Information Systems Frontiers

Serious games for the treatment of children with ADHD: the BRAVO project

--Manuscript Draft--

Manuscript Number:	ISFI-D-23-00224R1
Full Title:	Serious games for the treatment of children with ADHD: the BRAVO project
Article Type:	Manuscript
Keywords:	ADHD; Serious Games; Virtual Reality; Biofeedback; Emotional Activation
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Funding Information:	Ministero dello Sviluppo Economico (F/050415/01-03/X32 - CUP: B88I17000750008) — Dr. Annamaria Schena
Abstract:	Children affected by attention-deficit hyperactivity disorder (ADHD) exhibit several symptoms characterized by inattention, impulsivity and motor hyperactivity that impair both school performance and everyday life. The BRAVO (Beyond the tReatment of the Attention deficit hyperactiVity disOrder) project dealt with the development of several serious games based on extended reality that help patients improve in self-control, respect for rules, attention and concentration. In order to achieve both logopaedic and behavioral educational goals, serious games were developed concerning three different categories: Topological Categories, Infinite Runner and Planning. Experimental tests conducted over a six-month period assessed the patients' performance and the emotional impact of the games, also showing a general improvement in cognitive and behavioral functions.

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Dear reviewers,
first of all, we would like to thank you once again for your valuable comments and constructive suggestions, which helped us to improve the clarity of the exposition of concepts in our paper. We have carefully considered your suggestions, and in this revised version we have made the changes by highlighting the new additions in red and, for clarity, we have kept your comments in black while responding to them in blue.
We sincerely appreciate your time and effort in providing us with your valuable feedback. We hope that this revised version of the article meets your expectations and adequately responds to your suggestions.

Reviewer #1: The paper is interesting, concerning the topic, and well written.
However, there are several remarks.
It is not completely clear in Introduction part, how exactly the software works: is it for individual use, or a helping mean for a therapist. It would be good to write it shortly and clearly at the beginning, not only explain it later in the further sections.
We have added some sentences in the introduction to make this concept clearer.

Introduction part and literature review have more citations of older works than recent ones.
We added some references to more recent works in the Introduction and Related Work sections.

In page 12 there are 2-3 sentences that repeats exactly the same in the same page.
At the beginning of section 3.5, we removed the redundant sentences that repeated the same concepts.

Discussion is well presented.

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Serious games for the treatment of children with ADHD: the BRAVO project

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Abstract Children affected by attention-deficit hyperactivity disorder (ADHD) exhibit several symptoms characterized by inattention, impulsivity and motor hyperactivity that impair both school performance and everyday life. The BRAVO (Beyond the tReatment of the Attention deficit hyperactiVity disOrder) project dealt with the development of several serious games based on extended reality that help patients improve in self-control, respect for rules, attention and concentration. In order to achieve both logopaedic and behavioural educational goals, serious games were developed concerning three different categories: *Topological Categories*,

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Infinite Runner and *Planning*. Experimental tests conducted over a six-month period assessed the patients' performance and the emotional impact of the games, also showing a general improvement in cognitive and behavioural functions.

Keywords ADHD, Serious Games, Virtual Reality, Biofeedback, Emotional Activation

1 Introduction

Attention Deficit Hyperactivity Disorder (ADHD) is among the most frequently diagnosed behavioural and developmental disorder, with a prevalence esteemed between 5% and 7% in scholar-age (Thomas et al, 2015) and between 2.5% and 4% in adults (Fayyad et al, 2017). It is characterized by symptoms such as inattentiveness, hyperactivity, and impulsiveness (Barkley, 2015). Attention deficits lead ADHD patients to experience executive function defections. This implies difficulties in managing time, staying focused and completing tasks that require planning skills (Johnson and Reid, 2011). On the other hand, hyperactivity disorder leads to impulsivity, causing difficulties in controlling behaviour and emotional responses. This affects academic performance (Loe and Feldman, 2007) and social skills (Barkley, 2015), and often results in extreme behaviours such as social rejection and creating conflicting relationships with family and friends (Danforth et al, 1991).

Traditional therapy for the treatment of ADHD is distinguished into drug therapy (not without side effects and risk of addiction (Barkley, 1998)) and motivational and cognitive-behavioural therapy. By addressing the symptoms listed above, cognitive-behavioural therapies aim to help patients with ADHD improve specific skills such as working memory, cognitive flexibility, time management, planning and self-control, and motor organization (Fabiano et al, 2009).

The contribution of technologies from the ICT world is proving to be increasingly peculiar in this field, offering solutions at multiple levels, useful both for supporting the diagnosis and treatment of ADHD (Alexopoulou et al, 2019). Specifically, among the various types of intervention, serious games are of great interest in the literature and, due to their characteristic of providing training in the form of entertainment, show proven effectiveness in the treatment of ADHD (Zheng et al, 2021). First of all, serious games are highlighted as a tool able to alleviate the symptoms of the disorder. Indeed, by providing constant stimuli and timely feedback, they positively influence ADHD children's attention, promoting their participation, keeping their interest level high and stimulating their voluntary motivation (Roh and Lee, 2014). In addition to this, the use of serious games contributes to an improvement in executive functions (inherent in planning, organising and completing tasks) on the same target (Alabdulakareem and Jamjoom, 2020) and helps to bring young patients closer to therapeutic practice, which is often approached in a hostile manner, facilitating the process of evaluation and diagnosis of the disorder (Kato and de Klerk, 2017).

In a previous study, the theoretical bases for the development of serious games for ADHD were provided, highlighting how an effective serious game in this field must make explicit reference to specific psychological frameworks (Barba et al, 2019). Specifically, it was shown that the most widespread frameworks are the self-regulation model (Cameron and Leventhal, 1995), the social cognitive theory (Bandura, 1986) and the learning theory (Kato et al, 2008); adherence to these imposes a series of constraints that the game dynamics must respect in order to favour the acquisition of adequate skills by the patients.

Zheng and colleagues (Zheng et al, 2021) offer a classification of serious games for ADHD into three categories: console games, mobile games and computer games. Console games (of which Nintendo's Wii is perhaps one of the biggest examples) usually exploit the TV screen and a series of sensors to offer players control of characters through body movements, in a multiplayer game mode (Chuang et al, 2010). Leveraging the use of smartphones or tablets, albeit with more basic interaction modes, mobile games offer the advantage of portability. However, it is on computer games that the research community focuses most of its interest and efforts.

The use of electroencephalographic (EEG) systems based on neurofeedback is perhaps the most fruitful intervention, proving to be 'efficient and specific' in influencing inattention, impulsivity and hyperactivity (Arns et al, 2009). Feedback on internal processes is given through different sensory channels (usually visual and auditory) in specific game-context stimuli, helping young patients to train their brainwave activity (Arns et al, 2009).

Recent lines of research significantly improve the gaming experience through the use of Extended Reality (XR) technologies, offering users immersive scenarios that subvert traditional (mouse and keyboard-based) interaction modes (Pallavicini et al, 2019). XR is an umbrella term that subsumes the entire spectrum of immersive technology-assisted realities (Virtual Reality (VR), Augmented Reality (AR), Augmented Virtuality (AV), Mixed Realities (MR)) into Milgram's reality-virtuality continuum (Milgram and Kishino, 1994), also encompassing all possible interactions between the users and the environment in which they are immersed. VR, in particular, greatly exercises players' ability to react and feel in the game process, making training more engaging and challenging in increasingly realistic game environments. The activation of one or more sensory stimulations provides a strong sense of presence in the virtual environment, which facilitates the transfer of skills learned during training into real life. This trend is expected to grow over the next few years as immersive environments become increasingly multisensory and capable of including body signals in a multimodal immersivity (Arpaia et al, 2022b; De Paolis et al, 2021). Regarding the specific use of VR games in neurorehabilitation contexts, higher efficacy and faster improvements in several cognitive abilities have been highlighted compared to traditional therapies (Rosa et al, 2016). Immersive Virtual Reality (VR) has been shown to be particularly effective in improving the performance of children with ADHD in terms of memory, attention and global cognitive functioning, with positive consequences in school performance and peer relationships (Corrigan et al, 2023). Several studies highlight the effectiveness of virtual classrooms as a clinical tool to assess attention in ADHD (Bioulac et al, 2012) and provide a cognitive recovery programme oriented to reduce distractibility (Bioulac et al, 2020). Although according to the meta-analysis in (Rosa et al, 2016) more research is needed to further differentiate classical interventions, some studies in recent years shown encouraging results about the effectiveness of VR as an optimal rehabilitation tool in children with ADHD (Bashiri et al, 2017).

This study is part of this strand, presenting the results of the BRAVO (Beyond the tReatment of Attention Deficit Hyperactivity) project, an immersive gaming and therapeutic platform aimed at improving the relationship between young ADHD patients and therapy, delivered through adaptive serious games. The developed platform allows for game-based therapy sessions involving each child individually. It supports the therapist during treatment and uses wearable VR/AR devices and game scenarios that dynamically adapt to the patients' therapeutic evolution, guided by appropriate psychophysiological variables measured and processed by a biofeedback analyser module. For each patient, the system suggests games according to the goals set by the therapist, who has the possibility of adjusting the level of difficulty based on an initial assessment or based on progress in previous sessions. In addition, the therapist can set other game-based activities that the child can perform at home via a tablet or PC.

In the six-month experimental campaign 60 patients were enrolled and equally assigned to the control and experimental groups, and subjected to batteries of various standardised tests. Therefore, the present study aims to be a first test of the effectiveness of a technological system based on adaptive serious games in virtual reality for the treatment of ADHD in children.

The paper is structured as follows: in the next section we will outline the current scenario in the literature of studies similar to the present one; we will then present the project as a whole and explain the details of the developed serious games. We will then proceed with the description of the experimental campaign carried out and then a discussion of the results obtained, outlining limitations and possible future developments.

2 Related Work

The use of serious games to support the diagnosis and treatment of paediatric ADHD is beginning to be an increasingly explored topic in the literature, as part of the more general framework of interventions aimed at treating children with special educational needs (SEN). A first important distinction has to be made between tools oriented to support the diagnosis and those more interested in providing support for the treatment of the condition (Goharinejad et al, 2022).

The detection/classification of ADHD in children is a field that requires specific instruments for measuring levels of attention during game play. Roh & Lee (Roh and Lee, 2014) were concerned with identifying specific measurement variables to test their ability to differentiate children with ADHD from normal children. Specifically, four variables were identified for this purpose in the study: omission error (as an index of incorrect responses to target stimuli), commission error (as an index of impulsivity), response time, and standard deviation of response time (as a measure of irregularity in providing responses). Recent studies directly exploit game data (Santos et al, 2011; Heller et al, 2013; Crepaldi et al, 2020) or EEG signals collected during gaming sessions (Alchalabi et al, 2018, 2017; Alchalcabi et al, 2017) and their subsequent classification by machine learning techniques in order to detect possible patterns characterising ADHD. The use of serious games as an alternative to traditional screening tests helps to reduce the so-called "white coat effect", significantly facilitating diagnosis (Alchalabi et al, 2018). Chen and colleagues Chen et al (2018) capture multidimensional datasets during testing, including a set of physiological data, movement data and task data, to support the diagnosis of ADHD. Virtual Reality gives the possibility to develop customisable environments for a more accurate assessment of ADHD, based on an objective measurement of users' reactions to stimuli and concentration abilities (Mishra et al, 2023) instead of subjective information collected through interviews and questionnaires.

A larger number of studies try instead to exploit serious games as a useful tool to support treatment and therapeutic practice. Several studies (Lakes et al, 2022) have been published about digital solutions for the treatment of ADHD, focusing on cognition, social-emotional skills, behaviour management, academic/organizational skills, vocational skills, motor behaviours and so on. The most common mechanisms implemented in mobile games for ADHD typically require users to respond to cues, remember details and make associations between different entities (Jiang et al, 2022). A review of serious games for ADHD patients outlined some important design aspects (Rodrigo-Yanguas et al, 2022): training should be constant over time and should be adapted to the patient's proficiency and progress, which should be emphasised and rewarded through positive reinforcement; other relevant factors are time management, inhibitory control, reasoning and competitive nature. In this context, the most interesting but also challenging aspect of gamification is the possibility of generating skills during training that are generalisable and transferable to everyday life. In a randomised controlled experiment, Bul and colleagues verified the effectiveness of the game "Plan-It Commander" (Bul et al, 2015, 2016), oriented towards the transfer of acquired skills, combining a number of elements including a focus on behavioural strategies, careful adherence to theoretical foundations (e.g. the self-regulation model and social cognitive and learning theory), the use of mentor feedback and motivation and reward strategies. It consists of an online game consisting of three mini-games, each focusing on specific skills and providing support for the young patients to achieve different independent goals. Another study (Lussier-Desrochers et al, 2023) proved the benefits produced by serious games in the performance of daily routines by autistic and ADHD children and revealed also the further improvement produced by the addition of parental support.

Serious therapeutic games oriented towards the treatment of ADHD can be classified according to a number of basic objectives: general self-regulation skills, social and communication skills, academic and cognitive skills, and daily life skills. General self-regulation skills relate to organisational issues (e.g. time management) (Retalis et al, 2014; Frutos-Pascual et al, 2014), monitoring and controlling behaviour (Park et al, 2016) including managing impulsive behaviour (Colombo et al, 2017), increasing breathing and relaxation skills (Amon and Campbell, 2008; Sonne and Jensen, 2016a,b; Bossenbroek et al, 2020; Sadprasid et al, 2022), motivational skills (Shaw et al, 2005), and improving Executive Functions (EF) (Schena et al, 2023) and working memory (Dovis et al, 2015; Prins et al, 2013; Rijo et al, 2015). Several studies focus on training social and communication skills (Van Dijk et al, 2008; Hakimirad et al, 2019; Park et al, 2016). EmoGalaxy (Hakimirad et al, 2019), for example, is a serious mobile game available on the Android platform that aims to support the emotional and social skills of young patients by implementing a virtual journey through four game planes, corresponding to four different emotions. The pilot randomised controlled trial demonstrated the effectiveness of the game in improving children's social skills. With regard to academic and cognitive skills, several studies focus on the training of reading and writing skills (Park et al, 2019; McGraw et al, 2004; Wrońska et al, 2015), learning skills (Mancera et al, 2017), reinforcement of specific school skills (Matic et al, 2014) and more general skills in daily life (Sharma et al, 2018). The IAmHero serious game (Schena et al, 2023) proposes activities focused on cognitive-behavioural skills such as attention, planning, critical reasoning, visual perception, visuomotor skills, abstract reasoning and language skills. Test results showed reductions in hyperactivity/impulsivity and improvements in executive functions (planning, organization, sustained auditory attention, problem-solving).

A recent trend is to develop serious games based on natural user interaction, taking advantage of motion sensing sensors such as the Microsoft Kinect (Zhang, 2012). The use of these sensors gives children greater freedom to use hand and body gestures in learning experiences that stimulate both motor skills and executive functions, such as concentration and self-awareness (Avila-Pesantez et al, 2018; Retalis et al, 2014; Park et al, 2016; Kourakli et al, 2017). Recent work focusing on motor skills in ADHD children (Barkin et al, 2023) revealed a higher effectiveness when a game-based intervention is guided by a therapist.

The combination of serious games and XR technologies is a more recent trend supporting the treatment of ADHD, by offering immersive and increasingly stimulating gaming experiences, both in the case of VR (Gongsook, 2012; Bernardelli et al, 2021) and AR/MR (Avila-Pesantez et al, 2018; Tosto et al, 2021; Stefanidi et al, 2021) scenarios. The ATHYNOS system (Avila-Pesantez et al, 2018) combines serious games with AR using a natural user interface (via Kinect): this has the advantage of better capturing the attention of ADHD patients and stimulating cognitive skills related to hand-eye co-ordination and problem solving. A systematic review on the use of VR technologies for the treatment of ADHD can be found in (Corrigan et al, 2023): it highlights the potential of VR-based therapies in improving global cognitive functioning, attention and memory. A comparison between VR-based cognitive rehabilitation and traditional methods showed the benefits of VR in terms of selective and sustained attention for children with ADHD (Barati et al, 2021). A recent pilot study on six VR games (Cunha et al, 2023) revealed significant improvements in the processing speed of students with ADHD. The potential and opportunities offered by VR for children with ADHD have been also studied in (Zhang and Wang, 2023). Another survey deals with the use of immersive virtual reality for both autism spectrum disorder (ASD) and ADHD: it emphasises the importance of human guidance both during a VR session and afterwards to help children bring the skills gained in play back into everyday life (Satu et al, 2023). The use of the Metaverse to help students with ADHD and autism spectrum disorders has been tested in (Mohamed et al, 2023). Another input class used in the context of gaming scenarios, and often aimed at creating dynamically adaptive gaming experiences, is that from biosignals. Such data describe different aspects of the user's psychophysiological state, and are therefore often used to track the mental state of children, inferring their mood. Several studies in the field of ADHD treatment make use of neuro/biofeedback sensors, administered in traditionally non-immersive scenarios (e.g., on screen) (Sonne and Jensen, 2016a; Chen et al, 2017; Jiang et al, 2011; Rohani et al, 2014; Blandón et al, 2016; Bodolai et al, 2015; Skalski et al, 2021). The game ChillFish (Sonne and Jensen, 2016a) uses biofeedback in the form of the player's breathing rhythm from a stretch sensor to control a puffer fish in a virtual underwater environment.

An additional sensor is used to detect changes in body temperature during breathing. When the player inhales, the fish inflates and swims: the aim is to reduce the perceived stress levels of ADHD patients. Harvest Challenge (Blandón et al, 2016) is a neurofeedback game, developed to use the patient's measured attention levels to adaptively control the videogame. Sustained attention levels (via game metrics) appear to be improved as well as higher resting values in the power of alpha and beta bands.

More recent is the adaptation of neuro/biofeedback scenarios in fully immersive contexts (Bossenbroek et al, 2020; Reddy and Lingaraju, 2020). Bossenbroek and colleagues (Bossenbroek et al, 2020) proposed an adaptation of the biofeedback-based game DEEP and tested it on young ADHD patients. The game is played in a fully immersive virtual environment (experienced by wearing an HTC VIVE (HTC, March, 2023a)) and allows players to explore an underwater fantasy world using their breath to control movement. As far as the electroencephalographic signal is concerned, a recent work (although no tests have been conducted yet) is the one proposed in (Reddy and Lingaraju, 2020), in which neurofeedback (acquiring the neurosignal by means of a 14-channel Emotiv Epoc) is returned in a mobile AR scenario (via smartphone). The idea is to allow the user to inflate a virtual balloon, or bend a virtual spoon reaching the desired psychological state.

In more recent work (Machado and Frizera, 2022), neurofeedback was used to assess the mental state of attention during serious game sessions: test users were able to perceive their level of attention and control it during the game.

The study in (Ahmed Aboalola, 2023) proved the positive effect of a mindfulness-based intervention on the executive functions of children with ADHD. Mindfulness can produce important benefits on the inner skills of ADHD patients: it improves their ability to control attention, which becomes a tool for self-regulation (Arpaia et al, 2022a), and makes them more aware of their emotional state, reducing their impulsiveness (Drigas et al, 2022). Virtual Reality offers various potentials to enhance the therapeutic efficacy of mindfulness (De Paolis et al, 2021; Arpaia et al, 2022b; Gatto et al, 2020). VR-based mindfulness makes the patients more aware of surroundings, sensations and sounds, as if they were in a real-life situation. Moreover, it has positive effects on physiological and neuropsychological variables that interact with metacognitive abilities (Drigas et al, 2022).

3 Material and methods

The BRAVO project was aimed at creating an advanced therapeutic environment using innovative ICT technologies, in order to help young patients suffering from ADHD (Attention Deficit Hyperactivity Disorder), to improve their health conditions (Barba et al, 2019). The main objective of the project is to involve young patients in the treatment process, thus limiting the oppositional attitude often shown towards the classic therapy. The idea was to use video games to capture the child's attention and overcome the initial distrust in order to create a more relaxed environment, able to prepare the patient to the therapy. An additional advantage offered by the technological approach is the possibility to circumscribe the activity within a controlled space, in order to observe and detect all the patient's behaviours and to be able to use them to provide the doctor with a monitoring service of improvements and the patient with a personalized therapy service able to evolve in step with the results achieved. The central element of the ICT environment is a new generation of serious games designed to monitor, through wearable sensors, the patient's behaviour and then adapt the intervention of the system based on the outcome of therapy.

During the performance, the system is able to identify the child's level of attention and propose therapeutic exercises as a game that dynamically adapt to individual levels of play. The innovative element of the project is consequently the possibility to benefit from an adaptive and personalized therapy, conveyed through a virtual game environment thanks to the use of advanced technologies.

3.1 Serious Games

The analysis of the behavioural problems of a child with ADHD requires the definition of therapeutic goals in order to structure a therapy plan in line with the patient's specific needs and, at the same time, measure the evolution of symptoms. The analysis of ADHD-related therapeutic needs suggests that therapy should focus on three main elements:

- teaching self-control,
- teaching how to form and maintain friendships,
- helping the child to feel good about himself.

The acquisition of these macro-skills is the main way to enable the young patient to live a serene life, without the torment and frustration arising from an unsatisfactory school career and an unfulfilling social life.

The game-based approach is considered an ideal tool for developing learning systems for young people with ADHD (Luman et al, 2005) for several reasons:

- they have a motivational deficit and react differently to gratification than their peers not affected by the same disorder;
- the play approach helps to balance the motivational aspect with the learning aspect;
- video games have the ability to keep the child motivated and involved throughout the therapeutic process.

In recent years, a considerable number of serious games have been designed to improve working memory and executive functions. Although the literature is full of evidence on how such systems produce short-term results, the transfer of acquired skills to everyday life is not as evident (Melby-Lervåg and Hulme, 2013).

The latest trends in the literature relating to serious games for ADHD tend to favour educational objectives closely linked to behavioural learning. The idea is to promote more the learning of functional strategies such as time management, planning/organisation, social skills. It is therefore more than appropriate to work on video games that are able to have a real impact on the lives of children with ADHD (DeSmet et al, 2014). It is necessary to translate these behavioural objectives into appropriate psychological theories in order to have a theoretical framework. Indeed, numerous studies in the literature report that serious games that have a psychological framework at their base tend to be more effective (Baranowski et al, 2008). The most commonly considered frameworks for the mentioned competences are the self-regulation model, the social cognitive theory and the learning theory (Bandura, 1986).

The analysis of the game-based approach defines in detail how to build up the patient's motivation to follow the therapy and how technology can be made available to the therapist to support the therapy, improve the reading of the results and finally move repetitive activities to the home, leaving the most interesting activities during the session. In particular, gamification has the task of enticing the child to do the activities at home, while the serious game has the task of making the single therapeutic intervention, which is often boring, more enjoyable and stimulating.

The therapeutic act must focus on a properly cognitive level and a more behavioural one. Although these levels are not always clearly distinguished, an analysis has been conducted to better understand the pillars on which each therapeutic act is based and, since this issue has a concrete and immediate impact on the definition of therapeutic games, it has been widely discussed within the medical staff to understand what the predominant objective should be in the design of game dynamics.

Although each serious game has its own peculiarities, each can store the level of play, the time of completion, the number of attempts made, the level of anxiety detected, the state of mind of the patient (entered by the patient or therapist) the level of perceived amusement. The basic idea is to draw as many trials as possible in order to make the performance evaluation criteria for each individual child as varied and accurate as possible.

When starting to care for the child, the therapist defines educational goals, based on the diagnosis and the agreed treatment plan, and an initial assessment. The system suggests games related to the established therapeutic goals. Subsequently, within each therapy session, the therapist can use the level of difficulty automatically preset by the system on the basis of the data collected in previous interactions or choose the level of difficulty he or she considers most appropriate. During the therapy, the therapist makes the child play and sets the activity to be carried out at home by explaining to him/her what he/she should do on the tablet or PC at home. Even in the absence of immersive interaction with virtual reality, the game must be engaging so that the child can maintain interest in the training. The assigned treatment will be automatically tracked and visible to the therapist.

The whole therapeutic action tends to reward the child's virtuous behaviour by earning him virtual coins that he can spend within the gamification system.

The BRAVO game environment consists of three serious games used by medical and paramedical staff during therapy in combination with a wide range of sensory actuators (e.g. VR helmet, smart-watch, motion sensors, etc.) in order to record active patient behaviour and provide real-time adaptation.

The three categories of serious games implemented in the BRAVO platform are:

- *Topological Categories*,
- *Infinite Runner*,
- *Planning.*

The choice of each category is derived from the need to achieve the various educational objectives, both logopaedic (e.g. definition of topological concepts, definition of semantic categories, definition of antonyms, definition of logical associations,

Fig. 1 Sample scene of Topological Categories game

externalization of emotions, construction of narratives) and behavioural (e.g. following rules, knowing how to wait, predicting the effect of one's actions, increasing concentration time, increasing patience, increasing listening skills, sitting still, increasing self-esteem, increasing autonomy, increasing self-motivation, etc.).

3.2 Topological categories

The *Topological Categories* game (Figure 1) has the didactic objective of teaching the patient topological concepts (over - under, in - out, forward - back, near - far, right - left, near - far). To this end, it assigns the user the task of positioning himself or different objects within the game scene according to the directions provided by the game. At the same time, the game makes it possible to work on the patient's compliance with the rules and ability to wait. The game is administered in the clinic, through the use of HTC VIVE (HTC, March, 2023a) with the addition of a wireless adapter (HTC, March, 2023b), giving the user the possibility to move freely in the virtual space as if moving in the real space. The game is projected onto a large screen, allowing the therapist to follow the patient's execution of the tasks in real time and assess their progress.

Three different cartoon-style settings have been developed: a child's bedroom, a garden, a school classroom. Within each scenario the user is asked to position himself or specific objects in relation (i.e. near, far, above, below, inside, etc.) to other objects present in the scene. Each game level has several scenes, each of which is set up differently, so that different requests can be presented to the player. For each scene, there is at least one configuration for each topological concept. Figure 1 shows an example of a game scene set in the bedroom of a child, who is asked to put the ball under the chair.

Although the levels have a gradually increasing difficulty, they are not directly proposed consecutively, but on the basis of the game performance and the emotional impact the level has on the user. In particular, if the stress level displayed by the player is above a parameterised threshold, the game does not increase difficulty, but proposes alternative scenarios of the same difficulty (e.g. same level but in different locations).

Fig. 2 Sample scenes of Infinite Runner game

3.3 Infinite runner

The aim of the *Infinite Runner* game is to teach the patient to respect the rules (in particular the waiting time), to actively listen and to be aware of his or her limits. Other educational goals concern logical associations, semantic categories and the improvement of motor coordination and concentration time. The game also allows the child to discharge excess energy accumulated through physical activity.

The game is implemented through Kinect, a tool that allows you to control game actions without the use of joypads or buttons but simply with the use of your body, thus allowing you to decode the movements made by the player without the need for any element to be connected to the body. The game is projected on a big screen, in order to allow the therapist to follow in real time the patient's performance and evaluate the progress.

Two environments have been developed, depicting a country road and a city street (Figure 2). Within the game scene, the user must run in place to move along the path, moving left or right to avoid obstacles present and/or collect required objects. Additional levels are present, in which the user will have to grab objects that will be sent in eight different directions, by simply moving to the right, left or the center of the scene (without running in place).

The performance measurements are based on the number of obstacles avoided, correct items collected (and number of wrong elements avoided), as well as the

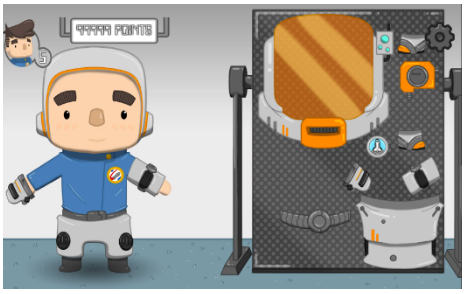

Fig. 3 Sample scene of Planning game

ability to wait shown and the respected rules. In fact, as the level increases, additional elements of difficulty are introduced into the game, such as crossing a herd of animals in the country locations and passing cars in the city, which will allow the patient to train his ability to wait; respect for the rules is trained in the city locations and is related to the correct crossing of crosswalks by the user and respect for traffic lights.

3.4 Planning

The *Planning* game (Figure 3) has the educational objective of improving the patient's ability to plan problem solving and the ability to interact with other people.

The game is played in the clinic, through the use of Kinect (it was later implemented the possibility of using also the mouse). The game is projected on a big screen, in order to allow the therapist to follow in real time the development of tasks by the patient and evaluate the progress.

The player plays the role of a young astronaut from Cape Canaveral, who is asked to bring a spaceship from Earth to the planet of an alien friend. In order to accomplish this mission, the player will have to face different trials, set in different locations, starting from the preparation of the crew in the base of operations, the pre-departure check of the spacecraft in the launch pad, the setting of the trajectory in the command bridge and the missions in space. The objective of the game is to be able to prepare the spaceship for the trip, face the journey and the different challenges, and reach the final planet where you can party with your friends.The game "Planning" has the educational objective of improving the patient's ability to plan problem solving and the ability to interact with other people. The game is played in the clinic, through the use of Kinect (it was later implemented the possibility of using also the mouse). The game is projected on a big screen, in order to allow the therapist to follow in real time the development of tasks by the patient and evaluate the progress.

The game involves the player flying with their own team, consisting of three members. The player drives the spaceship, but his team manages additional weapons, shields and engines that are useful to get out of dangerous situations. The crew members are controlled neither by the computer nor by other players, so they need to be guided by the player to perform their tasks. The player will have the task of

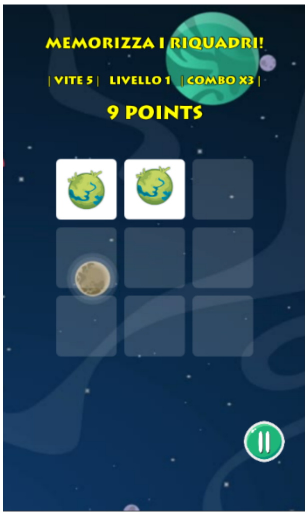

Fig. 4 Sample screen of Astromemory minigame

bringing the spaceship to its destination and this can only be done by interacting with the team.

3.5 Gamification platform

The aim of the gamification is to stimulate the patient in carrying out activities outside the clinic in total autonomy (but always supervised by the parent/guardian), through experiences that stimulate the training of memory, oculo-manual skills, logical-mathematical skills and language skills. The set of data derived from these games is available to the therapist who, combining them with those developed during the serious games and standard therapy, can best set the patient's therapy by assigning specific tasks and checking their execution through a dashboard.

The platform includes 3 minigames, described in the following paragraphs.

Astromemory minigame The *AstroMemory* minigame (Figure 4) has the educational objective of increasing the player's concentration time, while training his short-term memory. The game consists of covered tiles, which the player sees appearing on the screen. For each level, pairs of cards are temporarily revealed and the player must remember the position of the pairs and find them among the covered cards.

If the two turned tiles present the same figure, the player advances to the next level; if the two tiles present two different figures, the player loses one life and a new pair of cards is proposed.

As the player advances through the levels, the size of the grid and the number of cards discovered at the same time increase. The game ends when the player loses all available lives.

Fig. 5 Sample scene of Space Tris minigame

Space Tris minigame The *Space Tris* minigame (Figure 5) aims to improve the ability to plan short-term strategies and the capacity for attention and concentration.

In the game there is a sort of chessboard, containing objects and symbols related to the space theme. The player must select an object and swap it with an adjacent one: if three identical objects are lined up, they explode and disappear from the playing field, making the objects above them fall (in turn, the resulting empty spaces at the top are filled with other random objects that fall from the upper edge, thus recomposing the complete grid). The player at this point must try to compose another row of three objects, as long as it is possible to continue doing so. The game ends when:

- The level objective has been reached;
- Time has expired;
- There are no more moves available.

In the game it is possible to generate and use bonus items (which increase the number of objects that can be eliminated and consequently the points gained).

Planning minigame The *Planning* minigame (Figure 6) is the app version of the *Planning* game already used in the clinic, which aims to improve the ability to plan short-term strategies and the capacity of attention and concentration. The game is always articulated in seven levels (playable not necessarily in sequence), in each of which the user uses his or her planning strategies to solve problems and ability to relate to other people. For the seven levels there are always three different degrees of difficulty (easy-normal-difficult).

3.6 Biofeedback Analyzer

One of the main innovative elements of the project is given by the adaptive and personalized therapy realized by evaluating in real time, through appropriate sensors

Fig. 6 Sample scene of Planning minigame

and algorithms, the level of attentiveness of the patient (attention, impulsiveness, hyperactivity) as well as the presence of stress.

Attentiveness and stress levels are calculated by analyzing biofeedback data detected through an EEG helmet (14-channel Emotiv Epoc helmet) and a heart rate monitor.

The level of attention, closely related to the measurement of ADHD, can be measured by means of native functions present in the API stack supplied with the helmet or calculated from "raw" signals retrieved by means of other functions made available within the same API stack.

By means of the native functions it is possible to recover in real time 6 different dimensions related to the sphere of emotion and subconscious: excitement, interest, stress, engagement, attention and relaxation. Starting from the raw signals related to each electrode we can work with specific algorithms for signal analysis as described by (Wang et al, 2010).

Impulsivity, on the other hand, is to be considered as an indirect measure and detectable by relating the user's level of attention to the responses given during the game, with respect to the speed of execution. For example, if on a specific task the user responds quickly but incorrectly and with a poor level of attention, it means that the response was impulsive.

Stress detection is provided by joint analysis of evidence from involuntary physical manifestations such as sweating, heartbeat, breathing, etc. The idea was to develop an algorithm able to contextualize the biofeedback detected by the sensors with respect to the game activities. In this way, the presence of multiple stress indicators (e.g., accelerated heart rate, more frequent breathing and increased sweating compared to the patient's baseline values) are interpreted differently in a context in which the patient must move very quickly compared to a context of more static interaction.

In general, given the wide availability of sensors capable of detecting biofeedback related to sweating, heart rate, breathing, and facial muscle movement, the use of data extraction algorithms was not envisioned but relied on data already made available by the device integrated into the system.

The biofeedback analyzed for each user is compared with their baseline values recorded in the history of interactions with the system. In the case of sweating, the Skin Conductance Response index is used as a measure of the stress level. Heart rate is analyzed with respect to acceleration and frequency. Breathing is analyzed with respect to frequency and amplitude.

4 Cognitive-behavioural tests

The children's cognitive abilities and behavioural skills were assessed both before and after the therapies by means of a series of standardised psychological tests, useful for identifying and understanding specific problems of children with neurodevelopmental disorders.

- BIA (Italian battery for the assessment of children with ADHD) assesses executive functions. The test involves tasks of auditory and visual attention, working memory, inhibition and control. In addition, there is the administration of questionnaires to the family and school in order to investigate the child's adaptive-disadaptive behaviour in various contexts. In particular, the following tests were selected and administered to patients:
  - *frog test* for the assessment of attentional and control processes in auditory-visual tasks;
  - *tau* for the assessment of sustained auditory attention, sustained visual attention, search and visual working memory;
  - *Mf20* and *Mf14* for the evaluation of impulse response control;
  - *Cp* for the assessment of sustained visual attention;
  - SDAI questionnaires (for teachers), SDAG (for parents) and SDAB (for children over 9 years) for detecting inattention, hyperactivity, impulsivity behaviour.
- BVL (battery for assessing language in children aged 4 to 12 years) investigates language in its 3 components (comprehension, repetition and verbal production) with related sub-levels; in particular, the following tests were selected and administered to the patients:
  - *grammatical comprehension* to assess the ability to decode sentences;
  - *semantic fluency* to assess the productivity of words, related to two semantic categories, namely animals and household objects;
  - *phonological fluency* to assess the productivity of words, related to two phonological inputs (initial phoneme);
  - *narrative fluency* to assess the spontaneous productivity of utterances, on an iconic-narrative stimulus;
  - *repetition of non-words* to assess auditory-verbal discrimination and memory capacity;

  - *repetition of sentences* to assess verbal memory capacity and grammatical skills.
- MT-3 (tests for the assessment of reading and comprehension skills for primary and secondary school) assesses the ability to speed, correct and comprehend a passage, differentiated by age and class. It was administered in full in the study presented in this paper.
- DDE-2 (Dyslexia and Developmental Dysorthographia Evaluation Battery-2) investigates sub-lexical and lexical writing and reading strategies and modalities; in particular, the following tests were administered:
  - "trial 1" about reading of graphemes
  - "trial 2" about reading of words (list a.a. words with high frequency of use and high image value, list b.b. words with low frequency of use and low image value)
  - "trial 3" about reading of non-words (non-syllabic words)
  - "trial 6" about dictation of words
  - "trial 7" about dictation of non-words.
- BVSCO (battery for the evaluation of writing and orthographic competence) investigates all aspects involved in the learning process of writing: graphism, spelling competence and the production of written text, with regard to the parameters of speed and correctness. The battery estimates the child's competences for the entire school career in primary and secondary school. In particular, 'graphical speed tests' and 'sentence dictation' were selected.
- AC-MT 6-11 (assessment test for calculation and problem-solving skills) investigates basic arithmetic skills (the four operations), numerical knowledge and problem-solving skills. For the study presented in this paper, the battery was administered in full.
- OMINO GOODENOUGH assesses the ability of self-perception, the graphic representation of the body scheme and emotional-affective expression; the test involves handing the child a sheet of paper, on which he/she is to draw the human figure freely.
- VMI (Visual Motor Integration) assesses the visual-graphic-motor imitation ability in the perceptual-spatial, fine motor and praxical-constructive components. The test involves copying figures and geometric shapes of increasing complexity on a grid.

The administration is related to the type of therapy to which the patients in this study were subjected: for patients undergoing psychomotricity therapy, the BIA, VMI, OMINO tests were used; for patients also undergoing speech therapy, the BVL, MT3, ACMT, DDE2, BVSCO tests were also used.

4.1 Experimental hypotheses, methodology and results

The effectiveness of the BRAVO system compared to traditional therapies was assessed by means of a repeated measures analysis of variance (ANOVA-MR) of the scores obtained in the cognitive-behavioural tests. This made it possible to evaluate from a statistical point of view not only the difference between the two moments of detection (before and after therapy) but also between a control group treated with traditional therapy and the experimental group involved in the serious gaming sessions.

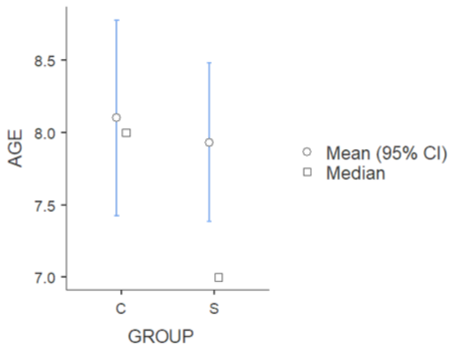

Fig. 7 Results of the t-test on division into experimental groups

Gender	Group		Total
	Control	Experimental	
Female	6	7	13
Male	23	23	46
Total	29	30	59

Table 1 Chi-square test results on homogeneity of experimental groups

Before performing the ANOVA-MR, the balance in the allocation of the children to the two groups was checked in order to avoid age or gender differences that could have distorted the results of the analysis. To this end, a t-test was conducted to verify the hypothesis that the groups did not differ according to age (t (57) = 0,38, p = 70) and a chi-square test to verify the absence of homogeneity between the two groups according to gender (χ^2 (1) = 0.06, p = .81). Both tests, represented in Figure 7 and Table 1 respectively, confirm that the two groups are balanced for both factors considered.

The results of the ANOVA-MR, besides showing a general average improvement in the cognitive performance of all the children, underline the statistical significance ($p < 0.05$) of the differences between time t_0 and time t_1 with regard to the following cognitive features:

- ability to select in one's mental lexicon target words belonging to certain semantic categories;
- ability to access words in one's mental lexicon using a phonological strategy, through lexical skills and concentration, inhibition and selection skills;
- ability to perceive and correctly repeat certain sequences of phonemes that do not constitute real words even though they have a legal phonotactic organisation;
- visual-motor integration skills;
- performance age in relation to children's maturation and IQ.

Results confirm that both groups had a similar improvement in the above-mentioned skills, although in some cases it was more pronounced for the experimental group. This suggests an additional benefit in relation to the use of the BRAVO system, characterised by the satisfaction, involvement and positive emotions manifested during the games.

Test	Control			Experimental			F (p value)		
	N	pre	post	N	pre	post	Time	p interaction	p group
BIA frog	8	9.81	11.56	6	7.98	4.64	0.55 (.47)	**5.69 (.03)**	2.69 (.13)
BVL Grammatical comprehension	17	21.32	20.79	25	21.62	25.90	3.54 (.07)	**5.82 (.02)**	0.53 (.47)
BVL Phonological fluency	17	5.28	6.58	26	4.41	7.14	**10.21 (.01)**	1.30 (.26)	0.01 (.93)
BVL Semantic fluency	17	13.33	15.92	25	13.98	17.34	**12.35 (.01)**	0.21 (.65)	0.21 (.65)
BVL Repetition of phrases	17	7.97	9.38	23	7.36	9.10	**7.49 (.01)**	0.08 (.78)	0.08 (.78)
BVL Repetition of non-words	16	8.58	9.20	25	7.90	10.18	**11.95 (.01)**	3.88 (.06)	0.01 (.93)
OMINO GOODENOUGH Performance age	11	5.20	5.81	12	5.44	6.03	**16.52 (.01)**	0.01 (.95)	0.43 (.52)
VMI	11	14.39	16.39	10	13.53	14.93	**4.67 (.04)**	0.14 (.71)	0.37 (.55)

Table 2 ANOVA-MR results

This was confirmed by further psychological tests that highlighted, on the basis of the ANOVA-MR results, important interaction effects between the variables "time" and "group", supporting the hypothesis that certain abilities improved between pre- and post-therapy only for children who also used the BRAVO serious games:

– ability to understand the meaning of sentences with the most diverse grammatical structures, establishing the level of maturity of the receptive grammatical system reached;
– selective attention, sustained attention and motor inhibition in a task involving auditory and visual stimuli.

The data obtained are summarised in Table 2.

5 Game performance and biofeedback

Virtual reality games made it possible to track the performance of patients on specific parameters agreed with the therapists. The use of wearable sensors during gaming sessions enabled the collection of biofeedback that could be used to analyse the patient's emotional distress.

Game performance data and biofeedback were recorded during the execution of each task of each level of each game, calculating a cumulative index for each game played in the session.

For game performance, topological and semantic category type and level, attention capacity in seconds, attention capacity level, attention, rule compliance, planning capacity, environmental stress were considered.

At the same time, the Empatica E4 wristband was used to evaluate biofeedback in terms of Temperature, Galvanic Skin Rate (GSR), Blood Volume Pulse (BVP), InterBeat interval (IBI).

The data collected in the six-month trial were analysed to verify:

– the performance of the patients in the three games according to the scores gained in the game sessions;
– the emotional impact of games on patients.

5.1 Performance trend of patients in games

Each task in each game provides a score to the user's performance in a range from 0 to 100. The score calculation is peculiar to each game and takes into account not only the correct execution of the task, but also other factors such as level difficulty, environmental stress, assessment of planning ability, attention given, respect for the rules, and errors made.

5.1.1 Topological Categories

In the *Topological Categories* game, 3903 tasks were performed, divided into the difficulty levels shown in Table 3.

Levels	Counts	% of Total	Cumulative %
1	998	25.577 %	25.577 %
2	850	21.784 %	47.360 %
3	841	21.553 %	68.913 %
4	334	8.560 %	77.473 %
5	666	17.068 %	94.541 %
6	213	5.459 %	100.000 %

Table 3 Difficulty levels of the *Topological Categories* game

The therapists gave more priority to the first three levels of difficulty, both to make users confident with the game and to maintain good levels of eustress, and then gradually moved on to more challenging and complex levels according to improvements in the children's cognitive-behavioural skills.

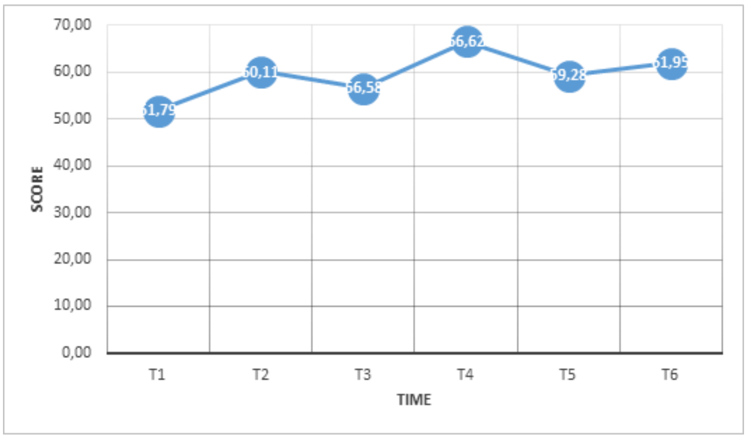

Fig. 8 *Topological Categories* game scores

The graph in Figure 8 shows a general trend of improvement in the users' scores as the therapy progresses over the months, with a peak in the fourth month.

The distributions of scores in the different months, depicted in Figure 9, show a decrease in intermediate scores and an increase in higher scores: in fact, the average scores are higher in the last few months, as the latest distributions include many more values above 80 points, although they are more platicurtic.

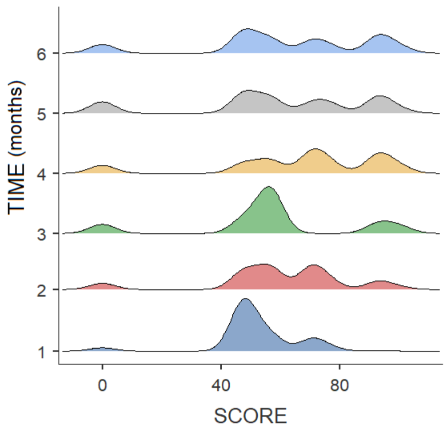

Fig. 9 Distribution of scores over time for the *Topological Categories* game

An analysis of variance (ANOVA) was conducted to test the significance of differences in scores between the different detection times (Figure 10). Since Levene's test shows a particularly small p-value ($F(5, 3896) = 48.50017$, $p < 0.0001$), Welch's method, based on the nonequality of the variances of the groups, was used. The ANOVA shows a significant effect of time (and thus therapies) on scores ($F(5, 776) = 38.07395$, $p < 0.0001$).

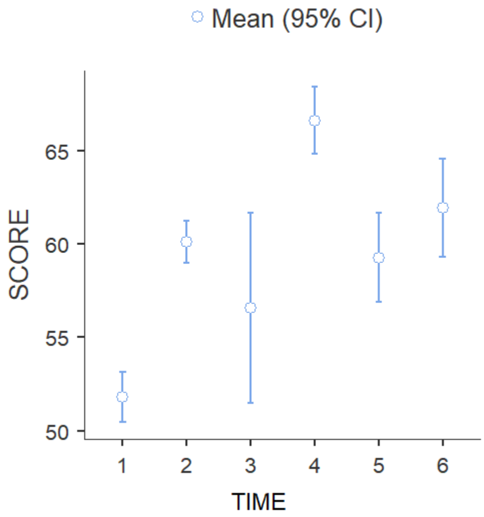

Fig. 10 ANOVA to assess the impact of time on the scores of the *Topological Categories* game

In the analysis of the various post-hoc tests conducted using the Games-Howell method on all possible pairs of detection groups, it is important to emphasize the significance of the difference between T1 and T6 (t-value (635) = -6.74935, p < 0.0001), which highlights the improvement in performance between the beginning and end of therapies.

5.1.2 Infinite Runner

In the *Infinite Runner* game, 1201 tasks were performed, divided into the difficulty levels shown in Table 4.

Levels	Counts	% of Total	Cumulative %
1	225	19 %	19 %
2	157	13 %	32 %
3	308	26 %	57 %
4	60	5 %	63 %
5	14	1 %	64 %
6	7	1 %	64 %
8	6	1 %	65 %
9	282	24 %	88 %
10	102	9 %	97 %
11	39	3 %	100 %

Table 4 Difficulty levels of the *Infinite Runner* game

The therapists chose to extensively use the first three levels to make the children confident with the game, and then focus on the last ones, after verifying the users' competence and abilities in the presence of minor difficulties. The evolution of performance over time, depicted in the graph in Figure 11, proved this type of strategy right. After a slight decrease in the third month, probably due to users' intial difficulties on the more challenging levels, performance grew in the following months ending with an average of about 10 points higher than at the beginning.

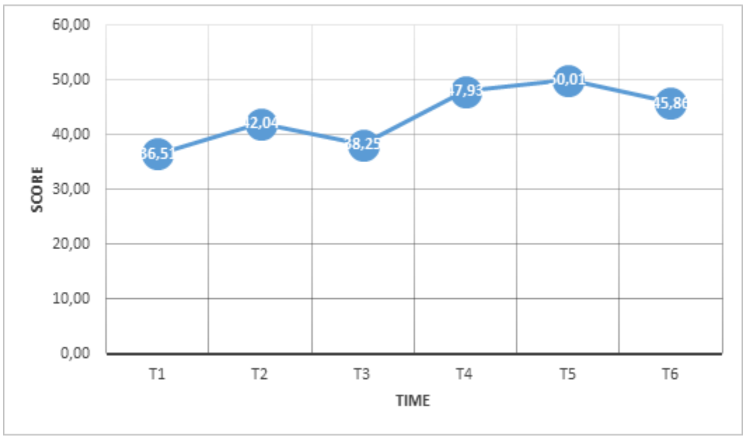

Fig. 11 *Infinite Runner* game scores

The frequency distributions of scores, depicted in the graph in Figure 12, appear similar across survey times, showing two very close frequency peaks in each month. One aspect that is not evident in the graph is the important decrease in 0 scores: this results in a greater predominance of completed tasks with high scores and a consequent rise in the mean value of the distribution. The figure for the reduction in uncompleted tasks (score = 0) demonstrates a relevant improvement in the child's abilities and in attentional skills in particular.

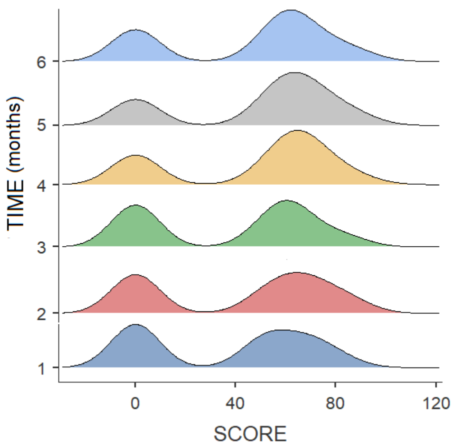

Fig. 12 Distribution of scores over time for the *Infinite Runner* game

Again, an analysis of variance (ANOVA) was conducted to test the significance of the differences in scores between the different detection times (Figure 13). Since Levene's test shows a low p-value ($F(5, 1194) = 7.11$, $p < 0.0001$), Welch's method, based on the nonequality of the variances of the groups, was used. ANOVA shows a significant effect of time (and thus therapies) on scores ($F(5, 286) = 3.97$, $p = 0.0017$).

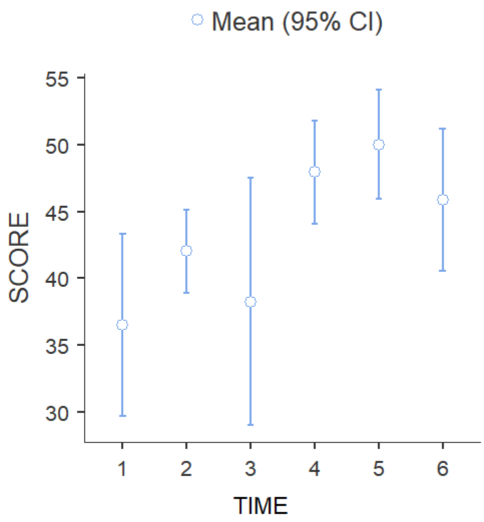

Fig. 13 ANOVA to assess the impact of time on the scores of the *Infinite Runner* game

In the analysis of the various post-hoc tests conducted using the Games-Howell method on all possible pairs of detection groups, it is important to emphasize the significance of the largest difference (13.69 points) between the initial detection and the peak of the fifth month (t-value $(151) = -3.38$, $p < 0.0012$), which highlights the important improvement in performance.

5.1.3 Planning

In the *Planning* game, 474 tasks were performed, divided into the difficulty levels shown in Table 5.

Levels	Counts	% of Total	Cumulative %
1	124	26 %	26 %
2	108	23 %	49 %
3	85	18 %	67 %
4	44	9 %	76 %
5	49	10 %	87 %
6	22	5 %	91 %
7	41	9 %	100 %

Table 5 Difficulty levels of the *Planning* game

Although this is the game that was given less space than the others, each level was used with satisfactory frequency. Each child was first made accustomed to the tasks required in the lower-difficulty levels and then gradually brought to perform effectively even the more challenging tasks, which require more refined and complex skills. Again we can see an improvement over time, as shown by the graph in Figure 14. The small number of tasks played in one of the survey time ranges (and the consequent lack of representativeness of one time span) led to the joining of two time spans, which motivates the representation of only five times.

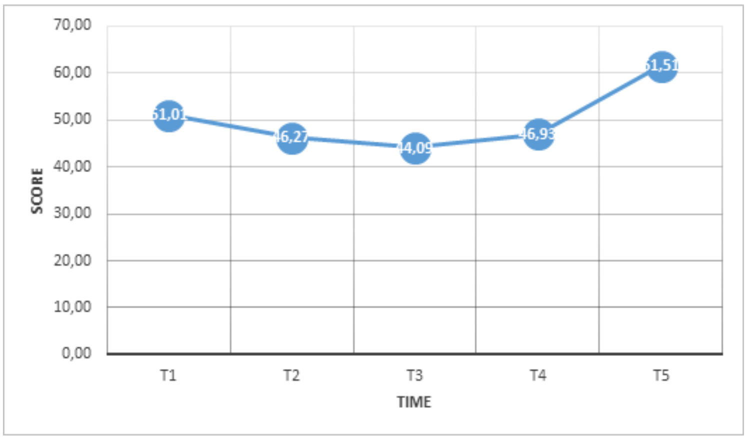

Fig. 14 *Planning* game scores

Early survey times show little difference in average scores with an initial downward trend, probably caused by the first obstacles encountered as tasks became more difficult. The trend improves especially at the end, suggesting an increase in children's performance and safety even in more challenging tasks.

In the distributions of scores broken down by time of detection depicted in Figure 15, the similarity between the scores in the early periods is evident and the near absence of scores equal to 0 at time 5 is even more striking, highlighting the children's greater concentration and attention.

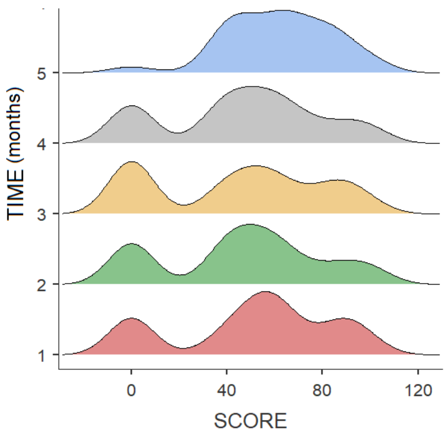

Fig. 15 Distribution of scores over time for the *Planning* game

Again, an analysis of variance (ANOVA) was conducted to test the significance of the differences in scores between the different detection times (Figure 16). Since Levene's test shows a low p-value (F (4, 468) = 2,73, p = 0.0029), Welch's method, based on the nonequality of the variances of the groups, was used. ANOVA shows a significant effect of time (and thus therapies) on scores (F (4, 139) = 3.25, p = 0.0014).

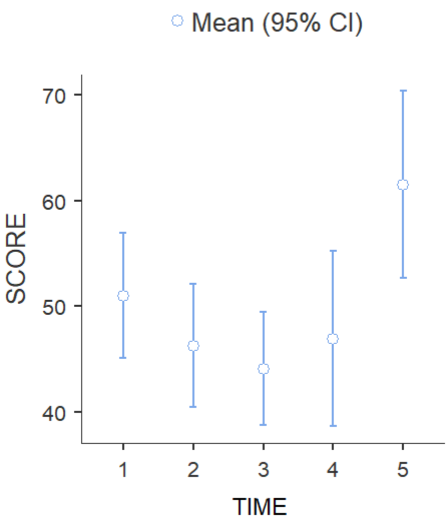

Fig. 16 ANOVA to assess the impact of time on the scores of the *Planning* game

In the analysis of the various post-hoc tests conducted using the Games-Howell method on all possible pairs of detection groups, it is important to emphasize the significance of the largest difference (17.41 points) between the lowest scoring detection (after which the trend becomes positive) and the final peak (t-value (151) = -3.38, $p < 0.0012$), which highlights the important improvement in performance as a result of increased use of the serious game.

5.2 Emotional impact of games on patients

Given the complexity of the biofeedback data collected, analysis of the emotional impact of games on patients began with the Galvanic Response Index, which is particularly suitable for assessing increased stress (especially in games that require less physical movement).

The following is an analysis of the Galvanic Skin Response (GSR) detected for a specific child through the Empatica E4 wristband (Empatica, March, 2023): it takes into account the subjectivity of baseline physiological activity, along with the uniqueness of the personal skin response range, which leads to heterogeneity in GSR distributions among different children. In the case presented below, the child had the opportunity to use the three games proposed by BRAVO, obtaining good average scores as a result of very wide ranges: there was no shortage of failed tasks (score = 0) but there were difficult tasks passed with the maximum score (score = 100), a symptom of an improvement in the subject's performance and abilities.

Table 6 shows mean, standard deviation, and range of the score and galvanic skin response divided by game (as the scores of different games are calculated with different formulas and GSR was measured during quite different physical-motor activities).

	Game	Score	GSR
Mean	1	59.25	8.59
	2	60.77	6.51
	3	72.48	7.06
St. deviation	1	19.05	7.20
	2	27.89	6.32
	3	25.29	6.79
Range	1	100.00	24.11
	2	86.23	16.60
	3	62.20	14.22
Minimum	1	0.00	0.32
	2	0.00	0.22
	3	37.80	2.91
Maximum	1	100.00	24.43
	2	86.23	16.82
	3	100.00	17.13

Table 6 Score and GSR distributions

The charts in Figure 17 represent the score distributions for each game and informative box-plots of the salient features of the same distributions, showing the range width and concentration of scores around the median. The box boundaries show the width of the interquartile range and represent the first and third quartiles.

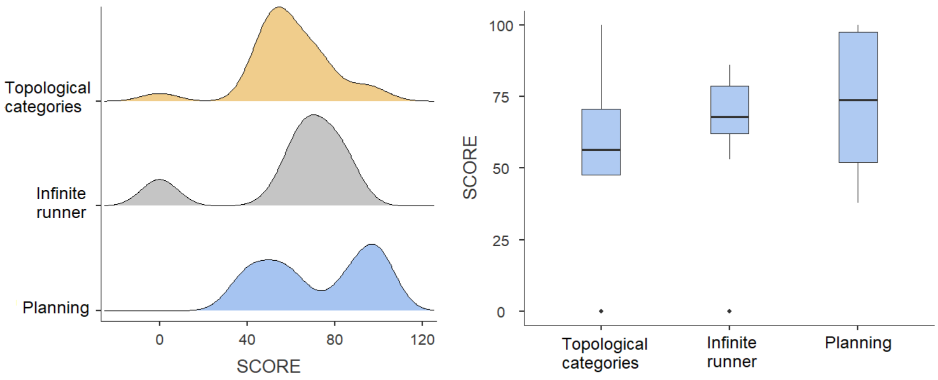

Fig. 17 Width of score ranges

The change in scores corresponds to an important change in galvanic skin response: the wide distributions of GSR for the different games, especially for the *Topological Categories* game, suggest that the change in biofeedback parameters follows the change in emotional reactions, as the *Topological Categories* game does not require any particular motor actions that would justify increased sweating (as is the case, in contrast, in *Infinite Runner*, which involves running in place and lateral movement). The plot of the GSR distributions in Figure 18 exhibits high frequencies for a wide range of values for the *Topological Categories* game, a symptom of large and continuous heterogeneity, in contrast to the other two distributions that show inflection points and obvious frequency peaks. The same evidence emerges from the box-plots, which show the largest range for the *Topological Categories* game and emphasize the distance between the first and third quartiles for the *Topological Categories* and *Infinite Runner* games.

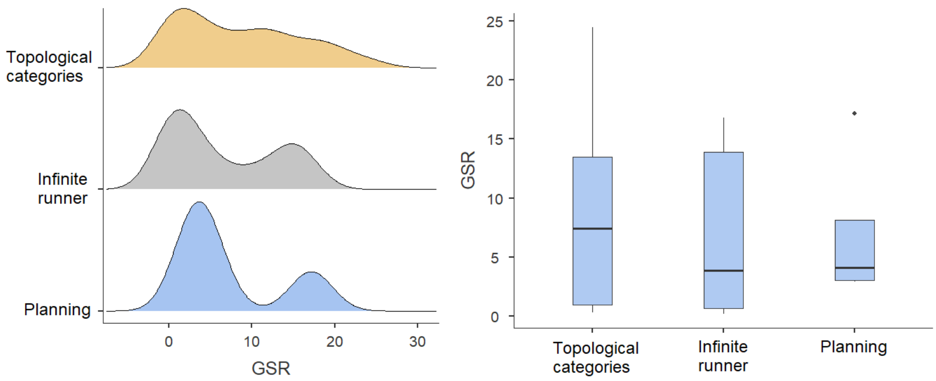

Fig. 18 GSR variations in the three serious games

What has been described so far separately for score and GSR finds an obvious explanation in the scatterplots in Figures 19, 20 and 21 that relate the score obtained to the skin response. For the *Topological Categories* game, the GSR trend line decreases for scores between 50 and 75, and then rises immediately thereafter, showing the increase in sweating and thus emotional activation for those tasks where the subject scored close to 75; on the contrary, activation decreases, while remaining at average levels, when the subject achieves the highest score (which presupposes a high level of difficulty). It appears, therefore, that there is no univocal correspondence between biofeedback parameters and scores. The optimal emotional activation (expected when the child successfully completes the more difficult levels of the game) is around an average GSR value, while too low or too high values correspond to lower scores. A similar argument applies to the *Infinite Runner* game in which it is even more evident that there is a peak of emotional activation for positive but not excellent performance, which results, instead, from average GSR values. The *Planning* game, in contrast to the other two games, seems to show a direct and positive correlation between emotional activation and performance, even though the latter game was used less than the others and the data may be less representative.

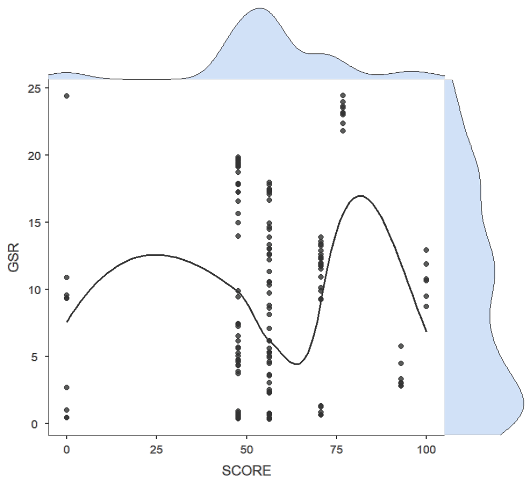

Fig. 19 Scatterplot of score and GSR for the *Topological Categories* game

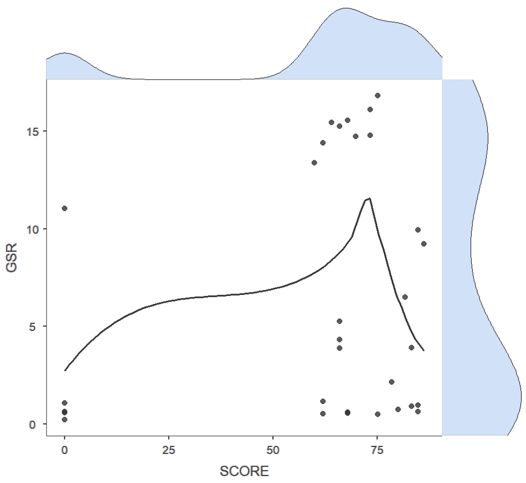

Fig. 20 Scatterplot of score and GSR for the *Infinite Runner* game

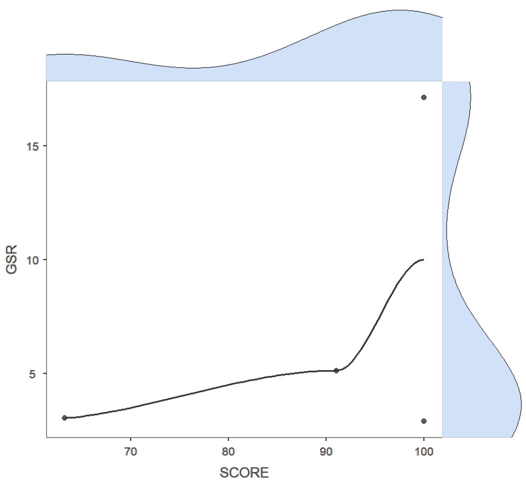

Fig. 21 Scatterplot of score and GSR for the *Planning* game

6 Discussion

Three different serious games focusing on different training and educational objectives were used in the therapy sessions. As in other serious games for children, colorful scenarios were implemented to take full advantage of their propensity towards visual learning, which also fosters greater assimilation and retention of knowledge (Fraiwan et al, 2015)(Jiang et al, 2022). Moreover, the adoption of a cartoon aesthetic makes the scenarios more attractive and enables the representation of facial emotions (Francillette et al, 2021).

It is known that the hypoactivity of cortical regions that underlies the "impulsivity" trait of ADHD tends to increase the risk of addiction to video games (Yen et al, 2017)(Mathews et al, 2019)(Salvarli and Griffiths, 2022)(Rodrigo-Yanguas et al, 2022), despite a report showing the possibility of reducing video game abuse through serious games-based therapy (Tajima-Pozo et al, 2015). Impulsivity consists in lack of impulse control and time management, high sensitivity to sounds, lights and immediate rewards. In view of these risks, the described serious games display precise instructions indicating when to wait and when to act in order to teach patience and respect for the rules.

Initial insights result from observing the trends in scores over time: patients are expected to improve, but at the same time they have to cope with the gradually increasing difficulty of the game levels chosen by the therapists.

For the *Planning* game it is interesting to note, after a slight inflection in the middle months probably related to some initial difficulties in more challenging levels, a noticeable improvement in scores in the last period, despite a gradual increase in the difficulty of the game levels as the months of experimentation passed. The increased level of concentration and attention allowed patients to achieve a significant improvement in their ability to solve problems and interact with other people, which are the main educational goals of the game. An important contribution to this improvement probably also comes from the gesture-based interaction, which allows users to see themselves within the virtual world as they perform actions, thus increasing engagement and creating a sense of control over the cause-effect relationships that users can observe in the virtual environment (Wang and Reid, 2011). This increasing performance trend over time may be partly indicative that the length of treatment can have a significant impact on the extent of improvement in cognitive function, contrary to the assumptions of some previous surveys (Corrigan et al, 2023).

For the *Infinite Runner* game, after an inflection in the scores in the third month, a growth in scores is observed until the penultimate month, which again shows a substantial improvement in performance that tends to outweigh the difficulties as time passes. Again, the remarkable improvement in patients may be partly related to the use of the Kinect device for detecting body movements, which leads the user to identify with the character in the virtual world and experience a sense of control over it through their movements. The sense of control has strong positive effects especially on motor coordination (Lelong et al, 2021), but it also increased the user engagement, with positive effects on the other educational and formative goals of the game concerning logical associations, semantic categories, concentration, respect for rules and patience (Wang and Reid, 2011). The visual feedback implemented in this scenario is also particularly important. In general, it has been shown that during a motor learning task a feedback system is important not only to provide information but also to enhance the user's motivation (Lelong et al, 2021)(Levac and Lu, 2019). Serious games must have well-defined objectives and promote positive affirmation to boost self-esteem (Baghaei et al, 2016), with a feedback and reward system that gives the idea of progress and keeps children's attention (Jiang et al, 2022). This leads to improvements not only in exercise adherence but also in performance (Rodrigo-Yanguas et al, 2022).

It has also been shown that feedback delivered with a narrative approach does not produce greater benefits, probably due to the greater cognitive load required to process the chronological or causal order of events (Levac and Lu, 2019). Nevertheless, it was also necessary to provide narrative feedback in the *Infinite Runner* scenario in order to invite the patient to pay attention to dangers and thus teach him to manage his impulsiveness. An example of this type of feedback is the animal crossing warning, which invites the user to stop and wait. Nevertheless, it was also necessary to provide narrative feedback in the *Infinite Runner* scenario in order to invite the patient to pay attention to dangers and thus teach him to manage his impulsiveness. An example of this type of feedback is the animal crossing warning, which invites the user to stop and wait. In any case, even in the presence of the increased cognitive load associated with these events and related warnings, the users were still able to make progress in the various sessions. However, the therapist can moderate the difficulty by choosing the level deemed appropriate based on the behaviour observed in the patient.

For the *Topological Categories* game, the pattern of scores over time is somewhat more irregular and peaks after half of the months of therapy observation, although the score in the final month is still significantly higher than in the initial phase of therapy. Instead of detecting body movements and reproducing them on a virtual character, this game is based on a first-person experience that takes place in a fully immersive environment via HTC VIVE. In this context, the initial astonishment at the VR environment may partially distract patients at the beginning of the experience, but then, as they become familiar with the new way in which information is presented, the sense of immersion contributes to an enjoyable experience (Checa et al, 2021).

In activities that do not require particular physical exertion, which could cause increased sweating, biofeedback parameters can be partial indicators of emotional reactions. Future studies could exploit these indicators to evaluate on a more representative sample the positive correlation between emotional activation and performance, which appears only in the *Planning* game. For the *Topological Categories* game, on the other hand, the emotional activation tends to subside slightly after the achievement of a moderately high score (which, however, is not the highest), perhaps because a sense of contentment then takes over or because the surprise effect of VR is partly dispelled.

7 Conclusions

This paper presented the BRAVO project, a platform consisting of serious games developed for the treatment of children with ADHD. Experimental tests showed an overall improvement in patients treated with serious games greater than the improvement found in patients treated with traditional therapies. In particular, children who played the BRAVO serious games showed improvements in the ability to understand the meaning of sentences, selective and sustained attention and motor inhibition. Especially in the *Planning* serious game, it is interesting to note significant improvements in scores in the final months despite the increased difficulty of the game levels.

Moreover, it has been shown that biofeedback parameters can be seen as indicators of emotional reactions for games (such as *Topological Categories*) that do not involve intense physical activities that can cause increased sweating.

In future work, interaction with avatars that converse with patients will probably also be tested. In addition, a protocol will be set up to evaluate the effects of therapy on the basis of therapists' evaluations of patients' sessions.

Competing interests and data availability statements

- The research was supported by the European Union and Italian Ministry of Economic Development through the call Horizon2020 - PON I&C 2014-2020, Axis I, Action 1.1.3, project BRAVO (Beyond the tReatment of the Attention deficit hyperactiVity disOrder), project number F/050415/01-03/X32 - CUP: B88I17000750008.
- Annamaria Schena, Attilio Covino, Pierpaolo Di Bitonto, Ada Potenza report a relationship with Villa delle Ginestre - Centro di Riabilitazione that includes: board membership and consulting or advisory.
- The authors are not authorised to make available the test data, which were in any case collected anonymously and with the consent of the parents of the patients involved in the trial.

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