG conditions ($t_{(18)} = .474$, p = .642, 95% CI = − .558/.344).

To better understand the effects, pseudoword reading skills (list and text) after shootingG and puzzleG were analysed using two ANOVAs with 2 (test: list and text) × 2 (game: shootingG and puzzleG) design. In reading speed, only the main effect of task was significant ($F_{(1,18)} = 23.214$, $p < .001$, $\eta^2 = .563$): pseudoword text (mean = 1.28, SD = .49) was read faster than the pseudoword list (mean = 1.07, SD = .44). In contrast, in reading errors, a main effect of the game was found ($F_{(1,18)} = 11.711$, p = .003, $\eta^2 = .394$). Post-hoc analysis showed that after the shootingG (mean = 9.58, SD = 5.94), participants committed a lower number of errors than after the puzzleG (mean = 12.55, SD = 7.39, Cohen's d = .778, 95% CI = .254/1.286; Fig. 2 B, D and SI Fig. A1, panel B, C).

All these analyses were conducted also splitting the sample in two subgroups with performance above or below the mean reading skills in the standardized reading task of Table 1. The main results were not affected by reading skills. Similarly, the sample was also divided on the basis of main hours of video-games per week (see Table 1). The main results were not affected by previous video-games experience.

Sensorimotor Skills

1. Placing pegs

The inefficiency index (time/accuracy rate) was calculated. A repeated measures ANOVA on the three conditions (baseline, shootingG and puzzleG sessions) was executed. The ANOVA on inefficiency was significant ($F_{(2,26)} = 11.253$, $p < .001$, $\eta^2 = .385$). Post-hoc analysis showed that inefficiency was significantly reduced after shootingG (mean = 133.94 SD = 24) in comparison to baseline (mean = 150.64, SD = 26.42, p < .001 Cohen's d = 1.042, 95% CI = .47/1.595) and puzzleG (mean = 145.36, SD = .28.2, p = .011 Cohen's d = .762, 95% CI = .241/1267; Fig. 3 A and SI Fig. A2 panel A and B). Seventy-nine per cent of children improved their performance. No significant difference was present between baseline and PuzzleG (p = .503, Cohen's d = − .33, 95% CI = −.788/.137).

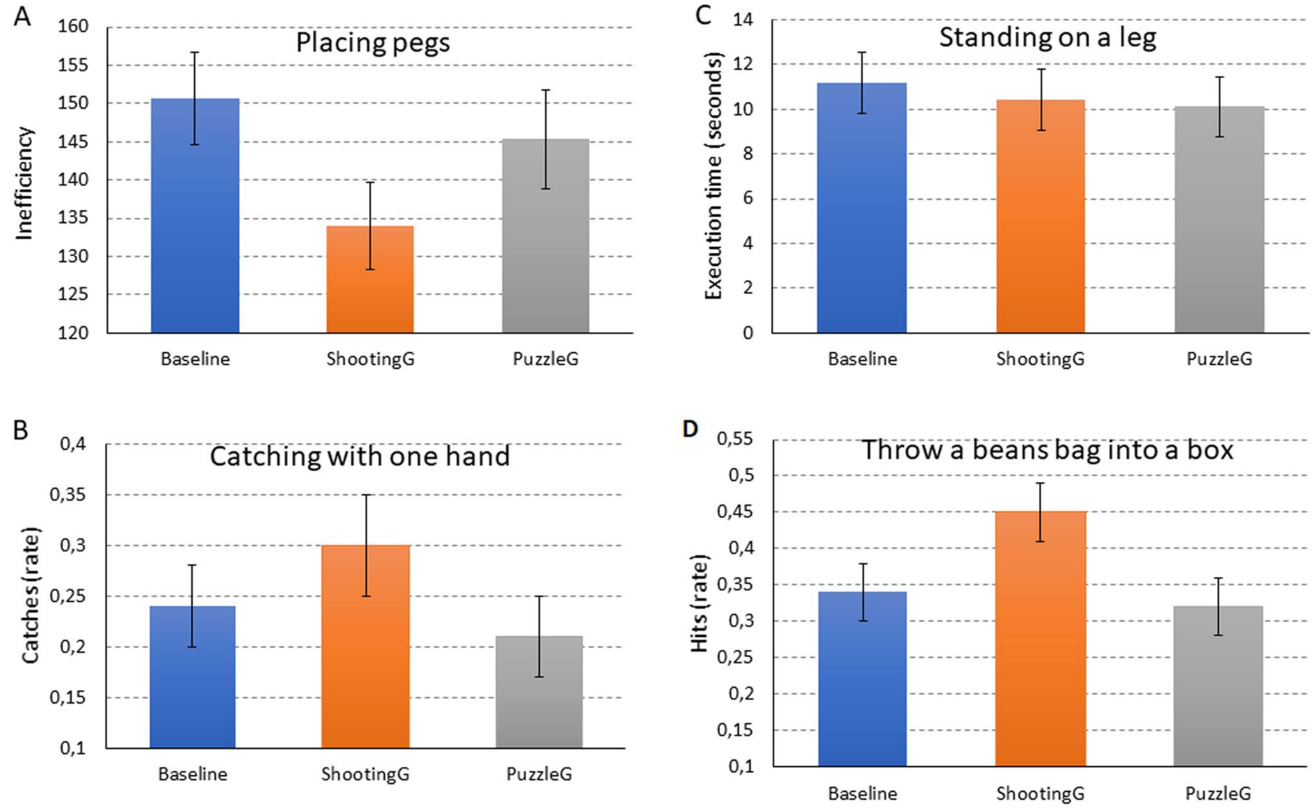

Fig. 3. Mean performance of sensorimotor tasks in children with DD and DCD. Panel A shows the inefficiency score in Placing pegs task, panel B shows catches in Catching with one hand task, panel C shows execution time in Standing on a leg task, panel D shows hits in Throw a beans bag into a box task. Data are reported as means ± SEMs

2. Catching with one hand

The repeated measures ANOVA showed a significant effect of condition ($F_{(2,36)}$ = 15.888, p < .001, η^2 = .469; Fig. 3 B and Fig. S2 panel C). Post-hoc analysis showed that the mean number of catches was higher after the shootingG (mean 2.99, SD = 2.01) than baseline (mean = 2.12, SD = 1.88, p < .001 Cohen's d = 1.234, 95% CI = .622/1.826) or PuzzleG (mean = 2.12, SD = 1.78, p < .001 Cohen's d = 1.148, 95% CI = .555/1.723). Eighty-four per cent of children improved their performance. No significant difference was present between baseline and puzzleG (p > .99, Cohen's d = 0, 95% CI= −.45/.45; Fig. 3 B and SI Fig. A2 panel C).

3. Standing on a leg

The ANOVA on mean time (seconds) was not significant ($F_{(2,36)}$ = .608, p = .55, η^2 = .033; Fig. 3 panel C and SI Fig. A2 panel E).

4. Throw a beans bag into a box

The ANOVA on the mean number of hits was significant ($F_{(2,26)}$ = 10.708, p < .001, η^2 = .373; Fig. 2 E). Post-hoc analysis showed that the mean number of catches was higher after the shootingG (mean = 4.45, SD = 1.78) than baseline (mean = 3.4, SD = 1.78, p < .001, Cohen's d = 1.155, 95% CI = .56/1.731) or PuzzleG (mean = 3.16, SD = 1.84, p = .004, Cohen's d = .874, 95% CI = .334/1.397; Fig. 3 D and SI Fig. A2 panel D). Seventy-nine per cent of children improved their performance. No significant difference was present between baseline and puzzleG (p = .476, Cohen's d = .167, 95% CI = −.288/.618).

Visual Perception in Global and Local Navon Task

Two children were identified as outliers (performance higher than three times the height of the boxes of descriptive statistics) and were excluded from the analysis.

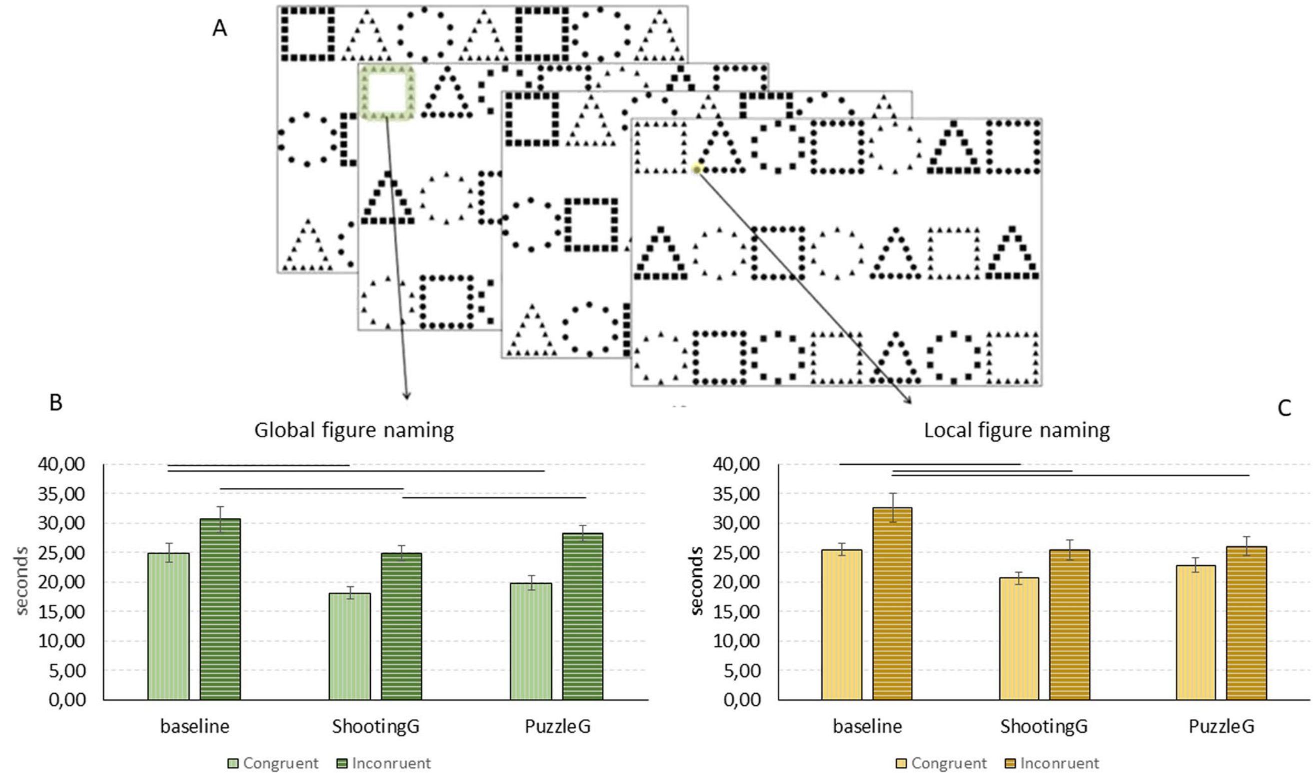

Fig. 4 **A** Visual perception Navon task. **B** Response time (in seconds) to global figure naming. **C** Response time to local figure naming. Data are reported as means ± SEMs. Horizontal lines indicate the post-hoc (Bonferroni correction) significant differences

An ANOVA on naming times (seconds) with 3 (condition: baseline, shootingG and puzzleG) × 2 (task: global and local) × 2 (congruence: congruent and incongruent) design showed that the main effect of condition ($F_{(2,32)} = 18.585$, $p < .001$, $\eta^2 = .537$) and congruence ($F_{(1,13)} = 44.095$, $p < .001$, $\eta^2 = .734$) were significant. Also the condition × task × congruence interaction was significant ($F_{(2,26)} = 3.626$, $p = .042$, $\eta^2 = .185$). Post-hoc (Bonferroni correction) showed that compared to baseline in both shootingG and puzzleG administration, there was a test-retest effect. Crucially, we observed that after shootingG, the naming time in global incongruent condition was significantly improved compared to both baseline (p = .005, Cohen's d = .908, 95% CI = .329/1.467) and puzzleG (p = .03, Cohen's d = .707, 95% CI = .164/1.232) conditions (see Fig. 4).

Correlations

The individual relationship between the change of the emotional states (measured by video-games and self-evaluation questionnaire) and the cognitive enhancements (reading, sensorimotor and visual perception skill) induced by the two video-games (shootingG and puzzleG) was investigated by using a bivariate correlation analysis. The five items of the game and self-evaluation questionnaire were not significantly related (all ps > .11).

Delta score in the funny item was positively correlated to the reduction in the mean number of errors in word and pseudoword reading tasks (r = .55, p = .016) and to the enhancement in the number of hits in throw a beans bag into a box task (r = .53, p = .02). Delta score in the funny item was also marginally related to the acceleration in the Navon global incongruent condition ($r_{(17)} = .48$, $p = .054$), but not to reading performances (all ps > .07). In addition, the delta score in the happiness item was related to the score improvement in catching with one hand task (r = .48, p = .038) and to the improvement in pseudoword reading tasks time (r = −.48, p = .036).

Experiment 2: Adult Typical Readers

The aim of Experiment 2 was to investigate whether the short-term effects of video-game playing on sensorimotor, perceptual and cognitive enhancement – observed in Experiment 1 – were caused by the specific characteristics of the shooting game (as demonstrated in long-term effects of AVG training; Bavelier and Green, 2019). Thus, the same third-person shooter video-game used in Experiment 1 was also employed in Experiment 2. To challenge the possible generalization of the findings found in Experiment 1 and in Experiment 2, we measured the effects of gaming in a large sample of healthy adults.

However, the results of Experiment 1 suggest an alternative hypothesis in which positive emotions – induced by play itself – could be linked to cognitive enhancements, regardless of the specifications of the video-game. To better test this alternative hypothesis, we selected a more emotional fighting video-game as NAVG than those used in Experiment 1. We studied only reading skills, since reading represents a complex cognitive function, as a unique cognitive function in humans, in addition to involving a close interaction with sensorimotor spoken language skills.

Material and Methods

Participants

The study originally involved 53 volunteers (44 females). The participants whose performance (or difference between performance in the two sessions) in reading tasks were higher than three times the height of the boxes of descriptive statistics analysis were excluded (n = 4). Mean age of the 49 participants (without outliers) was 24.25, SD = 5.23. Based on a video-game questionnaire (Franceschini et al., 2013), 29 of the 49 participants declared that in the last 6 months, their video-game experience was of at least 15 min for a month or more (mean hours per week = 2.69, SD = 3.7). No one declared to have experience with the games used in the experimental sessions. Sample size was established based on previous literature (Franceschini et al., 2020). A power analysis using the Gpower computer programme (Faul et al., 2009) indicated that a total sample of 49 participants would be needed to detect small effects (d = .35) with 80% power using a one tail (positive) correlation test with alpha at .05.

Procedure

Participants were tested twice at 1–7 days apart (see Fig. 1 C). Evaluations were scheduled in the morning, at the same hour. For each participant, a saliva sample was collected immediately before and after the end of video-game play. They were asked, before each session, to avoid consuming foods containing caffeine for 12 h and to sleep a number of hours adapted to their habits. The saliva samples were collected directly into 50-ml conical centrifuge tubes (Sarstedt, Nümbrecht, Germany) and stored at − 80 °C for the further analyses.

At the beginning of the two experimental sessions, participants were familiarized with the administrator and testing materials: a series of word and pseudoword list, as well as a pseudoword and a word text, was administered. In this familiarization phase, reading abilities of participants were evaluated administering clinical standardized word and pseudoword lists (Stella & Tintoni, 2007; see SI Table B1). In both experimental sessions, in counterbalanced order, participants played for 20 min one of two video-games: "Dead or alive 5" [NAVG; Pan European game association evaluation (PEGI) = 16 years] or "Geometry Wars 3: dimensions Evolved" (AVG; PEGI = 3+ years). In Dead or alive 5, the gamer impersonates a fighter of a martial arts tournament. A series of combatants face each other in one to one fighting match. Geometry Wars game contents were already described in Experiment 1. The two video-games were selected because they: (i) could be played with the same device; (ii) were free of complex game rules; (iii) requested oculo-motor coordination; and (iv) were characterized by an increase in the level of challenges. Finally, the AVG maintained the same characteristics of the shooting game of the first experiment, while the second game – without the typical AVG characteristics – could produce a similar level of engagement/fun. Both games were played on PlayStation3 with a 28-inch monitor. In both games, participants were instructed to do their best to reach their maximum score. Immediately after the period of play, the same self-evaluation questionnaire used in Experiment 1 was administered. Then, word and pseudoword reading were measured.

Experimental Sessions Tasks

Paper and Pencil Reading Tasks

Word text reading: Text reading abilities were evaluated using two texts of similar length and reading difficulty (Judica & De Luca, 1993). Reading speed (syllables per second) and number of errors were measured. The two texts were administered in counterbalanced order in the two sessions between participants. 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 word of the text. Reading speed was analysed by dividing the syllables by the reading time (syllables per second). A word wrongly read was counted as one error independently from the quantity of wrong letters or syllables pronounced. Self-correction was counted as a 0.5 error.

Pseudoword text reading: Phonological decoding ability was measured using two texts, each of 46 pseudowords composed of 1–3 syllables (same syllables in different order for both texts) for a total of 100 syllables for each text (Franceschini et al., 2016). The two texts were administered in counterbalanced order in the two sessions between participants. Decoding speed (syllables per second) and the number of errors were measured. All participants were invited to read each text aloud as quickly and as accurately as possible. A pseudoword that was wrongly read was counted as one error independently from the quantity of wrong letters or syllables pronounced. Self-correction was not classified as an error.

Computerized Reading Tasks

Single word reading task: Two lists of 48 words, paired for number of letters (6–9) and frequency (list 1 mean = 134, standard deviation SD = 217; list 2 mean = 135, SD = 215), were used. The two lists were administered in counterbalanced order in the two sessions between participants. Participants were instructed to keep their eyes on the black cross-fixation point (0.1° and 0.6 cd/m^2) on a grey computer screen (40 cd/m^2) for the duration of the trial. After a randomised quantity of time (500–750 ms), one word (colour = black, font = Courier New, size = 18, 0.4° for each letter) appeared at the centre of the screen. The target word remained on the screen until the participant answered. When the microphone was activated, the word was replaced by a mask. Vocal response time (in ms) and accuracy of each single response were recorded. Words that were wrongly read were counted as one error independently from the quantity of wrong letters or syllables pronounced. Five training trials were proposed before the experimental session.

Single pseudoword reading task: Two lists of 48 pseudowords, paired for letters number (6–9), were used. Pseudowords were made up starting from two word reading lists, inverting syllables and in some cases changing syllables between the two lists. Vocal response time (in ms) and accuracy of single responses were recorded. The administration procedure and evaluation were the same as the single word reading task. Five training trials were proposed before the experimental session.

Video-games and self-evaluation questionnaire

The same questionnaire used in Experiment 1 was administered.

Anxiety evaluation

We used the 20-item questionnaire adapted from the State-Trait Anxiety Inventory (Lazzari & Pancheri, 1980) to evaluate the state of anxiety. The total score was measured and analysed.

Cortisol and a-amylase evaluation

Cortisol and a-amylase were measured in all participants immediately before and after AVG and NAVG sessions. Immediately after thawing, the whole saliva samples were centrifuged 10 min at 3000×*g* to remove particulate material. Salivary cortisol levels were quantified in duplicated using a commercially, high sensitive solid-phase enzyme-linked immunosorbent assay (ELISA) kit (Cortisol Saliva ELISA, RE-52611, IBL International GmbH, Hamburg, Germany). Briefly, 50 ul saliva were added to each well of a microtiter plate and analysed according to manufacturer's instructions. Microtiter plates were read at 450 nm in an iMark Microplate Absorbance Reader (Biorad, Hercules, CA, USA). Salivary a-amylase levels were quantified in duplicated using a commercially, high sensitive solid-phase ELISA kit (alpha Amylase Saliva Enzymatic Assay, RE80111, IBL International GmbH). Briefly, saliva samples were diluted 1:300, and 10 ul of diluted saliva were added to each well of a microtiter plate and analysed according to manufacturer's instruction. Microtiter plates were read at 405 nm in an iMark Microplate Absorbance Reader (Biorad).

Table 2 Performance in the four reading tasks after the AVG and NAVG sessions

	AVG mean (SD)	NAVG mean (SD)	t value	p value	Cohen's d (95%CI)
Pseudoword text (syll/sec)	3.51 (0.69)	3.58 (0.73)	1.348	0.184	0.193 (−0.091/0.474)
Pseudoword text (errors)	1.94 (1.9)	1.96 (2.22)	0.072	0.943	0.01 (−0.270/0.290)
Word text (syll/sec)	5.67 (0.73)	5.71 (0.72)	0.896	0.375	0.128 (−0.154/0.409)
Word text (errors)	5.79 (4.21)	5.37 (3.55)	0.867	0.39	0.124 (−0.158/0.404)
Single pseudoword resp. time (msec)	637 (147)	632 (140)	0.522	0.604	0.075 (−0.206/355)
Single pseudoword (errors)	**5.4 (3.67)**	**4.75 (3.4)**	**2.474**	**0.017**	**0.353 (0.063/0.64)**
Single word resp. time (msec)	479 (101)	474 (80)	0.699	0.488	0.1 (−0.181/0.380)
Single word (errors)	0.39 (0.68)	0.43 (0.62)	0.34	0.735	0.049 (−0.232/328)

Significant difference (p<.05 are reported in bold)

Results

Anxiety, Video-Games and Self-Evaluation Questionnaires

Paired sample *t* test showed that the AVG was evaluated more difficult (Cohen d = .82), whereas the NAVG was evaluated funnier (Cohen d = .299). After the NAVG participants evaluated themself more vivacious than after the AVG (Cohen d = .415; see Fig. 1 D and Table B2 in SI), no other difference was significant.

Reading Skills

Comparing performance in reading tasks after the two video-games, we found an improvement after the NAVG in the accuracy of the single pseudoword reading task (12% of errors reduction, Cohen's d = .35; see Table 2).

Correlations As in Experiment 1, in order to investigate the link between positive emotions and cognitive enhancement, we calculated the delta score (i.e. difference after the AVG and NAVG) in the video-game self-evaluation questionnaire and in reading performance (errors and speed).

Delta score in the funny item was significantly related to all the three self-evaluations: "tense" ($r = -.45$, $p = .001$), "happy" ($r = .62$, $p < .001$) and "vivacious" ($r = .7$, $p < .001$). Crucially, the delta score in the "funny" item was also significantly related to the delta score in text reading errors ($r = -.36$, $p = .011$; see Fig. 5 A) and speed (syll/sec; $r = .31$, $p = .029$; see Fig. 5 B). Independently from game type, reading skill was ameliorated after playing the funnier game: funnier was the game, and better were the speed and accuracy in the text reading task (see Fig. 5). Also the delta scores of "vivacious" and "tense" self-evaluations were linked to the delta score in text reading errors ($r = -.37$, $p = .009$ and $r = .28$, $p = .048$), indicating that reading errors were reduced after playing the more positively activating game. No other correlation with reading abilities was significant (all ps > .059).

Delta score in the anxiety questionnaire was related to all the video-game questionnaire items: "funny" ($r = -.46$, $p = .001$), "tense" ($r = .42$, $p = .002$), "happy" ($r = -61$, $p < 001$) and "vivacious" ($r = -.51$, $p < .001$), but not to reading performances.

Regression Analyses

In order to establish the causal relationship between differences in emotions and reading skills after the two

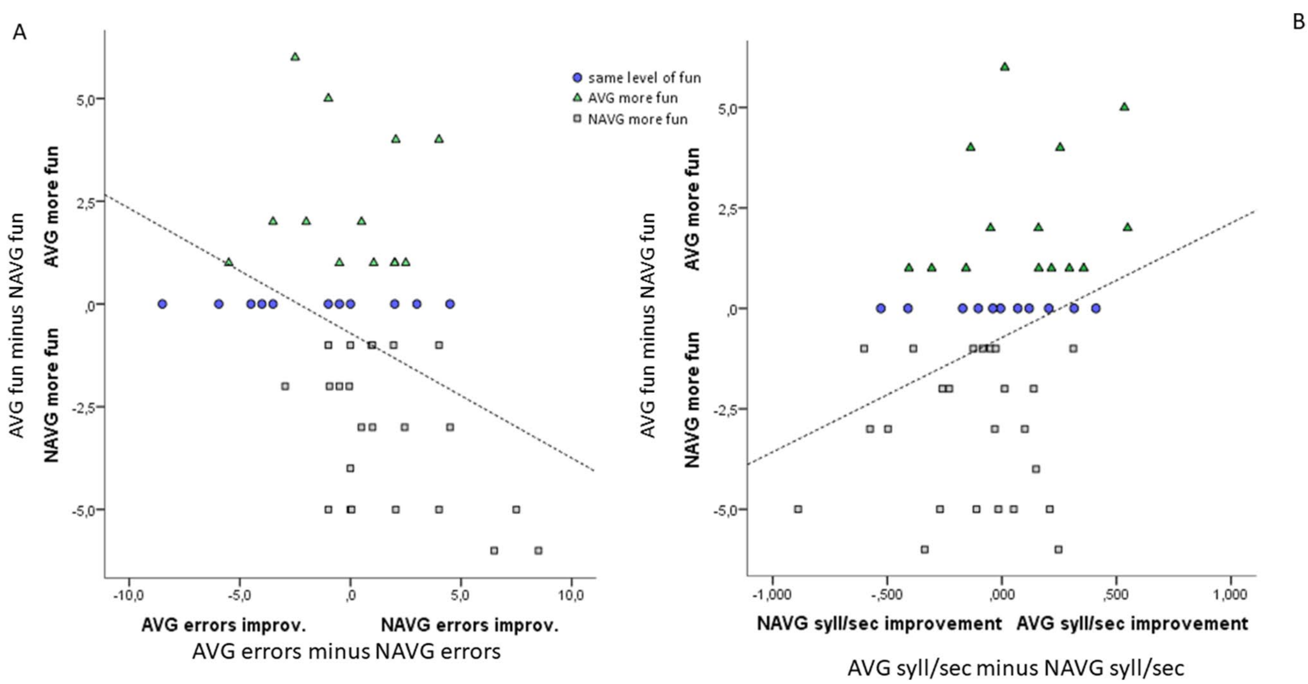

Fig. 5 Correlations between the differences in perceived fun (fun after the AVG minus fun after NAVG) and the changes of the number of text reading errors (AVG minus NAVG; **A**), as well as the change of the text reading speed (syll/sec; AVG minus NAVG; **B**) after the two video-game sessions

video-game sessions, we conducted two linear regression analyses. A single index of text reading performance was calculated. Based on the performance of the entire sample of participants, we calculated the z-score mean between speed and accuracy of each participant. This value was used as a dependent variable indexing the reading performance change.

The first linear regression analysis was conducted in order to measure the effect of the different levels of perceived fun between the two video-games on reading performance improvement, controlling for the possible influence of the difference in the tense level. The second linear regression analysis was conducted inverting the order of the two independent variables. Results of the first regression analyses show that tense difference, entered first, accounted for a significant amount of the variance (R^2 change = .11, $F_{(1,47)}$ = 5.829, p = .02). Entered second, the difference in fun explained an additional amount of unique variance (R^2 change = .11, $F_{(1,46)}$ = 6.27, p = .016). The second regression analyses showed that fun, entered first, accounted for a significant amount of the variance (R^2 change = .19, $F_{(1,47)}$ = 11.328, p = .002), whereas the difference in tense level was not significantly linked to difference in reading skills (R^2 change = .02, $F_{(1,46)}$ = 1.342, p = .253), after video-game play.

One Sample t Test

To measure the effects of fun on reading abilities, we divided participants in three groups, those that evaluated funnier the AVG (triangle group), the NAVG (square group) or the same level of fun (circle group; see Fig. 5). Differences versus zero (no change) in the three groups were executed. Only the group that evaluated the funnier the NAVG (squares in Fig. 5) showed a significant reduction in number of errors (mean = 1.56, SD = 2.91, $t_{(23)}$ = 2.633, p = .015; Cohen's d = .537 95%CI = .103–.961). The reduction in text reading errors was 21%, compared to the errors committed after the less fun game. The same group showed a significant improvement also in the reading speed (mean = .14 syll/sec, SD = .30, $t_{(23)}$ = 2.239, p = .035, Cohen's d = .457 95% CI = .031–.874). This reading speed enhancement was higher than the mean improvement expected in a college student (= 0.125 syll/sec) after 3 months of spontaneous reading development (Stella & Tintoni, 2007). In contrast, the other two groups did not show any significant variations in their reading performance (all ps > .194). These findings indicate that the participants that preferred – in terms of fun – the NAVG showed larger effects in this complex cognitive task requiring a broad lexico-semantic processing, but not in the other reading tasks requiring lexical or sublexical processing.

Salivary Biomarkers

Salivary cortisol and a-amylase concentration levels were normalized dividing each subject's raw hormone value by her/his highest measured. In this way values could range from above 0 to 1 (Hébert et al., 2005).

Similar to the results by Skosnik et al. (2000), analysis on salivary concentration of cortisol showed that its concentration was not changed by video-games: analysing the normalized levels of salivary cortisol, an ANOVA with a 2 (game: AVG and NAVG) × 2 (time: pre- and post-video-game) design showed no main or interaction effects (all ps > .154, η^2 = .043). Differences in cortisol variations (post minus pre) between the two video-games were not related to reading performance or emotional self-evaluations (all ps > .242; see SI table B3).

Analysing the normalized levels of a-amylase, an ANOVA with a 2 (game: AVG and NAVG) × 2 (time: pre and post) design showed that only the main effect of time was significant ($F_{(1,48)}$ = 4.559, p = .038, η^2 = .087). Main effect of game ($F_{(1,48)}$ = 1.822, p = .183, η^2 = .037) and time × game interaction ($F_{(1,48)}$ = .018, p = .895, η^2 < .001) were not significant (see SI Table B3). The last result showed that the a-amylase variations were not different after both video-games. Interestingly, the a-amylase variation between the two video-games was negatively related to both single word and pseudoword response time (r = − .37, p = .009 and r = − .29, p = .043, respectively). No other correlation was significant (all ps > .08).

Discussion

Although the functional and adaptive significance of play remains largely unknown, it has been shown that the long practice of play could facilitate the learning of behavioural abilities in rats (Pellis & Pellis, 2013), monkeys (Berghänel et al., 2015; Graham & Burghardt, 2010) and humans (Bavelier & Green, 2019). It has been shown that the symbolic play and visual object recognition by global shape and language follow a common developmental pathway (Smith & Jones, 2011).

Multiple evidences from different fields of biology and psychology show a circular connection between positive emotions and specific cognitive skills. Positive emotions elicit a global perception of visual processing (Fredrickson & Branigan, 2005; Gasper & Clore, 2002; Ji et al., 2019), and vice versa (Ji et al., 2019). Positive emotions enhance also lexico-semantic abilities (Baas et al., 2008; Rowe et al., 2007), and enlarged semantic information analysis and global perception appear to be related together (Brunyé et al., 2012, 2013; Franceschini et al., 2020; Gasper & Clore, 2002).

The aim of this research was to investigate the relationship between play-driven positive emotions and short-term effects on behavioural and cognitive enhancement and, consequently, the use of video-games as possible adjuvants in therapy.

In the first experiment, the funnier and more activating game enhanced breadth of visual perception and reduced sensorimotor and reading disorders in children with DD and DCD. In the second experiment, comparing the effects of the same shooting with a fighting video-game in healthy young adults, we show that regardless of game characteristics changes in positive emotions are correlated with contextual reading enhancement.

The results of the first crossover randomized controlled trial in children with DCD and DD showed that 1 h of fun and activating video-game allows children to read words faster and more accurately. Accordingly, phonological decoding improved in terms of accuracy. The speed and accuracy reading improvements exclude a speed/accuracy trade-off explanation (Nelson & Strachan, 2009).

The beneficial effects of play-driven fun were observed also in behavioural coordination. The performance was dramatically improved in three out of four sensorimotor tasks. The task that was not improved was one linked to balance abilities. We suggest that placing pegs, catching with one hand and throw a beans bag into a box tasks largely involve visuo-motor coordination and temporal aspects of visuo-spatial attention than standing on a leg task. It is possible that visuo-attentional abilities – also simply at a level of internally generated information – play a pivotal role in cognitive enhancement (Kozhevnikov et al., 2009). Nevertheless, it should not be completely excluded that the absence of improvement in the standing on a leg task could be due to the fact that the video-game sessions do not imply the use of legs. Finally, in line with literature on positive emotions (Fredrickson & Branigan, 2005), execution time in the global Navon task showed that after playing the funnier game, the extraction of global visual information was enhanced, and these improvements were related to the level of fun.

Thus, our results suggest that children with DCD and DD can reduce their sensorimotor and reading deficits simply by playing a funny game and activating AVG, probably enhancing the ability to synthesize multiple information as shown by selective enhancement in global perception. These findings confirm the existence of the enhanced cognitive states and suggest possibilities for accessing covert resources of our brain to temporarily boost our behaviours (Kozhevnikov et al., 2018). This enhanced cognitive state could be a powerful help in both educational and intervention programmes.

However, the results of Experiment 1 could be interpreted as an effect induced by the "action" characteristic of the video-game, rather than caused by positive emotion induced by playing with this video-game. Action video-games are characterized by the speed in terms of transient events and moving objects, the high degree of perceptual and motor load and the emphasis on peripheral processing (Bavelier & Green, 2019).

In order to disentangle this question, in the second crossover randomized controlled trial, we compared the same AVG used in Experiment 1 with a fighting video-game in a large sample of adult typical readers.

Interestingly, the results of Experiment 2 showed an improvement in pseudoword reading accuracy after the funnier fighting video-game. Crucially, changes in positive emotional states are correlated with speed and accuracy text reading enhancements. Moreover, only the participants that preferred the fighting video-game showed a significant improvement both in speed and accuracy text reading. These results suggest that positive emotions, triggered by different genres of video-games, could be the crucial factor.

Salivary biomarkers used in Experiment 2 confirm the role of physiological activation (Skosnik et al., 2000). Indeed, a-amylase variation was related to improvements in word and pseudoword reading speed. As expected, the participants must be in an active and positive state to obtain the effects, and a-amylase is a good tool to measure the state of activation, despite no direct link to the perceived condition of activation as shown by the absence of correlations with self-evaluations.

Thus, the results of Experiment 2 show that independently to the type and characteristics of video-game, the positive emotions and active state enhanced a complex behaviour, that is contextual reading fluency that requires a multiple information integration.

The evidence obtained in Experiments 1 and 2 indicates that the effects on cognitive skills did not appear linked to specific game genres. This could be important at the level of therapeutic use of video-games: whereas specific games (or serious-games) could be used to improve targeted abilities, the broadened effects in cognitive and sensorimotor skills linked to the perceived fun should be obtained by the use of preferred game genres. However, the specific video-game characteristics that make the game funnier and engaging should be further investigated in future studies.

Stressful situations and anxiety can induce a deterioration of sensorimotor abilities in humans and rats, also for well-rehearsed abilities (Pellis & Pellis, 2013; Pine et al., 2020). However, the direct correlations between fun and cognitive performance in both experiments, as well as the absence of any correlation between the variation of anxiety and the reading changes in the second experiment, show that play does not simply reduce the level of anxiety producing a generalized performance improvement. The correlation between enhancement of a-amylase and reading speed in word and pseudoword is not compatible with a general stress reduction. In contrast, play seems to trigger the activation of an orbito-frontal and limbic network favouring a broad integration of unconnected top-down and bottom-up information (Hipp et al., 2011). Moreover, regression analyses in Experiment 2 show that the perceived fun – more than the perceived level of tense – resulted causally linked to the text reading improvement. Similarly, in Experiment 1, the three evaluation sessions showed that a high level of fun improves performance (shooting game session), whereas a lower level of fun (puzzle game session) leads to show "as usual" (baseline) performance.

Compared to other procedures that induce a positive mood, such as positive images, food or music (Baas et al., 2008), video-games playing appears a more efficient way to induce positive emotions and an active state. This is fundamental, because at long term, play experience calibrates the stress-response mechanism allowing a more effective use of available social, cognitive and motor skills (Pellis & Pellis, 2013; Pine et al., 2020). Given their high ease of use and access, video-games appear to be an effective tool to enhance the efficacy of training and therapy, not only in presence of specific developmental motor coordination and reading related difficulties, but also in healthy adults. In this sense, the results of our study should also be confirmed by investigating the short-term effects of the same video-games in a large group of typically developing children, as well as adults with DD. Further studies could also control for these short-term effects using groups in which children do not play or play more traditional games (e.g. puzzles or lego®), evaluating multiple measures of emotional tone.

The presence of the same person at the time of administering video-games and neuropsychological evaluations could be a limit of our study. However, it should be noted that the administrators were blind to the purpose of the experiments and were trained to maintain constant methods of administration of the tests. Moreover, the reading tests were corrected offline by replaying the recordings, and the sensorimotor tests were administered and corrected following a standardized procedure.

The short-term effects reported here in complex cognitive and behavioural tasks could be an additional factor at the basis of the long-term effects obtained after video-games (Bavelier & Green, 2019; Colzato et al., 2010) and sport activities (Chaddock et al., 2011) training. Although we cannot definitively exclude that the differences in perceived fun could be linked to differences in the stimuli characteristics of the three video-games used here, previous studies had demonstrated that the short-term effect of cognitive enhancements is linked to engaging activities which are judged enjoyable by the players. Indeed, it is intriguing to note that video-games playing and active meditation improve multiple cognitive abilities in video-gamers and meditators, respectively (Kozhevnikov et al., 2018; Obana & Kozhevnikov, 2012).

The half-life of fun effects is about half an hour (Kozhevnikov et al., 2018). Nevertheless, it is interesting to note that long interventions that can last even 35 h for the treatment of reading disorders (McArthur et al., 2012) and motor coordination disorders (Jane et al., 2018) show effects size equal or smaller than the ones observed in our experiment with children with DCD and DD. Considering the large overlap of difficulties in sensorimotor, visual perception and attention, language and reading abilities, found in many neurodevelopmental disorders (Franceschini et al., 2017; Grinter et al., 2010), fun induced by play could be a key element in structuring multiple effective intervention programmes.

Although, at the best of our knowledge, no study has specifically investigated the long-term effects of fun on specific cognitive functions, it is intriguing to note that the Montessori educational methods, a largely studied preschool and school programme developed to stimulate the socioemotional and cognitive skills of children, promoting interactions and self-organization, seem effective in improving school performance and autonomy, energizing children during homework and making school activities more enjoyable (Lillard et al., 2017). Thus, further studies measuring the long-term effect of training programmes should also control fun and positive emotions, as well as short-term activation induced during the specific training.

Our results also reverberate on the remote causes of playing, showing that evolutionary hypotheses focused on the activation, through positive emotions, of cognitive skills in learning and development (e.g. facilitated execution of sensorimotor tasks, multiple information processing, global perception and reading abilities) seem at the moment more robust than hypotheses focused on other adaptations based on the idea that playing is an exercise for adulthood (e.g. instinct practice, recapitulation, training, simulation and socialization).

Broadening of visual, sensorimotor and semantic abilities appears strictly interrelated, and part of a specific network enforced by play with fun experience. Play with fun impacts on several behaviours, such as visual perception, sensorimotor skills and one of the most peculiar cognitive skills of our species: reading. These results could have direct implications for updating educational and intervention programmes that are crucial for human health and the promotion of well-being.

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Sara Bertoni: Conceptualization, methodology, software, validation, formal analysis, resources, data curation writing, visualization, supervision

Matteo Lulli: Methodology, validation, formal analysis, resources, data curation writing, visualization

Telmo Pievani: Writing, visualization, supervision, evolutionary topics

Andrea Facoetti: Conceptualization, methodology, validation, formal analysis, resources, data curation, writing, visualization, supervision

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Data Availability The datasets analysed during the current study are available from the corresponding author on reasonable request.

Code Availability Not applicable

Declarations

Ethics Approval The ethic committees of the University of Padua approved the research protocols (Children: n.1451; 1452; 1849; Adults: 2018_19 R2).

Consent for Publication Informed written consent was obtained for each child from their parents. Informed written consent was obtained for each adult.

Consent to Participate Informed written consent was obtained for each child from their parents. Informed written consent was obtained for each adult.

Conflict of interest The authors declare no competing interests.

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