The BlockQuest Game: Digital Behavioral Phenotyping of ADHD Using Embodied Serious Game in Virtual Reality

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Abstract. Children with Attention-deficit-hyperactivity disorder (ADHD) exhibit higher levels of inattention, hyperactivity, and impulsivity compared to their typically developing peers, impacting their daily functioning. To characterize the effects of ADHD, traditional research methodologies have predominantly used an outcome-oriented approach—scoring at which ages children solve particular problems compared to typically developing children. However, such an approach neglects how children solve tasks and overlooks how perceptual, cognitive, and motor processes unfold from moment to moment during problem solving. Recent research attempted to address this knowledge gap using computerized gamification of tasks. However, most gamified paradigms are stationary and overlook the aspect of locomotion and embodiment, which are strongly related to daily functioning. Here, we argue that the effects of ADHD on daily living should be characterized through the use of virtual reality as a modernized embodied tool that provides digital behavioral phenotyping of ADHD. We present a novel embodied block-construction serious game paradigm in virtual reality that links ADHD characteristics and the real-time interaction between perception, cognition, and movement.

Keywords: Virtual Reality; Neurodevelopment; Locomotion; Attention-deficit-hyperactivity; Embodiment; Problem Solving; Digital Phenotyping

1 Introduction

Attention-Deficit-Hyperactivity-Disorder (ADHD) is a neurodevelopmental disorder that manifests in various ways among children. Children with ADHD exhibit varied levels of cognitive flexibility, attentional control, and impulse regulation. Their motor skills also often deviate from their typically developing peers, primarily evident in balance and coordination deficits during locomotor and manual tasks [1]. These differences have implications for daily functioning and learning outcomes. Critically, challenges in motor skills are not only physical but are intertwined with cognitive and sensory processing abilities, impacting academic outcomes and social behavior [2] [3].

Traditionally, developmental and cognitive research on the effect of ADHD has been driven by the perspective that cognition is a collection of learned rules and conventions, independent of the body's interaction with the environment [4] [5]. However, over the past few decades, an alternative perspective—embodied cognition—has gained prominence. The embodied cognition perspective argues that cognitive processes are fundamentally grounded in physical experiences with the environment [6] [7] [8].

However, research on the effects of ADHD over development is limited in examining embodiment. Most studies use an outcome-oriented approach in which children are tested in standard, non-embodied tests, and their outcomes are compared to those of typically developing children [4]. For example, in the cognitive domain, children with ADHD perform worse on standardized mathematical tests [9] and tend to be less accurate in spatial reasoning tests [10].

Few studies examined motor skills in children with ADHD, but those did not account for embodiment. For example, ADHD is associated with decreased motor control and lower performance in timed tasks (i.e. catching or throwing a ball [11] [10]). Children with ADHD also have more variable trajectories of arm movements [1] compared to their typically developing peers, suggesting ADHD leads to the use of trial-and-error strategies instead of response preparation and planning ahead [2]. Others found that ADHD is associated with alterations in perceptual functioning and its integration with motor movements [3] [9], which manifests in decreased performance in tasks that require coordinated visual-motor skills [13].

How are those perceptual-motor associations related to the effect of ADHD on cognitive development? To address this question, we argue that researchers should adopt a process-oriented perspective that tests how perception, action, and cognition interact and unfold from moment to moment. When solving problems, children first gather information from the environment (perceptual process), process this information (cognitive process), and then act upon the environment to solve the problem (motor process). Alterations in this interaction significantly impact children's behaviors and problem solving [3], [14], [15]. Therefore, ADHD should be characterized by tasks and environments spanning multiple domains. This approach will lead to a digital phenotyping of ADHD that will involve diverse measurements such as eye movements, facial expressions, detailed real-time motor behavior, and performance on embodied executive function tasks. We also argue that such digital phenotyping must rely on serious games because those provide an engaging and interactive platform that naturally integrates perceptual, cognitive, and motor processes, thereby allowing the detection of patterns and anomalies that may not be evident through traditional assessment methods.

2 Cognitive Evaluation of ADHD Effects Over Development

2.1 Continuous Performance Tests (CPTs)

Continuous Performance Tests (CPTs) are the main evaluation tests for cognitive functioning of children with ADHD. It was first developed in the early 1950s as a model for identifying sustained attention deficits in individuals with frontal lobe lesions [16]. CPTs require sustained attention over up to 10 minutes. Due to the variability in attention levels being a key characteristic of ADHD, early studies used the CPT paradigm to assess neuropsychological characteristics on task performance [17]. However, due to the differences in developmental trajectories in ADHD[18], [19], researchers are still limited in understanding the degree to which CPT corresponds to ADHD characteristics and how this correspondence changes over development[20]. Performance on some of these tests was found to improve over development but in a subset of children, specifically in inhibitory control measures [21] [20]. CPTs are also sensitive to ceiling effects due to their over reliance on cognitive stimuli that clearly indicate target or non-target cues. As a result, there is a high likelihood of either false positives or accidental flawless performance [20] [22]. Even when some CPTs are accurate, they are limited in measuring error rates and reaction times, often yielding conflicting results in the latter [23].

2.2 Gamified CPT Paradigms

With recent technological advances, alternative multimodal methods that are more engaging for children than traditional CPTs have emerged. Those were found effective in testing neurodevelopmental conditions and specifically ADHD[24]. For example, the use of computerized games as CPTs allowed researchers to customize the tests and capture additional measures, including mouse trajectory (serves as a specific measure of information seeking and reasoning [25]) or touch trajectory on tablet based games [26]. The gamified CPTs were validated against traditional CPTs [27] , and although they were found beneficial in identifying new ADHD characteristics, they were also limited by their omission of interaction measures with the experimental environment and their focus on outcome-oriented metrics (e.g., reaction time and final task score). Finally, gamified CPTs have the benefit of being available on multiple platforms such as PC, PlayStation or mobile devices[28].

2.3 Immersive Virtual Reality (VR) Paradigms

The activities in gamified CPTs remained stationary, neglecting the crucial aspect of embodiment, which is essential for a full, multi-process characterization of ADHD. Therefore, VR has emerged in recent years as a popular and valuable research tool for studying the effects of ADHD. The embodied nature of using head-mounted VR displays offers a comprehensive evaluation of multiple domains confined within a single task [15] [16]. VR games are also highly customizable because they provide a rich, continuous behavioral data, including gaze tracking, decision-making, and movement. Such high-dimensional data provide insights into mechanisms underlying cognition when it is embedded within active behavior. Integrating VR with other technologies (e.g., bio- or neuro-sensors) and serious games offers the opportunity to examine behavior and physiology in highly engaging tasks.

However, similar to gamified CPT paradigms, researchers use VR primarily in sedentary tasks[17], [30]. Thus, its potential is not fully exploited, as it does not fully address embodiment as a concept to characterize ADHD.

3 BlockQuest – Embodied Serious Game to Characterize ADHD

Here, we introduce BlockQuest—a VR serious game to characterize ADHD over development. BlockQuest generates goal-oriented behavior in an engaging setting and requires full-body movement, including locomotion. The game is appropriate for school-aged children (aged 6 and above) and adults with and without ADHD.

3.1 Setup

BlockQuest consists of five difficulty levels, all sharing the same goal—constructing a structure from hidden elements (See Fig 1). Players receive verbal instructions for each level and then complete the construction task in an immersive VR environment that includes boxes in two different colors and marked construction space (see Fig. 1). Players can move freely within the play boundary, measuring 320 cm by 406 cm, generated using the PICO Neo 3 Pro Eye's internal feature (other headsets can be used as well).

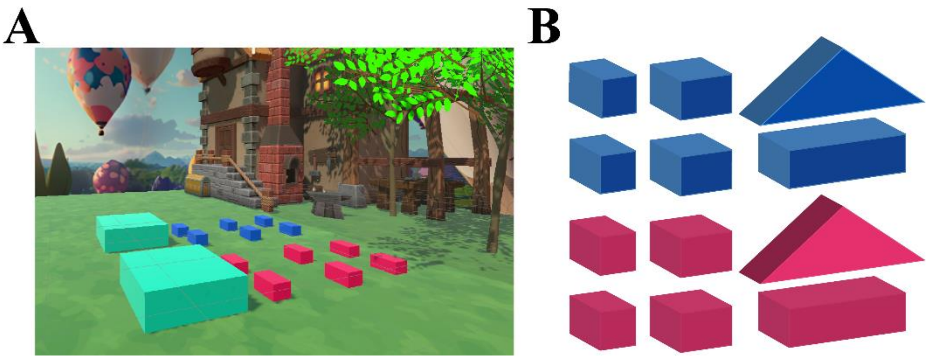

Fig. 1. BlockQuest serious game. (A) BlockQuest virtual environment. **(B)** Elements that are used for construction. Those elements are hidden within boxes in the virtual environment.

The environment follows real-world physical laws (e.g., terrestrial gravity) and the hidden elements have realistic physical properties. For example, smaller elements are lighter and are thrown further compared to bigger elements. Players are required to be precise when they open the boxes and grasp the hidden objects.

To succeed in the game, players must look ahead, coordinate their movements, demonstrate spatial awareness, and plan strategically. They need to integrate perceptual, motor, and cognitive skills simultaneously, and the interaction between these processes is recorded. Movement is recorded by three HD cameras and analyzed using computer vision, similar to previous research [23],[24]. Body position, hands position, eye gaze, and object dynamics are recorded via the headset. Object dynamics include object grasping and releasing, object movements, and box opening.

3.2 Task

The players are fully immersed in the colorful virtual world, and their quest is to locate and collect all hidden objects (See Fig 1) which are scattered within the play area. From Level 2 onward, players are asked to build a model object from collected hidden elements. Each level presents its own unique challenge associated with different processes affected by ADHD. The environment itself encourages exploration (there is no time limit for each level).

3.3 Procedure

Players start with practice activities to ensure comfort and understanding of the mechanics of the game. Subsequently, levels increase in difficulty. All levels include the initial information search aspect, where each hidden element must be collected from the box that hides it. An increase in difficulty changes cognitive load, which is associated with greater delay in response to real-time discounting tasks in children with ADHD. Additionally, an increase in difficulty was found to exacerbate impulsive behavior [31].

Level 1. Information search task. Each pink and blue cube hides an element (see Fig. 1). The goal is to collect all hidden elements and place them in a designated area, corresponding to each colored array of boxes. Searching for visual information is an integral part of everyday activities and is associated with problem-solving activities, in which children with ADHD exhibit different search behaviors when compared to their typically developing peers. Additionally, children with ADHD exhibit increased patterns of foraging, which is linked to lower attentional states that favor exploration over exploitation in tasks [32].

Level 2. The goal is to collect all hidden elements and build a model, starting with color blue and ensuring the 3D triangle, ‘roof-like’ element is on top of the modelled construction – players must use all hidden elements. Then, they need to repeat modelling the same construction in the pink colors. At this level, instructions are scarce, and construction is allowed without much constraint. The justification for this level is based on previous funding showing that children with ADHD tend to respond to problems differently based on the type of received instructions [28]; they performed better when given strategic instructions over tactical ones.

Level 3. The construction is placed within the environment in a neutral grey color (see Fig. 2). Players can use it as a reference model when constructing. This level introduces more structured instructions and puts more demand on higher-level working memory. Studies have shown that individuals with ADHD exhibit organizational problems in structuring tasks and maintaining order in their environment [22] [23], which are linked to inefficiencies in working memory.

Level 4. Similar goal to Level 3, but the reference construction is not placed within the virtual environment. Players must use recall to build the same model as in Level 3 without a visual cue. This level also addresses memory challenges in ADHD and adds cognitive load as an unexpected difficulty[32].

Level 5. The goal at this level is to build one construction model using all hidden elements from both colors. Players are shown a guiding animation (Fig. 2) on how to place the hidden elements. This is the last level and it involves the highest cognitive load. Players use all the skills that were required in previous levels simultaneously. Because children and adolescents with ADHD do not attempt to solve cognitively complex tasks where structuring and planning action is required [35], this level also examines players' ability to complete a construction in efficient manner.

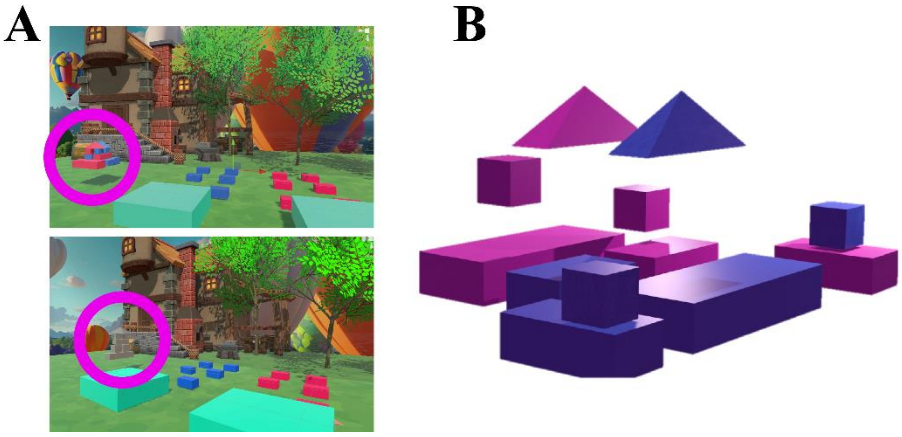

Fig. 2. (A) Reference object for Level 5 is placed outside the movement boundary to force mental representation of objects out of sight (Top), and Level 3 reference object in neutral grey color (Bottom). **(C)** Animation shown to players twice before starting level 5.

4 Final Remarks

The BlockQuest game provides a novel, digital-phenotyping approach to characterize ADHD [36], [37]. By integrating attention, working memory and sensorimotor measures, the game comprehensively assesses ADHD over development, which goes beyond the traditional outcome measures. BlockQuest aims to identify the underlying mechanisms associated with ADHD functional skills and their different developmental trajectories. By integrating measures from multiple domains into a single engaging task, BlockQuest pushes the envelope of ADHD characterization to an embodied experience which is more similar to daily life.

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Disclosure of Interests. The authors declare no interests**.**

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