Using fNIRS to Assess Cognitive Activity During Gameplay

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This work explores the use of functional Near Infrared Spectroscopy (fNIRS) to assess cognitive activity during videogame play, and compare it to cognitive activity during cognitive tasks that assess executive control. To this end, we assessed haemodynamic response to videogame and cognitive tasks in the prefrontal cortex, each manipulated on a spectrum of difficulty. In our study (n = 37), we find that mental effort expended during videogame play did not differ from mental effort expended during cognitive tasks—and speculate that regional cognitive activity during gameplay is indicative of functions pertaining to memory encoding and retrieval, planning, and sustainment of attention. Our findings suggest the utility of fNIRS as a means to understand challenge as part of the player experience, and contest the popular conception of videogame play as cognitively undemanding entertainment. Further, we were successful in distinguishing between difficulty levels in the gameplay tasks, situating fNIRS as broadly useful for granular assessment of gameplay difficulty. As such, we contend that fNIRS is an effective and useful tool for generating high-resolution insights regarding cognition (and particularly the experience of difficulty) during gameplay.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**; • **Applied computing → Computer games**; • **Software and its engineering → Interactive games**.

Additional Key Words and Phrases: cognition, cognitive activity, fnirs, functional near infrared spectroscopy, prefrontal cortex, pfc, challenge, difficulty, gameplay, experiment

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1 INTRODUCTION

In games, difficulty is understood to be an intrinsic and salient component of the gameplay experience [22, 58]—and in fact, the experience of challenge (and of overcoming said challenge) has been identified as a primary motivator for why we play games [3]. Challenge not only emerges through mechanical demands placed on the player—for example, performing a powerful combo quickly enough to subdue an enemy—but also through *cognitive* demand.

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When playing videogames, players are prompted to memorise, recall, plan, track multiple information streams, execute strategies, and perform continual risk-return analyses. For example, when playing a real-time strategy game, a player must: maintain awareness of all resources and forms of currency available to them; build towards a grand strategy of either attack or defense; predict opponent strategies; execute tactical decisions consistently when in battle (e.g., diverting a medic unit to an imperilled squadron); as well as numerous other more low-level tasks, such as memorising and navigating user interfaces, that nonetheless represent ‘mental work’.

Understanding the influence of challenge on the player experience, as well as being able to judge when a player is being appropriately challenged, is critical. This is evidenced by the considerable research and development efforts allocated to these endeavours. A wide range of methods have been used to evaluate the experience of challenge, informed by methodologies practiced in games research, human-computer interaction (HCI) more broadly, and general psychological research methodologies [51]. To this end, psychophysiological assessment has been shown to be an effective means of understanding various aspects of the player experience [52] and shows particular promise for assessing challenge.

While psychophysiological assessment has primarily been used to explore the *affective* component of the player experience [52, 61], its application to understanding *cognition* is less common. As such, challenge in games has typically been evaluated through the lens of the stress experienced by the player—often assessed via physiological arousal (that is, intensity of emotional experiences) and cortisol (a stress hormone) [18, 37, 40, 41]. When understanding challenge in play experiences, we argue that the player’s cognitive activity likewise represent an inexorable component of the player experience. By extending our understanding of the cognitive demands of activity that occurs during videogame play, we can likewise begin to better contest the popular misconception of videogames as inherently cognitively undemanding activities.

As such, we turn to functional Near Infrared Spectroscopy (fNIRS) as one path towards understanding player cognition during videogame play. FNIRS allows for insights into cognitive activity through the measurement of haemodynamic changes (e.g., blood oxygenation), often in the prefrontal cortex—the region of the brain broadly responsible for executive control [49]. A comparatively new entrant to psychophysiological measurement, fNIRS allows for greater spatial resolution and localised insights than other measures of cognitive activity (e.g., electroencephalography). As such, fNIRS stands as a promising, albeit relatively untested, entry to the arsenal of tools available to games researchers for assessing the cognitive processes associated with play.

In this work, we situate our contribution around the use of fNIRS in exploring and understanding the influence of videogame challenge on player cognition. We do so with the two-fold aim of both expanding extant understanding of player cognition during videogame play (thus, contributing knowledge about the cognitive demands of an activity often construed as lacking in such demands), and investigating the utility of fNIRS in player experience research. To this end, we aim to validate fNIRS as a tool to measure cognitive activity during gameplay, and to explore the influence of videogame difficulty on cognitive function in the prefrontal cortex.

Our work contributes to (and expands upon) extant knowledge of cognitive activity during gameplay, as well as effective methods to assess cognition during gameplay. We found that cognitive activity in videogame play is comparable to the activity that emerges in standardised cognitive tasks, with increases in both task and game difficulty corresponding with increases in prefrontal blood oxygenation. We suggest that games activate cognition in a similar way to tasks explicitly requiring the use of executive functions such a memory encoding and retrieval, planning, and sustained attention—contradicting the popular conception of videogames as cognitively undemanding, or as ‘brain rot’. In addition, we were able to distinguish between difficulty levels in the gameplay tasks, evidencing fNIRS’ utility in granular assessment of difficulty in games. We submit that this work evidences the usefulness of fNIRS in providing localised and high resolution insights into cognitive activity during gameplay.

2 BACKGROUND

2.1 Challenge and Game Difficulty

The evaluation of experienced difficulty (or challenge) in games has been at the forefront of player experience research. Much of the academic inquiry into difficulty in games has concerned the subjective experience: in employing self-report methods, researchers have found that players seek, and are driven by, challenge [3, 45]; that success in the face of challenge fulfils basic psychological needs, such as competence [62]; and that challenge is less satisfying when difficulty is too low, but still enjoyable when too high [39, 54].

The importance of challenge and difficulty in games is such that large swathes of research and development efforts are dedicated to the pursuit of achieving and understanding optimal levels of challenge for players. For example, many games offer differing difficulty levels (e.g., ‘easy’, ‘medium’, ‘hard’) to accommodate individual player ability. Further, games may also employ dynamic difficulty adjustment: reactive game systems that adapt dynamically to player performance, allowing for the maintenance of challenge-skill balance (wherein the skill of the player is matched by the challenge of the game) [32]. Some literature proposes that optimal challenge represents an antecedent to—or is, at least, predictive of—the experience of flow [22, 38]: an optimal state characterised by holistic absorption in, and enjoyment of, an activity (and often an end goal of game design) [15].

While the motivational and emotional experience of challenge is well-understood in games literature, less so is the cognitive experience of challenge. Despite a popular conception of videogame play as a comparatively undemanding cognitive activity, it has also been argued that gameplay requires the allocation of significant cognitive resources. Research in psychophysiological spaces has investigated the experience of gameplay through the lens of cognition, providing support for the notion that videogames exercise critical cognitive skills and executive function—including spatial reasoning and object orienting [65], allocation of attentional resources [9], and working memory, task shifting, and inhibitory control [50]—or that, more generally, videogame play requires notable mental effort.

Such research has predominately employed electroencephalography (EEG) and, to a lesser extent, functional Magnetic Resonance Imaging (fMRI). Both instruments allow for distinct insights into cognitive activity, and will be broadly described in the following sections.

2.2 Brain Activity

Electroencephalography (EEG) assesses the electrical activity of the cerebral cortex, as generated by postsynaptic potentials of cortical nerve cells and measured from the scalp [63]. EEG activity is processed via two parameters: amplitude (the size of the signal) and frequency (how fast the signal cycles), allowing for the detection of patterns, or ‘bands’, that emerge in cognitive activity [67]. Each of these bands (generally, alpha through gamma) can be roughly interpreted as representative of a mental ‘state’: for example, the ‘delta’ frequency only emerges during slow wave sleep; conversely, the ‘beta’ frequency is most commonly associated with active or anxious concentration [8].

In contrast, functional Magnetic Resonance Imaging (fMRI) employs a magnetic resonance scanner to measure brain activity through the detection of haemodynamic response (changes in brain blood flow and oxygenation). As cerebral haemodynamic response is associated with increased metabolic demands of the brain [55], assessing and understanding this response can help to generate insights into cognitive activity and mental demands during task engagement. fMRI offers excellent spatial resolution—but is also susceptible to noise, and unforgiving of a non-stationary participant.

Furthermore, the use of fMRI is constrained by its scanner environment: fMRI is not modular or portable.

While games research studies investigating electroencephalographical activity have been aided by the increasing commercial availability of relatively inexpensive and robust EEG headsets (e.g., the Emotiv EPOC [19] and NeuroSky MindWave [53]), games studies investigating haemodynamic response have been comparatively limited to research that is able to take place within clinical settings with direct access to stationary, expensive, and often impractical fMRI machines (while some advances have been made in the direction of fMRI machines that allow participants to sit up, the majority still require participants to remain prone within a 'scanner tunnel' [16]). Owing to these notable barriers, fMRI is currently not outwardly feasible for studies requiring the real-time investigation of gameplay. However, the comparatively recent introduction of functional Near Infrared Spectroscopy (fNIRS)—and more recently still, of portable and commercial fNIRS machines—allows for a more practical, and relatively less expensive, opportunity to assess cortical haemodynamic response in real-time gameplay experiences.

2.3 Functional Near Infrared Spectroscopy

Similar to fMRI, fNIRS measures cerebral haemodynamic response (blood flow), through concentration changes in oxyhaemoglobin (HbO2) and deoxyhaemoglobin (HHb)—wherein increases in the former, and decreases in the latter, are indicative of increased cortical activity in the measured site [57]. However, fNIRS differs from fMRI in that it uses a far more accessible method—the employment of infrared light—to measure haemodynamic responses. Although fNIRS is a comparatively recent invention having first been pioneered in the early '90s [21], it features extensively in neurological research—and has likewise enjoyed uptake in human-computer interaction research [26], suggesting a similar utility for games user research. In comparison to EEG, which features more prominently in games research owing to greater brain region coverage and temporal resolution, fNIRS offers greater accuracy in localised insights into the region of interest (e.g., the prefrontal cortex) [73]. Neuroscientific literature reports the investigation of fMRI and fNIRS as complementary measures, owing to fMRI's exceptional spatial resolution and fNIRS high temporal resolution [64]. As such, while existing—and more frequently used—techniques such as EEG allow for highly accurate interpretation of cognitive activity in terms of *when* it occurred, fNIRS allows for more granular insight as to *where* the activity is occurring in the brain. We propose that ongoing evaluation of fNIRS in videogames context will help to more readily situate it as a complementary measure to EEG, and to improve understanding as to how cognitive activity during videogame play manifests. Finally, fNIRS allows for a more direct measure of cognitive activity (that is, oxygenation is directly associated with increased cognitive activity) than EEG, which requires interpretation of frequencies with a one-to-many domain relationship—wherein one frequency may be representative of multiple, occasionally oppositional, mental states [11].

2.3.1 Functions of the Prefrontal Cortex. As fNIRS is typically employed in assessing cognitive activity via the Prefrontal Cortex (PFC), an understanding of the PFC's functions is essential for informed interpretation of the fNIRS data. Pursuant to this, it is helpful to examine the regions of the PFC, as they are typically implicated individually in mediating or controlling various cognitive mechanisms. The PFC can be divided into three broad regions of interest: the left, medial, and right prefrontal cortices. Independent examination of these regions has revealed associations with specific cognitive processes and functions. It must be noted that the nature of these relationships is complex and multifaceted—and, in fact, the mapping of different cognitive functions to discrete regions of the brain is, itself, contentious [5]. As such, a comprehensive detailing of these relationships is beyond the scope of this paper; however, this section will provide an overview of the findings commonly reported in contemporary literature.

The PFC, overall, has been implicated in many important mental processes (including speech and language, emotions, and memory [30]), and may be broadly understood as chiefly responsible for executive control [49]. Increased haemodynamic activity in the PFC is consistently associated with increased mental workload [6, 12, 48], with variations in haemodynamic activity corresponding uniformly with variations in task difficulty [48]. To this end, researchers are even able to ascertain disparities in participant neural efficiency (that is, individual differences in cognitive effort assigned to completing like tasks) [12].

The execution of these processes may be further atomised into specific regions. Per the Hemispheric Encoding/Retrieval Asymmetry (HERA) model, the left PFC may be associated with the *encoding* of memories (that is, the cognitive formation and recording of memory after an event has occurred)—whereas the right PFC may be associated with the *retrieval* of said memory (although, notably, this pattern reverses in older adults) [70].

Further, increased activity in the left PFC has specifically been associated with problem solving and planning [28], semantic working memory (that is, memory in connection to language and word-based tasks) and semantic retrieval [23, 72], and reward responsiveness—with asymmetric neural density in favour of the left PFC prompting greater bias in responding to reward-related stimuli [56]. In comparison, the right PFC has been associated with the sustainment of attention [46], the execution of self-control and inhibitory control [5, 42], and—as with the left PFC—planning [27, 28].

The role of the medial PFC is less defined in current literature. Some research suggests that this region may play a role in developing associations between various stimuli and adaptive responses (in particular, emotional responses) [20]. Moreover, recent literature has also implicated the medial PFC in performing a regulatory role over many cognitive functions, including memory, habit formation, attention, and inhibitory control [35].

2.3.2 fNIRS and Gameplay. Although other measures of cognition (such as EEG) feature far more prominently in games research, previous studies have employed fNIRS to investigate various aspects of gameplay and gameplay interactions. These studies generally focus specifically on the prefrontal cortex (PFC; although some studies localise further—e.g., dorsolateral prefrontal cortex, or DPFC). For example, Matsuda and Hiraki employed fNIRS to evaluate the effects of prolonged gameplay on children, finding a pattern of decreasing HbO2 (from baseline) in the DPFC throughout five-minute game sessions [47]. In a comparative investigation of 2D and 3D graphical interfaces, Takada et al. found 3D gameplay elucidated greater levels of oxyhaemoglobin generally throughout the cerebral cortex [69]. In an evaluation of social play, Reindl et al. found synchronised brain activity, occurring in the DPFC and frontopolar cortex, between parent and child in cooperative gameplay [60]. Finally, Li et al. investigated the individual effect of discrete game events in League of Legends (e.g., slaying an enemy), finding region-specific, time-locked haemodynamic response within the PFC [44]. Pursuant to this, Li et al. support the feasibility of using fNIRS to monitor real-time PFC activity during online videogame play.

The use of fNIRS represents an opportunity to further enrich our understanding of the player experience of videogames—and so has been employed in the specific investigation of game (or game-like task) difficulty in differing contexts. In a study using fNIRS to gauge cognitive workload in a complex game-like task (described as a *'quasi-realistic navy [...] command and control environment task'*), with a sample of eight, Izzetoglu et al. found an increased rate of oxygenation change in the DPFC when participants engaged with the task—indicating sustained attention in an activity requiring complex working memory and decision-making [34]. Further to this, Izzetoglu et al. found that a decrease in oxygenation in the DPFC under high workload conditions may be a predictor of performance decline (indicating mental fatigue and attentional withdrawal). This work has valuable implications for the cognitive experience of challenge in play, as assessed through oxygenation in the PFC, but the task chosen is arguably not representative of a typical contemporary gameplay experience (being a game-like 'psychological task'). Further, as an exploratory psychophysiological study, the research draws inferences from a relatively small sample size; future research may support this work's conclusions through the employment of a more robust sample size.

Other work also points to changes in PFC oxygenation in game, or game-like, tasks. In a study investigating differences in fNIRS activity between two *Pac-Man* difficulty levels (easy and hard), Girouard et al. were able to clearly distinguish gameplay from rest (with increases in oxyhaemoglobin associated with the former)—and, albeit less clearly, distinguish between the two difficulty levels [25]. Notably, Girouard et al. report that distinguishing between difficulty levels was more complex, owing to significant inter-subject variability; as the sample used was relatively small (9), a greater sample size may have allowed for a more robust difference in results to emerge.

In an investigation of flow states in player experiences, Yu et al. likewise employed fNIRS to evaluate PFC response to differing difficulty levels [75] with a sample size of 40. In this research, Yu et al. modified the difficulty of a musical rhythm game *Rhythm Master* to examine flow amongst video game players and non-video game players (as flow most reliably emerges when challenge and skill are balanced). The researchers found that PFC activity differed significantly between non-video game players and video game players in flow states, with the results overall supporting the value of fNIRS as a means to distinguish difficulty in videogame levels. While this work explored the impact of changes in difficulty in the videogame, no non-videogame tasks were undertaken. Additional insight related to cognitive functions and processes would be possible through direct comparison to validated cognitive tasks.

In contrast to literature primarily focusing on the PFC, Tachibana et al. investigated the effect of differing difficulty levels in *Dance Dance Revolution* on the parietal and temporal lobes—–finding generally increased oxyhaemoglobin in the more difficult task compared to a baseline condition [68]. However, the differences between difficulty levels were less clear. While there was increased oxyhaemoglobin in the right parietal lobe in the more difficult condition, no other differences were found. As with Girouard et al. [25], it is possible that the smaller sample size (7) may have precluded the emergence of more robust differences.

There is evidence that fNIRS is capable of assessing and distinguishing between challenge in digital tasks at a granular level. While not an evaluation of videogame play, Afergan et al. were able to use fNIRS to detect task difficulty in real-time during a path-planning simulation task [2]. To this end, the authors developed a dynamic difficulty system responsive to real-time changes in cognitive activity as captured by fNIRS. These results further suggest the potential utility of fNIRS in measuring task difficulty in videogame contexts also.

To date, literature exploring the effect of videogame difficulty on oxygenation in the brain (as assessed by fNIRS) has successfully been able to distinguish between play and rest—but distinguishing between varying levels of difficulty has proven more complex, although strides have been made towards this in games [75] and other domains [2]. In addition, work has also found that extended exposure may lead to increased *de*oxygenation [47], thus complicating the landscape of results via the introduction of a possible additional variable in the interpretation of extant results. Further, the videogames employed in these studies are arguably not representative of more conventional and contemporary videogames (while *Dance Dance Revolution* is extremely popular, the game's full body engagement sets it apart from typical game modalities; the same may be said for *Rhythm Master*, which likewise requires a unique rhythm-based input modality; similarly, *Pac-Man* is now approximately 40 years old and differs in many ways from modern videogames). Research exploring the potential differences in brain oxygenation concentration in a) a representative modern commercial videogame, with b) clearly delineated difficulty levels, and c) on a larger sample size will help to extend extant knowledge about the influence of videogame difficulty on cognitive activity. Further, we contend that comparing the cognitive activity that occurs during videogame play with the activity that occurs during known cognitive tasks that reliably induce specific cognitive processes (e.g., spatial working memory) will enable a richer understanding of how cognition in videogames may manifest.

2.4 Motivations for the Study

In this paper, we report a research study that expands the understanding of the influence of videogame challenge (as represented by variations in game difficulty) on human cognition. We were interested in exploring the following study objectives:

- **Objective 1**. Test whether fNIRS can reliably measure differences in prefrontal cortex activity associated with a videogame manipulation (i.e., variations in difficulty).
- **Objective 2**. Examine how prefrontal cortex activation patterns compare between gameplay and established executive functions tests.
- **Objective 3**. Examine whether prefrontal cortex activation patterns observed during executive function tests are associated with activation patterns observed during videogame play.

To do this, we assessed differences in PFC oxygenation and deoxygenation levels, as measured by fNIRS. To address previous limitations in the literature that may preclude drawing conclusions about the influence of game difficulty on PFC oxygenation, we employed a large sample size, clearly delineated difficulty levels, and a contemporary commercial videogame.

3 METHOD

3.1 Participants

41 male participants, recruited from the Queensland University of Technology, participated in the present study. Due to technical issues (i.e., faulty hardware prompting a computer crash during data collection), four participants' incomplete data was removed from analysis. The final sample was 37 participants, with a mean age of 21.32 years old (SD = 4.76). Participation was restricted to male participants due to a limitation with the BIOPAC fNIR100 headband, identified during the pilot testing phase, wherein the band was too large for most female pilot participants' heads—thus allowing an unacceptable amount of artificial lighting to penetrate the space between the band and participant's forehead, compromising the near-infrared functionality. All participants were right-handed, had normal or corrected-to-normal vision, and reported no history of neurological or psychiatric disorders. On a Likert scale of 1 - 7 querying participants' general level of experience playing videogames, with '7' representing 'very experienced', participants reported a mean of 6.27 (SD = 0.93)—indicating that the sample comprised generally highly experienced videogame players. On a similar item specifically addressing level of experience with tower defense and offense games, participants were less experienced, self-rating with a mean of 4.25 (SD = 1.31). No participants had previous experience playing the game, *Anomaly: Warzone Earth*, selected for the study. Participants received $20AUD in compensation for their participation in the study.

3.2 Ethics

The study was conducted in accordance with the Declaration of Helsinki [74] and was approved by the ethics committee at the University of the last author. After being informed of the experimental procedure and their proposed involvement, all participants gave their written consent.

3.3 Procedure

Participants were comfortably seated in the experimental room. After providing informed consent, participants were directed to complete a pre-experiment demographics survey provided on an iPad. To prepare participant skin for the fNIRS device, participants' foreheads were cleansed with an alcohol wipe. Then, a continuous wave 16-channel BIOPAC fNIR100 headband [10] was placed on their head. Participants then played the videogame, *Anomaly: Warzone Earth*, and completed the three cognitive tests (in the counterbalanced order of their group). Both the cognitive tasks and the iPad game were completed or played on an iPad tablet. The game was played three times in total, in escalating order of difficulty. The three cognitive tasks were selected from the CANTAB battery. The CANTAB (or Cambridge Neuropsychological Test Automated Battery) is a collection of cognitive assessments designed to measure cognitive function, correlated to neural networks [14]. The tasks employed in the current study are One-Touch Stockings of Cambridge (OTS), Spatial Working Memory (SWM), and Attention-Switching Task (AST). The order in which participants performed the videogame and the cognitive tasks was counterbalanced, with four possible different orders (Group 1: AST, OTS, videogame, SWM; Group 2: OTS, SWM, AST, videogame; Group 3: SWM, videogame, OTS, AST; Group 4: videogame, AST, SWM, OTS). With the exception of the OTS, all tasks were played in order of difficulty (with the easiest difficulty completed first, and hardest difficulty completed last). Due to the nature of the tasks and their presentation in the CANTAB software, it was only possible to pseudo-randomise difficulty in the OTS task.

Before each cognitive task, before the gameplay session, and at the conclusion of the data collection, participants were asked to relax—while focusing on a black screen—for 70 seconds. This period served as a baseline. A short training session was undertaken before each cognitive task, consisting of instructions and several practice trials, in accordance with the CANTAB software manual. More specifically, participants received instructions at the beginning of each task during a first "demonstration trial", meaning that instructions were given while the CANTAB software actually showed how to perform the task. Then, participants performed a few practice trials to ensure that they correctly understood teach task.

The training lasted approximately 2 - 4 minutes for the OTS and SWM, and 3 - 6 minutes for the AST, with slight variations depending on participants. The time for task completion (excluding instruction/training) was approximately 4 - 7 minutes for SWM, 10 - 12 minutes for AST, 10 - 15 minutes for OTS, and 5 minutes for each videogame level. After each task or each videogame level, a post-test survey was delivered. The post test survey included measures that were not analysed in the current study.

3.4 fNIRS Acquisition

The 16-optode fNIR100 system was used to record changes in HbO2 and HHb (both in μ mol/L, using the modified Beer-Lambert Law) concentration at 2Hz with two peak wavelengths at 730 nm and 850 nm. The fNIR 100 has a fixed 2.5 cm source-detector separation (see Figure 1). COBI Studio (v1.2.0.111) was used for data acquisition. fNIRS data were analysed using MATLAB R2019a with several functions from the HomER2 software package [33]. The raw data were first converted into optical density change (delta OD) using the optical density change calculation function (hmrIntensity2OD) of Homer2. Then the OD data were converted to HbO and Hhb concentration data by the modified Beer-Lambert law (MBLL) using the optical density to haemoglobin concentration function (hmrOD2Conc) of HomER2. The differential pathlength factor (DPF), which accounts for the increased distance traveled by light due to scattering, was set at 6. This value is in the recommended range for an adult head [29, 71]. Concentration data were band pass filtered using a FIR filter with an order of 20 (0.02–0.40 Hz) to remove long-term drift [13], higher-frequency cardiac or respiratory activity, and other noise with frequencies other than the target signal [13].

Finally, a correlation-based signal improvement (CBSI) of the concentration changes was employed in order to correct for motion artifacts. The correction function (hmrMotionCorrectCbsi) follows the procedure described by [17]. We report both HbO and HHb signals, however, a side-effect of the CBSI method is that it "forces" HbO2 and HHb signals to be inversely correlated. Therefore, one must keep in mind that both signals can be artificially contrasted with CBSI. For statistical analysis, the mean concentration changes from the 70-second baseline to the haemodynamic response during all task conditions were calculated for each participant. Based on previous literature using the same device [12, 24, 43], statistical analysis was focused on 3 ROIs: left lateral PFC (optodes 1-6), medial PFC (optodes 7-10), and right lateral PFC (optodes 11-16). Topographical maps were generated using fNIRSoft (v1.3.2.3).

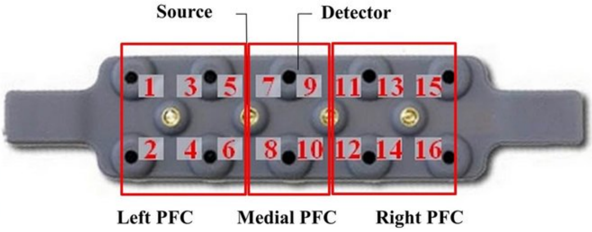

Fig. 1. The Biopac fNIRS headband used in the current study

3.5 Videogame Selection

The choice of videogame was determined by the following selection criteria: that the game offers levels with clear delineations in difficulty (that is, one difficulty level is clearly easy, one is clearly of medium difficulty, and one of clearly hard difficulty, for a general population); somewhat controllable in-game variables, allowing for comparable experiences between participants; that it is representative of a contemporary commercial videogame (thus improving generalisability to typical modern gameplay experiences); and that is has a reasonably low barrier to entry, with simple and easily explainable mechanics and controls.

The game selected was *Anomaly: Warzone Earth* (see Fig. 2), a reverse tower defense game for the iPad that fulfilled the selection criteria. In this game, players must retake earth from hostile extraterrestrial occupation. To do so, players send an entourage of assault and support vehicles (selected by the player) on a route (also, typically, selected by the player) through a level populated by static enemy defense units. The goal of most levels, including for the levels played by participants in this study, is for at least one surviving player vehicle to arrive at the end of the route. Throughout the route, the player vehicles and enemy units attack one another; while the player cannot reroute the vehicles once the level has started, the player assists progression by repairing and replacing vehicles, buying additional vehicles, selecting which units to attack, collecting resources, and placing offense and defensive area-of-effect abilities (e.g., EMPs).

3.6 Gameplay

Prior to starting gameplay, participants watched a 2:25 minute video tutorial that introduced game mechanics and objectives. Participants then played three levels in order of escalating difficulty: Level 1 - Casual Difficulty, Level 3 - Advanced Difficulty, and Level 5 - Hardcore Difficulty. Each gameplay session had a duration of approximately 5 minutes. To control for variability in the player

Fig. 2. A screenshot from *Anomaly: Warzone*

experience, the player's route was predetermined and set by the researcher (some routes were unviable, and would result in an early defeat). While necessary to create a consistent experience between participants, the use of predetermined paths meant that it was not possible to compare participants' performance via their score in the game.

3.7 Cognitive Tasks

Spatial Working Memory (SWM). This task involves retention and manipulation of visuospatial information in working memory. Participants were required to search for coloured tokens hidden inside boxes, touching them one-by-one to reveal their contents. The participants' goal was to find all tokens. Participants were instructed that once a token was found in a box, that box would not hide another token during the current trial. The number of displayed boxes modulates the difficulty of the task, since it's more difficult to remember where tokens were previously found when the number of boxes is high. We used three levels of difficulty: 4, 6, and 8 boxes (1 trial of each), always presented in this order to the participant. Task performance was measured as the number of times the participant opened a box, in which a token was already found in a previous search of the current trial (also referred to as "between-search errors" in previous studies that have used an identical task). Lower values indicate better performance. Task duration was approximately 4 - 7 minutes.

One Touch Stockings (OTS) of Cambridge. This task is similar to the Tower of London and Tower of Hanoi tasks. To summarise the principle, at the beginning of each trial, two sets of colored balls were presented in predefined positions, one in the top half of the screen and one in the bottom half. These were described as billiards balls, since they appear to be hanging in pockets. Participants were asked to determine the minimum number of moves necessary to rearrange the three balls in the bottom display, such that their positions matched the goal arrangement in the top half of the screen. As in the Tower of Hanoi, balls below other balls cannot be moved without first moving the balls above. We used three levels of difficulty: 1 (2 trials), 2 (2 trials), 3 (2 trials), 4 (3 trials), 5 (3 trials), 6 (3 trials) moves for a total of fifteen trials, with difficulty levels pseudo-randomised across trials. In this task, an error constitutes an incorrect guess as to the numbers of moves required to successfully complete a trial; for example, if a participant enters that it will take 6 moves to complete a trial, when the correct answer is 5. Task duration of the OTS was approximately 10 - 15 minutes.

Attention Switching Task (AST). AST provides information about participants' cognitive flexibility. On each trial, an arrow appears on the right- or left-hand side of the screen. A cue ("Which direction?" or "Which side?") is presented in each trial, indicating whether the participant should respond on the basis of the direction of the arrow or the side of the screen on which the arrow appeared. The participants completed three different conditions. They started with the "Which direction?" (non-switching condition) instruction, continued to the "Which side?" (non-switching condition), and finally completed the third more difficult task with the alternating instructions (switching condition: mental flexibility). Accuracy (percentage of errors) and response times were collected and compared during the non-switching versus switching conditions. Task duration of the AST was approximately 10 - 12 minutes.

3.8 Statistical Analysis

Repeated measures ANOVAs were used to test whether increasing difficulty during gameplay and the cognitive tasks would result in variations in HbO2 and HHb signals (separate ANOVAs were conducted for each signal). Post hoc testing was conducted with a Tukey's Honest Significant Difference Test [1]. A series of three Bravais-Pearson correlations were performed to examine the relationship between HbO2 concentration changes during difficult game play with HbO2 concentration changes during the most difficult condition of the three cognitive tests OTS, SWM, and AST. All statistical analyses were performed using Statistica 10 and significance was defined at $\alpha = 0.05$.

4 RESULTS

4.1 Cognitive Task Performance

Attention switching task (AST). Number of errors significantly increased between the non-switching condition and the switching condition, $F(1, 39) = 15.84$, $p < .001$, $\eta p^2 = .29$.

One Touch Stockings (OTS) of Cambridge. Number of errors significantly increased with the difficulty of the OTS task, $F(5, 195) = 18.39$, $p < .001$, $\eta p^2 = .32$, with a higher number of errors with 6 moves than all other levels of difficulty ($p < .05$ for all comparisons).

Spatial Working Memory (SWM). Number of errors significantly increased with the difficulty of the SWM task, $F(2, 74) = 4.02$, $p < .05$, $\eta p^2 = .10$, with a higher number of errors with 8 versus 4 boxes ($p < .01$).

4.2 Prefrontal Activity During Gameplay

For HbO2, a two-way (3 levels of difficulty × 3 ROIs) repeated measures ANOVA showed that concentration increased with difficulty during game play, $F(2, 48) = 50.32$, $p < .001$, $\eta p^2 = .68$, with higher concentration in the difficult condition than the moderate condition and higher concentration in the moderate condition than the easy condition ($p < .001$ for both comparisons). HbO2 concentration also differed significantly across the ROIs, $F(2, 48) = 4.99$, $p = .010$, $\eta p^2 = .17$, with higher HbO2 concentration in the left and right lateral regions than in the medial region ($p < .05$ for both comparisons). The difficulty x ROI interaction was also significant, $F(4, 96) = 4.77$, $p = .001$, $\eta p^2 = .17$, showing that the higher HbO2 concentration in the left lateral vs medial region was significant in the difficult condition ($p < .001$). These findings are shown in the top-left quadrant of Fig. 3.

For HHb, a two-way (3 levels of difficulty × 3 ROIs) repeated measures ANOVA showed the expected opposite pattern to HbO2 with decreased concentration when difficulty increased during the game play, $F(2, 48) = 25.62$, $p < .001$, $\eta p^2 = .39$. Specifically, lower HHb concentration was shown in the difficult condition than the moderate condition and in the moderate condition compared to the easy condition ($p < .05$ for both comparisons). HHb concentration also differed significantly across the ROIs, $F(2, 48) = 6.61$, $p = .003$, $\eta p^2 = .12$, with lower HHb concentration in the left and right lateral regions than in the medial region ($p < .05$ for both comparisons). The difficulty x ROI interaction was also significant, $F(4, 96) = 3.33$, $p = .013$, $\eta p^2 = .12$, showing that the lower HHb concentration in the left lateral vs medial region was more pronounced in the difficult condition ($p < .001$).

4.3 Prefrontal Activity During Cognitive Tasks

Attention switching task (AST). For HbO2, a two-way (2 levels of difficulty × 3 ROIs) repeated measures ANOVA showed increased concentration in the switching compared to the less difficult non-switching condition, $F(1, 32) = 21.35$, $p < .001$, $\eta p^2 = .40$. We also found a significant main effect of ROI, $F(2, 64) = 8.35$, $p = .006$, $\eta p^2 = .21$, with a lower HbO2 concentration in the medial region than in the left and right lateral regions ($p < .01$ for both comparisons). The interaction term was also significant, $F(2, 64) = 5.19$, $p = .008$, $\eta p^2 = .14$, showing that the lower HbO2 concentration in the medial region vs left and right lateral regions was significant in the non-switching condition ($p < .001$) in both comparisons) but was not significant in the switching condition (through a marginally significant trend, $p = .068$, is shown for the medial vs left lateral region). These findings are shown in the top-right quadrant of Fig. 3.

For HHb, a two-way (2 levels of difficulty × 3 ROIs) repeated measures ANOVA largely showed the expected opposite pattern to HbO2, specifically, a decreased concentration in the non-switching compared to the switching condition, $F(1, 32) = 23.58$, $p < .001$, $\eta p^2 = .42$. We also found a significant main effect of ROI, $F(2, 64) = 6.81$, $p = .002$, $\eta p^2 = .18$, with a higher HHb concentration in the medial region than in the left and right lateral regions ($p < .05$ for both comparisons). The interaction term was not significant (replicating the pattern of results we found with HbO2 for the switching but not the non-switching condition), $F(2, 64) = 2.04$, $p = .137$, $\eta p^2 = .06$.

One Touch Stockings (OTS) of Cambridge. For HbO2, a two-way (6 levels of difficulty × 3 ROIs) repeated measures ANOVA showed that concentration increased with difficulty during the OTS task, $F(5, 160) = 13.99$, $p < .001$, $\eta p^2 = .30$, with higher concentration with 6 moves than all other levels of difficulty ($p < .001$ for all comparisons), and with 5, 4, and 3 moves compared to 2 moves ($p < .05$ for all comparisons). The main effect of ROI, $F(2, 64) = 1.03$, $p = .361$, $\eta p^2 = .03$, and the difficulty x ROI interaction were not significant $F(10, 320) = 1.15$, $p = .320$, $\eta p^2 = .03$. These findings are shown in the bottom-left quadrant of Fig. 3.

For HHb, a two-way (6 levels of difficulty × 3 ROIs) repeated measures ANOVA showed the expected opposite pattern to HbO2, specifically that concentration decreased with difficulty, $F(5, 160) = 3.56$, $p = .004$, $\eta p^2 = .10$, with lower concentration associated with 6 moves in comparison to 5, 2, and 1 moves ($p < .05$ for all comparisons). The main effect of ROI, $F(2, 64) = 0.27$, $p = .758$, $\eta p^2 = .01$, and the difficulty x ROI interaction were not significant $F(10, 320) = 1.25$, $p = .255$, $\eta p^2 = .04$.

Spatial Working Memory (SWM). For HbO2, a two-way (3 levels of difficulty × 3 ROIs) repeated measures ANOVA showed that concentration increased with difficulty during the SWM task, $F(2, 68) = 3.25$, $p = .044$, $\eta p^2 = .09$, with higher concentration with 8 boxes than 6 and 4 boxes ($p < .05$ for both comparisons). HbO2 concentration also differed among the three prefrontal ROIs, $F(2, 68) = 5.84$, $p = .004$, $\eta p^2 = .15$, with lower concentration in the medial region than in the left and right lateral regions ($p < .05$ for both comparisons). The difficulty x ROI interaction term was also significant, $F(4, 136) = 4.90$, $p = .001$, $\eta p^2 = .13$. For the comparison of 4 boxes vs 6 boxes, no ROIs showed a significant change ($p > .05$ in all comparisons). However, for the comparison of 6 and 8 boxes all 3 ROIs showed a significant increase in HbO2 concentration ($p < .05$ in all comparisons). Additionally, the difference between the medial and the left and right lateral regions were more pronounced in the 8 boxes condition. These findings are shown in the bottom-right quadrant of Fig. 3.

For HHb, a two-way (3 levels of difficulty × 3 ROIs) repeated measures ANOVA showed the expected opposite pattern to HbO2, specifically that concentration decreased with difficulty, $F(2,$

68) = 3.67, p = .030, ηp^2 = .09, with lower concentration with 8 boxes than 6 boxes (p < .05), the comparison between 8 and 4 boxes did not reach significance. HHb concentration differed among the three prefrontal ROIs, F(2, 68) = 5.94, p =.004, ηp^2 = .15, with lower concentration in the left and right lateral region that in the medial one (p < .05 for both comparisons). The difficulty x ROI interaction term was also significant, F(4, 136) = 5.12, p = .001, ηp^2 = .13, showing that HHb concentration declined in the left and right lateral regions between 6 vs 8 boxes (p < .001 in both comparisons), but did not differ in the medial region (p > .05). Additionally, the HHb concentration did not differ between 6 and 4 boxes in any of the regions (p > .05 in all comparisons).

4.4 Comparisons Between Prefrontal Activity During Cognitive Tasks and Gameplay

A one-way ANOVA was performed to compare HbO2 concentration in the most difficult level of each condition (cognitive tasks and game). It showed a significant main effect of condition, F(3, 57) = 9.52, p < .001, ηp^2 = .33, with lower HbO2 concentration during SWM 8 boxes than all other conditions (p < .001 for all comparisons). HbO2 concentration during gameplay was not different than during AST and OTS tasks (p > .05 for both comparisons). We also found a significant main effect of ROI, F(2, 38) = 8.04, p < .001, ηp^2 = .21, with a lower HbO2 concentration in the medial region than in the left lateral one (p < .001), as well as a significant condition x ROI interaction, F(6, 114) = 3.07, p < .01, ηp^2 = .14. As expected, this interaction confirmed the patterns shown in the analyses of the individual tasks and gameplay (see section 4.2 and 4.3). In particular, it showed that HbO2 concentration was significantly higher in the left lateral region than the medial region during difficult game play. The same pattern (higher concentration in the left region than the medial) was found for SWM with 8 boxes (p < .001 in both comparisons). HbO2 concentration was also significantly higher in the right lateral than the medial region during SWM with 8 boxes (p < .05). These findings are depicted in Fig. 4.

Another one-way ANOVA was performed to compare HHb concentration in the most difficult version of all conditions. It showed the expected opposite pattern of results to HbO2 with one small exception (identified below). Specifically, a significant main effect of condition was found, F(3, 57) = 6.85, p < .001, ηp^2 = .26, with higher HHb concentration during SWM 8 boxes than all other conditions (p < .001 for all comparisons). We also found a significant main effect of ROI, F(2, 38) = 7.19, p < .01, ηp^2 = .27, with a higher HHb concentration in the medial region than in the left and right lateral ones (p < .05 in both comparisons). We also found significant task x ROI interaction, F(6, 114) = 3.99, p = .007, ηp^2 = .14. In particular, it showed that HHb concentration was more pronounced in the middle than the left and right lateral regions during game play (differing from the HbO2 analysis which only found a difference between the medial and left lateral regions). Finally, SWM showed the expected pattern with greater concentration in the medial than the left and right regions for 8 boxes (p < .01 in all comparisons).

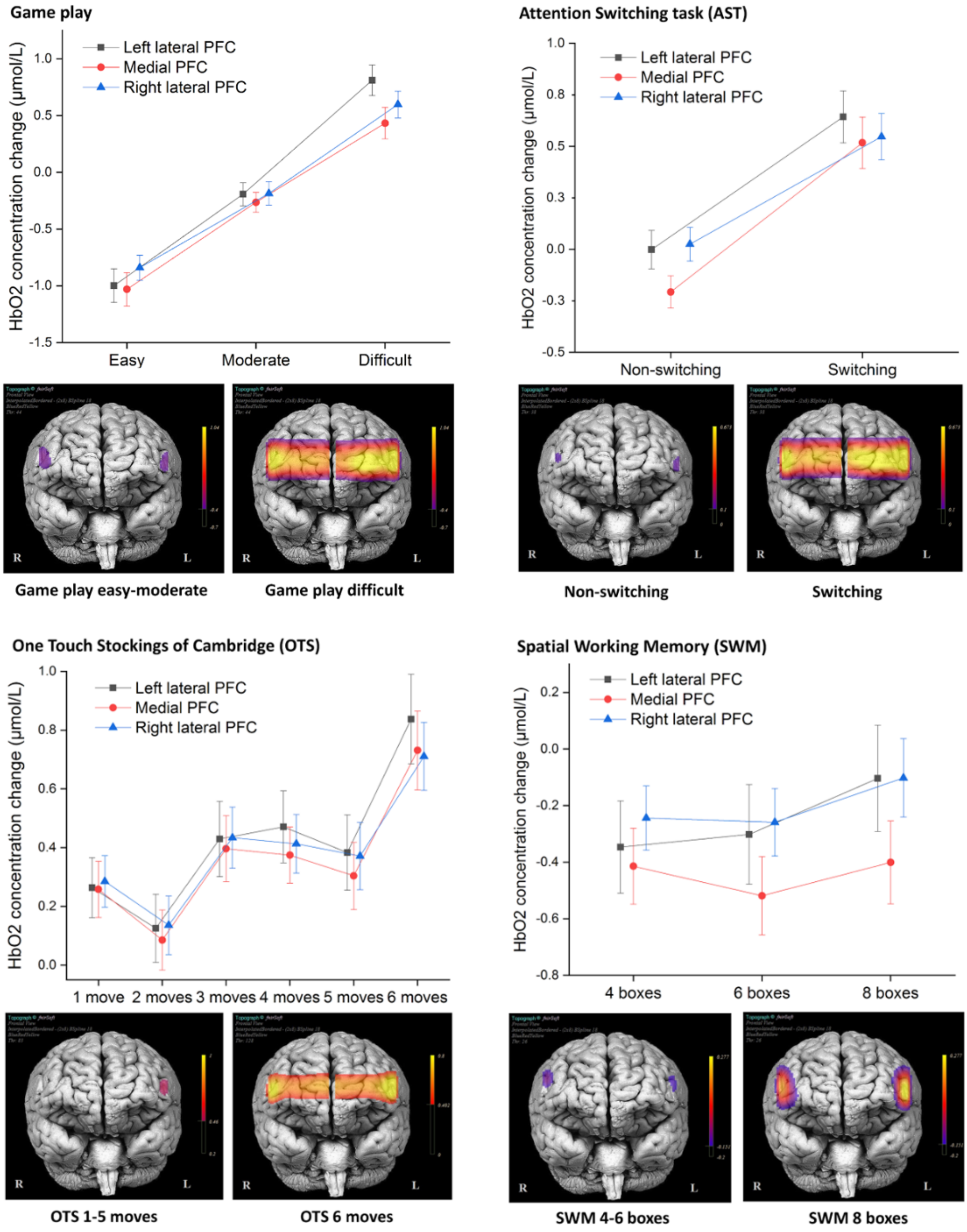

Fig. 3. Cognitive Activity in the Prefrontal Cortex at varying levels of difficulty for Videogame Play, Attention Switching Task, One Touch Stockings of Cambridge, and Spatial Working Memory.

Finally, we examined whether HbO2 concentration changes during the most difficult videogame condition correlated with each of the most difficult conditions of the cognitive tests. In other words, these correlations help investigate whether the cognitive resources engaged by each participant tends to be consistent between the game play and the cognitive tests. Given our findings for HbO2

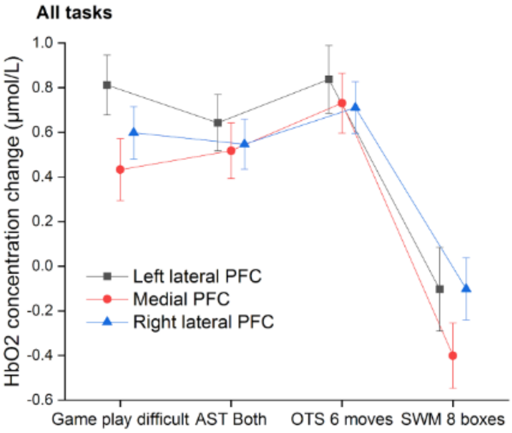

Fig. 4. Comparison of Cognitive Activity in the regions of the Prefrontal Cortex for the Most Difficult Videogame Play and Cognitive Tasks.

and HHb are largely consistent, here we report only the correlations for hBO2. We performed 9 correlations analysis (Game play (3 ROIs) vs the three cognitive tests (3 ROIs)). HbO2 concentration change during game play systematically correlated with each cognitive test within specific lateral prefrontal regions. HbO2 concentration change in the left lateral region during the difficult game play correlated with HbO2 concentration changes during SWM (8 boxes) and OTS (6 moves) in the same prefrontal region, r(24) = .47, $p < .05$ and r(22) = .47, $p < .05$, respectively. Also,, HbO2 concentration changes in the right lateral region during the difficult game play correlated with HbO2 concentration change during AST (switching condition) in the same region, r(24) = .48, $p <$ .05. These three associations are depicted in Fig. 5.

5 DISCUSSION

Within this section, we discuss the findings in connection to our three study objectives established in Section 2.4. As increased HbO2 and decreased HHb are indicative of increased brain activity, we discuss the results in this context, focusing on the trends across both measures (HbO2 and HHb). Two small differences emerged between HbO2 and HHb which we discuss below in Section 6.

Objective 1: Test whether fNIRS can reliably measure differences in prefrontal cortex activity associated with a videogame manipulation (e.g. increase in difficulty)

In relation to our first objective, there was clear evidence of an increase in PFC activity in line with increases in videogame difficulty. This suggests that more difficult levels of a videogame require greater cognitive demands and associated mental workload. Our results extend the findings of [25], who found only a small effect size for differences in difficulty and that the ability to detect differences in difficulty varied across participants. The difference in findings may reflect their use of a much simpler game (*Pac-Man*): it may be that only games with a certain minimum level of complexity show the expected changes in PFC activity. Our findings align with those of Tachibana [68], who showed an increase in cognitive activity associated with greater game difficulty, though their results focused on the parietal and temporal lobes. More broadly, these findings confirm the utility of fNIRS for use in videogame research that seeks to assess difficulty and challenge. In particular, like most psychophysiological measures, fNIRS offers the advantage of providing a continuous assessment that does not require interrupting gameplay nor relying on player recall.

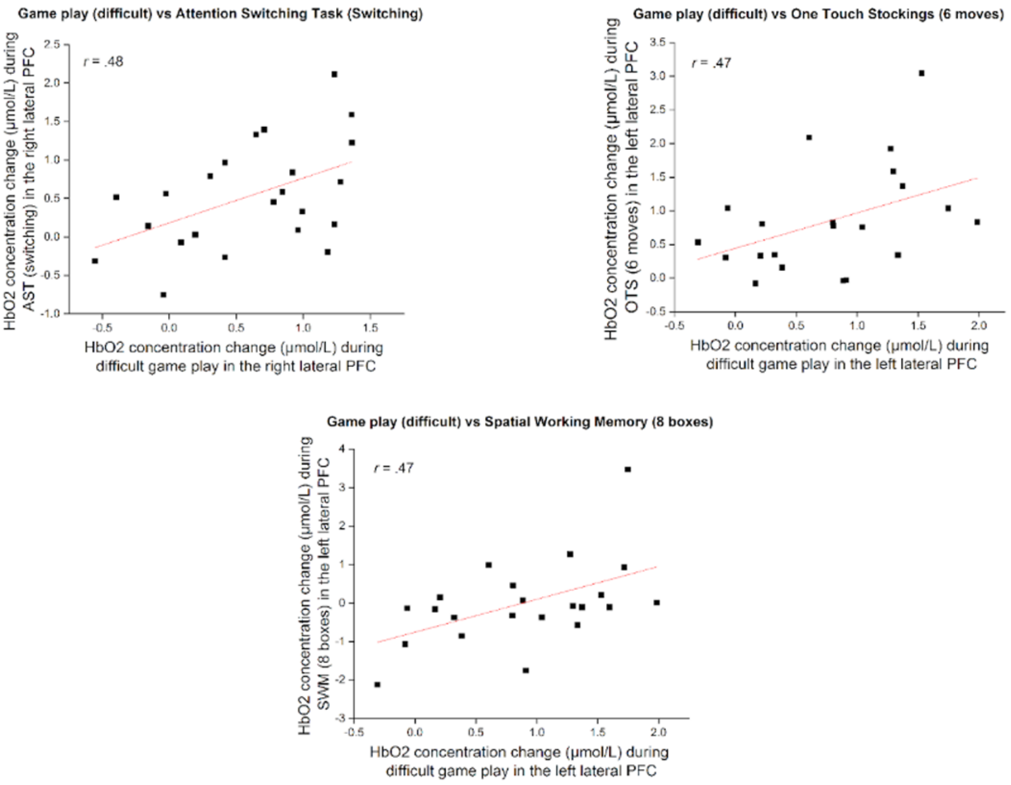

Fig. 5. Association between HbO2 concentration during difficult game play and during the most difficult condition of each cognitive test (*r* indicates correlation). Upper Left: HbO2 concentration in the right lateral PFC during difficult game play vs AST between. Upper Right: HbO2 concentration in the left lateral PFC during difficult game play vs OTS. Lower: HbO2 concentration in the left lateral PFC during difficult game play vs SWM.

Thus, fNIRS has clear applications in both academic research and videogame playtesting (where game designers seek to assess how challenging their game is at different points).

Objective 2: Examine how prefrontal cortex activation patterns compares between gameplay and the carrying out of established executive functions tasks

Before moving to comparisons between cognitive tasks and gameplay, it is worth noting a number of results that confirm the expected patterns associated with the difficulty of the cognitive tasks. Firstly, as would be expected, there were more errors made on the more difficult versions of the cognitive tests. Secondly, the fNIRS data reveal that the more difficult versions of each task were more cognitively demanding, requiring greater mental effort. With respect to the One Touch Stockings of Cambridge, the 6-move version of the task resulted in differing levels of activity than 1, 2, 3, 4 and 5-move versions. Similarly, for the Spatial Working Memory task, the 8-box version of the task showed greater activity than the 4- and 6- box version. These differences primarily emerged on the lateral regions, likely reflecting the tasks' reliance on memory (both encoding and retrieval). Finally, in the Attention Switching Task, greater cognitive activity was shown in response to the more difficult switching (rather than the non-switching) version of the task. Here again the findings were most consistent for the lateral regions of the PFC, likely reflecting memory encoding and retrieval.

Moving on to a comparison of videogame play with the most difficult version of the SWM, OTS, and AST tasks, our results show that the SWM emerged as requiring less cognitive activity than all other tasks and the game. This is likely a result of the comparative ease of the SWM to all other tasks; as demonstrated by task run times, the SWM was faster to complete than all other tasks (with a typical completion time of 4 - 7 minutes), potentially reflecting greater ease in participants' time to discover a solution. No general difference in cognitive activity was found between the difficult videogame play, the difficult version of the AST, and the difficult version of the OTS, suggesting these tasks and the difficult level of the game made similar cognitive demands and required similar mental effort.

Turning to the specific regions of interest explored in the study, it is interesting to note that one consistency emerged across two of the cognitive tasks (AST and SWM) and the game (when played at the highest difficulty). Specifically, cognitive activity was higher in the left lateral region than the medial region. This pattern broadly suggests the use of working memory–more specifically, the encoding (left lateral region) of memories [70])—as well as problem solving [27, 28]. It makes intuitive sense that these processes would be utilised during the Attention Switching and Spatial Working Memory Task as they are designed to draw on these capacities.

Turning to gameplay, it seems likely that the most difficult gameplay condition required participants to think more carefully about how to respond to in-game events, and how to resolve more complicated and challenging problems. Given the nature of the game, participants were more likely to think about the layout of the map, where different turrets are placed, which vehicles have received damage, and so on. The novelty of the game may also have informed this process. As no participants had prior experience with *Anomaly: Warzone Earth*, participants may have been observing and committing to memory new interactions as they occurred (e.g., 'this enemy unit has a short range, but is very powerful'). While our findings are consistent with the interpretations described above, relating to encoding of memories and problem solving, future research could usefully seek to further isolate and determine the specific processes at play. For example, research could seek to compare games that require a greater or lesser degree of memory encoding to more clearly assess whether left lateral PFC activity during videogame play is associated with this activity. More broadly, our findings here highlight the potential for fNIRS as a means to understand what regions of the brain are most active during videogame play, giving an indication of the potential cognitive processes occurring.

Our findings related to regional activity in the PFC emphasise the potential advantages of fNIRS over EEG for videogame developers and researchers. In comparison to electrophysiological approaches, fNIRS allows for the measurement of haemodynamic variations to within 1 - 2 cm of the target area [73]—as such, the relative precision of fNIRS offers a degree of certainty that is not always possible when interpreting EEG data. Similarly, that fNIRS provided valid and interpretable data during play of a tablet-based game is important given the relative cost and logistic advantages of fNIRS in comparison to fMRI.

Objective 3. Examine whether prefrontal cortex activation patterns observed during executive function tasks are associated with activation patterns observed during videogame play.

Comparing the brain activation patterns during performance of the cognitive tasks with those during gameplay revealed moderate associations in specific regions of interest. On the left lateral PFC, associations were found between the OTS task and the game, as well as the SWM task and the game. These associations suggest that the cognitive tasks and games are drawing on the need to encode memories and solve problems at approximately similar levels of effort. Similarly, the more difficult versions of theses tasks may require more intensive planning and problem solving. On the right lateral PFC, associations were found between the switching version of the AST task and the difficult version of the game. This association suggests that the AST requires a similar level of memory retrieval and sustained attention as playing the game on its most difficult level. These findings further confirm that cognitive effort during gameplay is comparable to cognitive effort needed to complete the OTS and AST tasks, and that similar processes may be occurring.

6 LIMITATIONS AND FUTURE WORK

While analysis of fNIRS data involves the inverse correlation of HbO2 and HHb signals, this does not always result in consistent patterns of results for each signal. In other words, it is common for HHb to show results not present for HbO2 and vice versa [57]. Best practice remains to present and interpret both signals [57]. With that in mind, before moving to the specific limitations of our method, it is important to acknowledge that two differences emerged in our pattern of findings (between HbO2 and HHb) that could be considered in future work.

Firstly, for the AST, in the switching condition, HHb indicated greater cognitive activity in the left and right lateral regions than in the medial region. In contrast, HbO2 showed only a marginally significant difference between the left lateral and medial region for the switching condition. This discrepancy is not of particular relevance to the current paper, but future research could seek to confirm whether the AST does or does not usually lead to greater cognitive activity in the right lateral region than the medial region. A second difference emerged in our findings related to gameplay. Specifically, in the comparison of the most difficult tasks and gameplay (see Section 4.4), HHb showed differing levels of concentration in the right and medial regions during gameplay, while HbO2 did not show this difference. Given this difference (between the right and medial regions) was also absent when comparing all levels of gameplay difficulty (see 4.2), it would have been premature to conclude there is a difference in cognitive activity between right and medial regions during the most difficult gameplay condition (and our discussion of results does not extend to this pattern). While an inverse relationship between HbO2 and HHb is a strong indicator of cortical activity, this relationship does not always emerge in fNIRS research as a matter of course; however, it remains best practice to analyse and report both [57]. As with the findings for the AST, future research could usefully explore whether or not gameplay is associated with greater cognitive activity in the right lateral than the medial region.

Moving to our methodology, the primary limitation of the current study relates to the use of a single videogame on a particular medium. It is not possible to know how applicable our findings are to other genres of videogames, nor to mediums other than a tablet. Further, *Anomaly: Warzone Earth* is a largely cerebral game—in that there was not a significant mechanical component required from user action (that is, the game did not prioritise reflexes or mechanical ability). To this end, future research may wish to examine contemporary games that make this additional demand of players.

A further limitation of the study is that the level of difficulty in the SWM task was relatively low, rendering it incomparable in difficulty to the other cognitive tasks and to the videogame. Our method would have been further strengthened by use of SWM trials involving more than 8 boxes.

As noted in Section 3.1, while not an original intention of our participant exclusion criteria, the unexpected limitations of the fNIRS hardware precluded the recruitment of female participants. This functional inability to recruit female participants represents an additional limitation of the work. As some previous research has found gendered differences in haemodynamic response to stimuli (e.g., in how stress attenuates cognitive flexibility [36]), there may be differences in cognitive activation patterns during gameplay amongst female and non-binary participants. Future research should seek to redress this imbalance and confirm whether similar patterns emerge with female and non-binary participants. Further, we note that this is not a universal limitation of fNIRS, with many articles reporting data gathered from both male and female participants. To that end, it may be possible to modify the fNIRS equipment we used in our study to accommodate data collection from people with smaller head circumference.

In addition, we did not check participant familiarity with the cognitive tasks; while we suspect that familiarity was low to non-existent, as our participants were largely undergraduates sourced from computer science disciplines and at no point expressed familiarity with the tasks, we are not able to conclusively make that assumption. Future work should endeavour to check participant familiarity with any cognitive tasks used in experimental conditions, as pre-existing knowledge of these tasks may influence experienced difficulty.

We also did not investigate group differences among participants, as our sample were fairly cohesive in age and experience, and we were interested in the general influence of gameplay on cognition. Our sample self-rated as particularly experienced with videogames, and thus our results are best interpreted within the context of this population. Existing research evidences that differences in cognitive activity in the PFC do emerge between non-videogame players and videogame players [75]. Future work should continue to consider variations in expertise and experience—for example, differences in levels of mental effort expended (or neural efficiency) between amateur and expert players of a videogame.

An initial research inquiry in this direction has already determined that it is possible to distinguish gaming expertise from PFC activity that occurs while simply observing gameplay, as measured by fNIRS [4]. This holds notable promise for research in the esports space, in which understanding expertise and high-level play is of particular relevance.

Another promising path of inquiry may be the explorations of facets of gameplay other than challenge—for example, how prominent gameplay concepts such as flow may manifest cognitively. As the prefrontal cortex is also responsible for semantic processing (that is, speech and language), investigating the influence of social play on the PFC may also be a fruitful avenue of research.

We also contend that one future direction of this research may be the implementation of fNIRS data as an input mechanism: that is, employing brain activity generated in the PFC to directly control or influence components of the game. One clear application may be that of Dynamic Difficulty Adjustment (DDA), wherein game difficulty adapts dynamically to player performance or state in both single- and multiplayer games [7, 31]. Previous research has investigated using 'excitement', as measured by EEG, to moderate difficulty in a third-person shooter game [66]; future research efforts may consider using real-time fluctuations in HbO2 or HHb as an input mechanism for DDA.

Finally, we restricted analysis in this work to the PFC. While this is a dominant region of interest for work employing fNIRS, there are many other regions that may have relevance to gameplay—for example, the occipital lobe, which is largely responsible for visual processing [59].

7 CONCLUSION

Given the centrality of difficulty and the experience of challenge, our results provide important initial empirical evidence of the utility of fNIRS for measuring cognitive activity in videogame research. Given the limitations of subjective measures of challenge (e.g., relying on recall), fNIRS offers a relatively unobtrusive, continuous method of assessment. Additionally, our results provide further support for the level of mental effort being expended when playing modern videogames—the notion that videogames are a "mindless" leisure activity is not supported in our study. Coupled with this finding, and our success in distinguishing between levels of difficulty in both gameplay and cognitive tasks, we conclude that fNIRS is an effective and useful instrument for assessing the complex cognitive challenges of videogame play.

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