To Play or Not to Play: An Investigation Into The Effect of Video Game Use on Executive Functions

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Abstract

Findings in experimental psychology research suggest that individuals who engage in video game play outperform those who do not play video games on a range of cognitions, in particular visual selective attention. It was predicted that the source of the differences observed in video game players (VGP) compared to non-video game players (NVGP) is the result of additional executive function resources. Findings suggest that only when the task is sufficiently demanding are the additional attentional and executive function resources in VGP observable compared to NVGP. Across three experimental paradigms, the executive functions of VGP were compared to those of NVGP. In Experiments One and Two, a hybrid response inhibition task was used to assess the response inhibition performance in the subcomponents of action cancellation, action withholding, and interference resolution in VGP compared to NVGP. In Experiment Two, measures of γ-aminobutyric acid (GABA), glutamate, and glutamine were recorded using magnetic resonance spectroscopy. In Experiment One, VGP significantly outperformed NVGP in measures of action cancellation and interference resolution, but the HRIT failed to measure action withholding. In Experiment Two, the results of Experiment One were not replicated, and there was no significant difference between VGP and NVGP in the subcomponents of response inhibition. A combined analysis of participants in Experiments One and Two replicated the effects observed in Experiment One, VGP outperformed NVGP on measures of interference resolution and action withholding. In Experiment Three, the ability to sustain attention was assessed using a continuous performance task with manipulations of cognitive load. The aim was to elucidate the inconsistent results observed in Experiments One and Two by manipulating cognitive load to allow observation of the increased executive function resources in VGP. The results of Experiment Three showed no significant difference between VGP and NVGP in metrics of sustained attention performance. Moreover, there was no difference between groups in their ability to sustain attention regardless of cognitive load. This thesis emphasises the potential for video game use to train and improve executive function capabilities, but that findings and directions for future research are constrained by methodological and theoretical limitations.

Declarations

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed....[redacted]............................

Date........31/07/2023..

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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The University's ethical procedures have been followed and, where appropriate, that ethical approval has been granted.

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Abbreviations and Initializations

ACC – Anterior Cingulate Cortex

ANT- Attention Network Task

AT – Adjusted Total

CC – Cognitive Control

CI – Confidence Interval

CVGEQ – Covert Video Game Experience Questionnaire

DLPFC – Dorsolateral Prefrontal Cortex

EF – Executive Function

F – Frustration

fMRI – functional Magnetic Resonance Imaging

fMRS – functional Magnetic Resonance Spectroscopy

FPS – First Person Shooter

GABA – γ-aminobutyric acid

Glx – Glutamate/ Glutamine

HRIT – Hybrid Response Inhibition Task

IQR – Interquartile Range

M – Mean

MD – Mental Demand

MMORPG – Massive Multiplayer Online Role Playing Game

MOBA – Massive Online Battle Arena

MRI – Magnetic Resonance Imaging

MRS – Magnetic Resonance Spectroscopy

MRT – Mean RT

NASA TLX – National Aeronautics and Space Administration Task Load Index

nparLD – non-parametric analysis of longitudinal data

NURG – Negative Urgency

NVGP – Non-video game players

P - Performance

PD – Physical Demand

PFC – Prefrontal Cortex

PREM – Lack of Premeditation

PRUG – Positive Urgency

PURS – Lack of Perseverance

RT – Response/Reaction Time

RTE – Relative Treatment Effect

SD – Standard Deviation

SMA – Supplementary Motor Area

SS – Sensation Seeking

SSD – Stop Signal Delay

SSRT – Stop Signal Reaction Time

SST - Stop Signal Timing

SUPPS-P – Short UPPS-P

tDCS – transcranial Direct Current Stimulation

TMS – Transcranial Magnetic Stimulation

TP – Temporal Demand

TUT – Task-unrelated-thought

UPPS-P - (negative) Urgency, (lack of) Perseverance, (lack of) Premeditation, Sensations Seeking, Positive urgency

VG – Video Game

VGEQ – Video Game Experience Questionnaire

VGP – Video Game Players

Chapter 1 General Introduction

Video game play has increasingly become a recreational pass time for a large proportion of the population. In 2021, Ofcom reported that over 60% of the UK population plays some form of video game (Ofcom, 2021). The Office of National Statistics identified a significant increase in the amount of time people spent playing video games during the COVID-19 pandemic compared to 2015 (Payne & Gueorguie, 2020), with video game play being the 12th most registered pastime at a daily average of 26.2 minutes. This is a considerable proportion of the UK population devoting a considerable proportion of their free time to one particular habit.

This increase in hours spent playing video games has been mirrored by an increase in the words typed about individuals playing video games. The effects of playing video games on behaviour and cognition have been a particular focus of news media articles, particularly biased toward reporting the findings of research articles that find negative consequences of video games regardless of effect size or journal article impact and underreporting the positive outcomes of video game play (Copenhaver et al., 2017). There is additionally a focus in previous research on the negative consequences of video game play (Ferguson, 2007a; Segev et al., 2016) such as aggression (Anderson & Bushman, 2001; Bushman & Huesmann, 2014; Coyne et al., 2015; Coyne et al., 2012; Coyne & Stockdale, 2021; Ridge et al., 2023; Willoughby et al., 2012), antisocial behaviour (Anderson, 2004; Anderson et al., 2015; Bodi et al., 2021; Demeter et al., 2021; Fontaine, 2008; Huesmann & Taylor, 2006; Hull et al., 2014; Kim & Sundar, 2013; Kimmig et al., 2018; Krahe et al., 2011; Krcmar & Farrar, 2009; Weber et al., 2006; Ybarra et al., 2014; Zwets et al., 2015), sexual violence (Al-Ali et al., 2018; Boduszek et al., 2019; Gilbert & Daffern, 2017; Guggisberg, 2020; Yao et al., 2010) and suicidal ideation (Huesmann & Taylor, 2006; Liu et al., 2016; Poorolajal et al., 2019; Teismann et al., 2014) to name but a few areas.

The focus in the literature on the negative effects of video game use has led, in part, to the governments of various countries to implement policies directed toward problematic video game use with little evaluation of said policies (Kiraly et al., 2018). Problematic video game play that is, video game play which is thought to result in harmful or adverse behavioural effects (Bender & Gentile, 2020; Bender et al., 2020; Bernaldo-de-Quirós et al., 2021; Collins & Freeman, 2014; Craig et al., 2021; Cudo et al., 2018; Cudo et al., 2020; Demetrovics et al., 2012; Mathews et al., 2019; Mettler et al., 2018; Panagiotidi, 2017; Seong et al., 2019) is the subject of debate (Aarseth et al., 2017) following a proposal that the American Psychiatric Association (APA) identified internet gaming disorder (IGD) to be listed in the DSM 5 as a potential diagnosis requiring more research (Király et al., 2015; Kuss et al., 2017; Luo et al., 2021). The APA's classification has renewed the focus on measuring and defining adverse video game use and negative outcomes.

However, with this reinvigoration of research into the potentially negative consequences of video game play, there has been a concurrent resurgence into the potential benefits of video game play (Ferguson, 2007b; Prot et al., 2014). For effect policy administration, it is vital to fully understand the effects of video game play and overcome the bias in reporting studies observing negative effects of video game use (Ferguson, 2007a). It is vital and warranted that there be a renewed focus on the positive effect of video game use on behaviour and cognition to ensure informed debates in both the public and private sectors.

A Brief History of The Research on Positive Outcomes of Video Game Use

The notion of video game use affecting our behaviour and cognition is not a new one. Video games find their roots in laboratories, “Spacewar!” is widely considered the first video game and was developed at the Massachusetts Institute of Technology in the 1960s and 1970s (Lowood, 2012). “Pong”(Atari, 1972), one of the first commercial arcade consoles, entered the consumer market shortly after Spacewar! in 1972 (Lowood, 2009). For almost as long as there have been video games, scientists have been theorising and testing the potential impact on hand-eye coordination (Griffith et al., 1983) and spatial cognition (Dorval & Pepin, 1986; Okagaki & Frensch, 1996).

As motivation for their study, Griffith et al. (1983) note an intense public debate; opponents of video games opposed their unrestricted use while proponents proposed potential benefits of use, but the debate lacked any empirical evidence. To assess claims that video games improve hand-eye coordination, Griffith et al. (1983) compared the performance of video game players (VGP) to non-video game players (NVGP, matched for handedness and sex). VGPs were reported to have 2 to 99 months of video game playing experience and played an average of 2 to 59 hours per week (either at home or the arcade). The NVGPs were reported as each having less than 10 hours of video game play experience over the previous 6-month period. Hand-eye coordination performance was measured on the photoelectric rotary pursuit unit. Performance was recorded as time on target, whereby participants must track a moving light below a stationary glass plate using a stylus. The longer time on target demonstrates enhanced hand-eye coordination. The moving light followed a circular, square, or triangular pattern with speed measured between 10 to 50 rpm, randomly varying by 5 rpm intervals.

Except at low speeds (10 and 15 rpm) on the circular track, which one might argue were the *lowest* demands evoked by this task, time on target was significantly longer for VGP compared to NVGP on all geometric patterns at the remaining speeds. This was reported to reflect superior hand-eye coordination, and indeed, video game use improving fine motor skills is a finding that is still observed and used to augment surgical training among medical students (Chalhoub et al., 2016; Chalhoub et al., 2018; Datta et al., 2020; Gupta et al., 2021). Griffith et al. (1983) also reported correlations between measures of video game play experience (months experience, average hours per week) and hand-eye coordination performance, but significance values (p-values) were reported. Nonetheless, it is evident that interest was given to the nature of the benefit of video game play, how one might codify a video game player, and what effect experience may have on moderating this relationship.

In an effort to introduce causality into these observations, Dorval and Pepin (1986) employed a training paradigm with a sample of 70 undergraduates (age $M = 22$) in test and control groups. The test group played a three-dimensional video game, Zaxxon. Training consisted of eight sessions; each session consisted of five games of unlimited duration across a six-week period (no more than two sessions a week). Zaxxon required participants to control a spaceship, shoot down enemy ships, and avoid obstacles. The procedure of the control group is not described, but one might assume a passive/ no-contact control. Spatial cognition, specifically spatial visualisation, was measured by scores on the pen-and-paper Space Relations Test of the Differential Aptitude Test (Bennett et al., 1947). There was no difference between the groups at baseline, but there was an observed effect of group in post-training with the video game training group scoring higher on the Space Relations Test than the control.

However, in a second experiment reported in Pepin and Dorval (1986) the authors attempted to replicate the effect in a sample of 101 adolescent participants (age M = 13) but were unable to replicate the post-training group effects observed in experiment one. Yet, there were demonstrable deviations in the methodology employed between these two studies with little rationalisation. The maximum duration of the video game play training session was reduced from five unlimited games to a discrete 25-minute period. Moreover, the training must be completed within three weeks instead of six.

The effect of age was suggested as a potential moderating variable in the difference observed between the two experiments of Pepin and Dorval (1986) and Dorval and Pepin (1986). A (more recent) review by Wass et al. (2012) suggests that the transfer of training (on working memory and “mixed attention” tasks) to cognitive task performance is more reliable the younger the training cohort. Wang et al. (2016) conducted a meta-analysis of action video game training in healthy adults. They observed that the effect size of training on overall cognition was higher in younger participants than in older ones. While both age groups benefitted from training, in each domain observed, processing speed/ attention, visuospatial ability, and executive function, the effects were more pronounced in younger cohorts. It should be noted that the age ranges of participants in the review (Wass et al., 2012) and meta-analysis (Wang et al., 2016) are far greater than the difference between groups in the experiments reported by Dorval and Pepin (1986) and Pepin and Dorval (1986). Wass et al. (2012) included studies where the ages of samples ranged from 11 months, 4-6 years, 5-12 years, 20-35 years, to 60-80 years of age. Wang et al. (2016) similarly compared groups from experiments consisting of participants ages 18-25 in younger groups and 65+ on average in older groups.

Given this, one might expect a larger effect in the second experiment reported by Pepin and Dorval (1986). It could be suggested that this inconsistency is likely influenced by the adaptations to the training methodology instead of the sample recruited. Alternatively, a pen-and-paper test does not accurately capture what might be limited transfer effects of video game training. Transfer effects refer to the generalisability of training effects from one domain to another (Jaeggi et al., 2014; Rabipour & Raz, 2012). This is training-related improvements restricted to improvements on task-specific skills (near) or effects of training that are task-general, impacting some broader abilities (far) and general cognitive abilities (Carroll, 1993; Noack et al., 2014). In video game training research, no transfer would be observed when training on video games results in improvements that are only observed in subsequent performance on the same game on which the training was conducted. The near transfer effect would be observed when training on video games results in improved performance on tasks that assess the same cognitions used to play the game, for instance, a computerised visuospatial attention task. Far transfer effects would be the effect of training to expand further improved performance on tasks that measure cognitive skills either loosely related to the game, such as working memory, or general cognitive abilities, such as executive functions.

Okagaki and Frensch (1996) attempted to replicate the effect of video game training on spatial cognition in undergraduates, with manipulation of the measure used to assess the effects of training on spatial cognition. The study was formed of two experiments utilising the Tetris video game for the training stimuli. The authors report that Tetris requires mental rotation to represent shapes in different orientations and spatial visualisation to visualize what would happen if those orientations were dropped into the grid below. Each experiment consisted of a control and a training group; no participant had any previous Tetris experience. Both groups completed baseline measures of performance and were retested two weeks later. The training procedure during the 14 days consisted of a 30-minute Tetris session every day except weekends. The control procedure was passive, in which participants were instructed to refrain from playing video games.

In the experiment, one pen-and-paper test of mental rotation, spatial visualization, and perceptual speed were administered, with the dependent variable being the number of correct responses. These cognitions were assessed as they would allow for further investigation of the ability of video game training to transfer from the source (trained) cognition to the target (tested) cognition. As mental rotation and spatial visualisation are thought to be tapped by the training game, an improvement in tasks measuring these cognitions would suggest near transfer. Meanwhile, improvement in processing speed, which Okagaki and Frensch (1996) posited was not tapped by Tetris, would demonstrate further transfer. Overall, there were no significant differences between pre and post-training on the three measures of spatial cognition. However, once gender was included as a group factor, the male experimental condition improved in mental rotation and spatial visualisation. At the same time, no significant effects were observed in the female experimental group or the control conditions.

In the second experiment reported by Okagaki and Frensch (1996), “computerised tests” were constructed to measure mental rotation and spatial visualisation. A rationale for this was to produce a more granular assessment of performance using response time instead of number correct. The second rationale was to assess performance in a medium that closely resembled the training medium and, as such, a closer transfer between source and target cognitions. Another modulation to the first experiment was the inclusion criteria being adapted to no previous experience with any video games during the past year. All other facets of the methodology were replicated. The authors observed that mental rotation and spatial visualisation performance improved in the experimental condition but not the control (with no effect of gender); on both tasks, the experimental group demonstrated faster performance compared to the baseline. Error rates were not reported as “there were no systematic differences”.

The second experiment reported by Okagaki and Frensch (1996) lacked the measure of perceptual processing speed included in the first experiment. This omission limits the conclusions that can be drawn regarding the extent of transfer when the medium used to train and measure skills is consistent. Despite this, the effects of training were limited to near transfer. However, as the measures of performance differed (number of correct compared to reaction time), it is difficult to confidently identify the source of variation.

When interpreting the results of Okagaki and Frensch (1996) to the findings from Dorval and Pepin (1986), Pepin and Dorval (1986) and Griffith et al. (1983), it becomes apparent that early research into the positive effects of video game play can be primarily categorized based on several key factors. These include being limited to near-transfer effects, utilizing inconsistent definitions of video game play or what constitutes a video game player, and employing inconsistent training methodologies.

Early indications of the ability of video game use to evoke a *further* transfer (than previously observed) of attention and executive function capabilities arose from the late 1900s to the early 2000s. Greenfield et al. (1994) investigated the potential for video games to affect performance on a divided spatial attention task in two experiments. Divided attention was measured using a task developed on the principles of cost and benefit effects to response times when the target appeared in expected and unexpected locations, respectively. This effect was originally observed by Posner et al. (1980) during investigations into attention and signals presented in the visual field. The task employed by Greenfield et al. (1994) was presented on a computer where targets could appear on either the left or right side of space. There were two conditions. In one condition, the target appeared in one location in 80% of the trials, in the other in 10%, and in both locations in the remaining 10%. In the other condition, targets appeared equally often in both locations (45% each), with a target appearing in both locations in the remaining 10%.

In experiment one, an extreme group design was employed to compare “experienced” and “novice” video game players. Participants were required to play a video game titled “Robot Battle” to determine the video game experience. In total, 34 male undergraduate participants played the game; those scoring above 200,000 were categorised as experienced (n = 8), while those scoring less than 20,000 were categorised as novice (*n* = 8). The remaining sixteen participants were not invited to continue the experiment as they met neither cutoff criterion. After classification, participants were instructed to complete the divided attention task described above. Greenfield et al. (1994) observed that video game novices experience cost effects when responding to targets in low-probability locations; response times were longer than in neutral-probability locations. Likewise, typical divided attention expected location benefit effects were observed where novices had shorter response times in 80% high probability locations when compared to the 45% neutral location. However, for experienced video game players, while the benefit effects were observed (quicker responding to 80% location targets than 45% location targets), the response times were not significantly different between low probability (10%) and neutral locations (45%) suggesting that experienced VGP were spared from cost effects. Moreover, experienced players were faster than novices in high and low-probability locations, with no significant difference between the groups in equal probability locations.

Greenfield et al. (1994) sought to expand on these findings by answering an important question: Do VGP have a greater attentional field that facilitates performance on video games and, therefore, does VGP play more video games, or does the playing of video games develop the attentional field of experienced VGP? In essence, is there causality between enhanced cognitive abilities due to implicit training from video game use, or do video games attract individuals who inherently possess superior cognitive skills?

To answer the questions of causality, Greenfield et al. (1994) conducted a second experiment where the divided attention task was used as a pre-and post-test measure, much like that of Dorval and Pepin (1986). Forty male undergraduates were split randomly into two equal groups: an experimental group that received 5 hours of video game practice and a no-contact control group. Participants within those groups were classified as more or less experienced video game players based on performance in an initial video game skill assessment session, with those above the median classified as more experienced and those below the median as less experienced.

After the pretest divided attention task baseline, an experimental group underwent a 5-hour video game play session, while a no-contact control group did not; both groups then completed post-test measures of divided attention performance. The findings of a reduced cost effect in more experienced video game players were not replicated in this paradigm. However, the experimental condition lowered this relative cost, whereas the control did not. Experienced video game players responded better to high probability and neutral targets regardless of treatment condition, suggesting a larger benefit effect instead of the previously observed reduced cost. Video game training likewise improved performance in low-probability areas regardless of video game experience. There are issues of purity of effect in the design deployed by Greenfield et al. (1994), where a more typical approach of training non-video game players would be beneficial in providing a causal relationship. Regardless, there is evidence that with more video game experience, there is an improvement in the allocation of attentional resources across the visual field and that a short video game training session can amplify this effect in experienced video game players and evoke it in the less experienced.

But it was not until Green and Bavelier (2002) first presented their work at conference that research into the effect of video game use *switched on*. Coupling extreme groups sampling and NVGP training methodologies, Green and Bavelier (2002) provided a framework that would be built upon in later research. They demonstrated the potential for video game use to affect far transfer.

Improved Cognition in Video Game Players

Green and Bavelier (2003) initially focused on the potential for *action* video game play to modify visual selective attention, and the rationale for this was the nature of stimuli present in modern video games. Video games, in particular those within the action video game genre, present a nature of stimuli that involves a high rate of stimulus presentation, large field of view, and multiple object tracking (Green & Bavelier, 2003, 2006a, 2006b, 2007, 2012; Green & Bavelier, 2015; Green & Bavelier, 2020; Green et al., 2017; Green et al., 2010). Spending time interacting with these stimuli in an engaged and motivated way could result in training effects of attentional cognitions used to process such resource-intense stimuli (Katz et al., 2014). The same logic applies to “serious” or educational games. Serious games are designed specifically to increase engagement and motivation with the given topic material, resulting in increased retention and comprehension of learning material (James et al., 2024; Zeng et al., 2020).

To assess the potential for “off the shelf” (commercially available and mass-produced) action video games to modify visual selective attention, Green and Bavelier (2003) conducted five experiments. Four of the experiments were cross-sectional, sampling habitual Video Game Players (VGP) and Non-VGP (NVGP), and the fifth was a training methodology. The first of the four cross-sectional experiments consisted of a flanker compatibility task. Participants respond to a target stimulus presented in one of six locations in a circular array centred around a fixation point. Participants are tasked with identifying whether a diamond to a square was presented in the circular array. They were instructed to ignore anything presented outside the circular array; this is where the flanking distractors were presented. The flankers were either compatible (square flanker on square target trials, likewise for diamond), or incompatible (e.g. diamond on square target trials). Task difficulty was increased by additional irrelevant shapes in the remaining five locations in the circular array (with the target occupying one of the locations). The more task-irrelevant shapes, the more perceptual load placed on the participant according to the Load Theory of attention (Eayrs & Lavie, 2021; Lavie, 1995; Lavie & Cox, 1997; Lavie et al., 2004). The task was designed to assess attentional capacity, interference resolution, and stimulus-response compatibility effects (Sanders & Lamers, 2002). The size of the distractor effect is an indication of ‘left-over’ attentional resources, surplus attention remaining once processing the central circular array. The attention surplus is directed to process the external distractor flankers.

The second experiment employed an enumeration task, which consisted of small and large set sizes of visual stimuli. Participants are tasked with reporting the number of visual stimuli briefly presented on a computer screen as quickly and accurately as possible. According to the Load Theory of attention (Eayrs & Lavie, 2021; Lavie, 1995; Lavie & Cox, 1997; Lavie et al., 2004) small set sizes have a low perceptual load (or cognitive demand) and are hypothesised to reflect automatic processing (subitizing). Whereas large set sizes place a higher level of load on the participant's limited perceptual capacity and are more cognitively demanding, resulting in slower and more controlled processing (Eayrs & Lavie, 2021; Green & Bavelier, 2006b). The number of items that can be subitised is an indicator of the capacity of visual attention and the number of items that can be attended to at once (Tuholski et al., 2001).

In their third experiment, Green and Bavelier (2003) employed a useful field-of-view task to assess the spatial distribution of attentional resources. In their fourth experiment, they employed an attentional blink. The attentional blink is the phenomenon wherein participants are unable to detect the presence of a secondary target if it is located in close temporal proximity to the first target. Attention ‘blinks’ and the target is missed (Shapiro et al., 1997). Typical results show ‘one lag’ sparring of the secondary target if it is presented immediately after the first target (Martens & Wyble, 2010; Willems & Martens, 2016). Thereafter, there is an immediate drop in detection rate that increases in a linear relationship with time in milliseconds (200-500ms) after the onset of the first target (Beanland & Pammer, 2012; Cain et al., 2014; Howard et al., 2017; Jakubowska et al., 2021; Verghese et al., 2018; Wang et al., 2021).

The fifth experiment trained NVGP on action video game play with a non-action video game active control. Participants were trained for 10 days, 1 hour per day. Pre- and post-training measurements were taken on tasks assessing enumeration, attentional blink, and useful field-of-view as above in the cross-sectional studies (with the notable exception of the flanker compatibility task, which is not reported). Green and Bavelier (2003) observed that post-training, all video game training groups (action versus non-action control) improved their performance on all tasks, with action VGP exhibiting greater improvements.

Specifically, in experiment one, it was observed that VGP demonstrated a larger flanker effect than NVGP at higher levels of task difficulty, suggesting that the spare attentional resources spilt over to process distractors in VGP in more difficult or higher-load task conditions. Meanwhile, NVGP had depleted their attentional resources by that level of task difficulty and had no additional attentional resources to ‘spill over’ and process the distractor flankers. In experiment two, they confirmed these hypothesised increased attentional resources in the enumeration task by observing that VGP could subitize more items than their NVGP counterparts, suggesting larger visual processing capabilities. Experiment three measured the allocation of these additional attentional resources across space; VGP outperformed NVGP in every metric of the useful field-of-view task (target detection and response time in all eccentricities, at all distractor levels). In the fourth and final cross-sectional study, it was observed that VGP exhibited a reduced attentional blink as early as lag one. Therefore, findings suggest that VGP have increased attentional resources (flanker and enumeration) that increase their visual attention capacity (enumeration and useful-field-of-view) and are spatially improved (useful-field-of-view), temporally enhanced attention.

The aforementioned training experiment in the findings of Green and Bavelier (2003) support the hypothesis that the observed effects in the cross-sectional experiments are the result of playing video games and not population differences between individuals who choose to play video games and those who do not. The finding of improved attentional resources as a result of playing video games demonstrates that training is transferred beyond the trained task and generalised to a wider range of cognitive functions.

As previously introduced in the brief history of the positive effects of video game play, transfer effects refer to the generality of effects of training, training-related improvements restricted to improvements on task-specific skills (near) or are the effects task-general impacting a number of broader abilities and general cognitive ability (Carroll, 1993; Noack et al., 2014). Near and far transfer effects are heavily debated topics in the realm of behavioural training to improve cognition (Al-Thaqib et al., 2018; Baniqued et al., 2013; Duyck & Op de Beeck, 2019; Linares et al., 2019; Masurovsky, 2020; Poos et al., 2017; Sala et al., 2019; Souders et al., 2017).

Skill generalization from a trained domain to untrained domains, far transfer (Barnett & Ceci, 2002), is a critical area of cognitive skill training due to its implications. While training on a particular domain has been shown to improve performance in tasks assessing the trained cognition (Simons et al., 2016) and near transfer between the trained domain and closely related sub-disciplines (Kassai et al., 2019), studies have failed to demonstrate far transfer (Sala et al., 2019; Sala & Gobet, 2017, 2019).

Transfer effects to general cognitive ability is the furthest possible transfer effect, as hypothesised by Carroll (1993). Evidence of a technique capable of this level of transference would be an exciting prospect, able to be used by the public to improve attention capabilities in a wide range of facets. This notably contradicts findings of ‘brain training games’ which were advertised to improve general cognitive ability but were in fact found to largely produce very limited near-transfer effects (Al-Thaqib et al., 2018; Baniqued et al., 2013; Duyck & Op de Beeck, 2019; Linares et al., 2019; Masurovsky, 2020; Poos et al., 2017; Sala et al., 2019; Souders et al., 2017).

The findings of Green and Bavelier (2003) have been replicated numerous times and suggest improved performance on tasks assessing visuo-spatial attention (Andrews & Murphy, 2006; Bavelier, Achtman, et al., 2012; Bavelier et al., 2018; Bediou et al., 2018; Castel et al., 2005; Chisholm et al., 2010; Chisholm & Kingstone, 2012, 2015; Donohue et al., 2010; Durlach et al., 2009; Dye et al., 2009a, 2009b; Green & Bavelier, 2006a; Hubert-Wallander, Green, & Bavelier, 2011; Li et al., 2010; Okagaki & Frensch, 1996; Pavan et al., 2019; Risenhuber, 2004). While these studies have largely employed cross-sectional experimental designs, training methodologies with active controls have found a similar pattern of results in tasks assessing visual spatial attention and enhanced cognitive function more generally (Glass et al., 2013; Hutchinson et al., 2016; Kuhn et al., 2017; Powers et al., 2013; Szalma et al., 2018). However, training effects are not always observed (Sala et al., 2018) with various training paradigms failing to observe differences between groups in a range of cognitions, including interference resolution, perceptual processing (Ballesteros et al., 2017; van Ravenzwaaij et al., 2014), and post-experimental follow-ups have observed that the effects of training are non-significant after 3-months (Ballesteros, Mayas, et al., 2015).

Likewise, a meta-analysis by Sala et al. (2018) could not find support for the far transfer of video game play to five outcome measures (visual attention, spatial ability, cognitive control, memory, intelligence/reasoning) in a series of three meta-analyses 1) correlations of video game play experience with outcomes, 2) quasi-experimental comparisons of VGP and NVGP, 3) video game play training. Video game experience correlations were weak, and while the quasi-experimental comparisons demonstrated small differences between groups, training studies demonstrated no causal relationship. However, the correlational meta-analysis by Sala et al. (2018) did not allow for non-monotonic curvilinear relationships, in which excessive (problematic) gaming could result in diminished cognitive ability and mask the improvement that regular nonproblematic play can afford. A systematic review by Nuyens et al. (2019) has found that, at least for cognitive control, when excluding problematic video game play, VGP outperforms NVGP in terms of measures of cognitive control.

Another potential source of the discrepancies above is the influence of task demands (Bavelier, Achtman, et al., 2012). The noted flanker effects in Green and Bavelier (2003) have been repeatedly replicated (Dye et al., 2009a; Wang et al., 2014). However, there have been studies that have failed to observe the results of improved performance of VGP over their NVGP counterparts (Boot et al., 2008; Gobet et al., 2014; Paap et al., 2020; Redick et al., 2017; Unsworth et al., 2015; van Muijden et al., 2012; van Ravenzwaaij et al., 2014). Gobet et al. (2014) noted in their inability to replicate typical flanker effects, the task may not have been sufficiently demanding to observe the difference in the attention resources between NVGP and VGP observed in Green and Bavelier (2003). In short, the effects were reliant on sufficient task demands.

Of note, Dye et al. (2009a) demonstrated that the improved attentional performance in VGP in the Attention Network Test (Fan et al., 2002) would result in additional processing of flankers. The ANT was developed by Fan et al. (2002) and is based on the three main attentional networks (Petersen & Posner, 2012; Posner & Petersen, 1990). The ANT is a computerised testing measure designed to assess the three networks of attention, orienting, alerting, and executive control identified by Posner and Petersen (1990). The ANT includes flankers designed to provide a measure of executive control (via nonverbal interference effects), and Dye et al. (2009a) observed that VGP demonstrated larger flanker effects compared to NVGP. Importantly, VGP were as accurate and faster than NVGP, suggesting there was no speed-accuracy trade-off.

Flanker tasks are thought to be a measure of resistance to distracter interference within the nonverbal interference task paradigms (Paap et al., 2020), with the flanker compatibility effect being the difference between congruent and incongruent flanker condition response time (Sanders & Lamers, 2002). In Dye et al. (2009a) the flanker compatibility effect was calculated on normalised response times, and incongruent flankers' effects were more pronounced than congruent flankers. As previously stated, VGP were faster than NVGP in incongruent trials and as accurate but exhibited a greater flanker interference effect.

The interpretation of findings from Dye et al. (2009a) was that VGP are able to distribute their attentional resources across a wider visual field and processes flankers and the central target, yet traditionally, processing of congruent flankers provides limited benefit, and processing of incongruent flankers incurs a high stimulus-response cost (Sanders & Lamers, 2002)This was taken as an enhanced ability in VGPs, who perform even better in incompatible circumstances. The additional executive resources allow for the processing of incongruent flankers while outperforming NVGPs.

Improvements in performance as a result of video game play can be observed in behaviours relevant to the neuroanatomical model of the attention network, which consists of three main attentional subnetworks identified by Petersen and Posner (2012), namely, Alerting (Colzato et al., 2013; Dye et al., 2009a, 2009b; West et al., 2008), orienting (Dye et al., 2009b; Focker et al., 2018; Mack et al., 2016; Schmidt et al., 2020), and executive control (Chisholm et al., 2010; Chisholm & Kingstone, 2012, 2015; Deleuze et al., 2017; Li et al., 2010; Littel et al., 2012; Wang et al., 2014; Wang et al., 2016; Wang et al., 2017; West et al., 2008).

The alerting network refers to the ability to achieve and maintain an alert state, that is, optimal vigilance. One such way of measuring alertness is to precede a target with a warning cue to place the participant in an alert state, ready to detect and respond to a target. In the ANT, this is the cue condition (Fan et al., 2002) or through vigilance tasks measuring sustained attention (Thomson et al., 2015, 2016). The orienting network is responsible for prioritising sensory input by selecting a location or modality to direct attentional resources toward, measured by presenting a target in an uncued location during cueing conditions. The difference between cued and uncued response times is the measure of importance. Executive control in the attention network (Petersen & Posner, 2012; Fan et al., 2002) is defined as two distinct neural networks. Firstly, a frontoparietal network, which is hypothesised to be responsible for task switching and adjustments to task demands within trials. The second network, a cingulo-opercular control system, which functions to provide stable background maintenance for task performance across trials, both executive control networks providing top-down attentional control.

Theories of Executive Function

The executive control attentional network described by Petersen & Poser (2012) is analogous to many hypothesised cognitions about producing and maintaining goal-directed behaviours. Baddeley and Hitch (1974) developed and Baddeley (2012); Baddeley (2020) updated models of the structure and function of working memory and developed the concept of a “central executive”. According to Baddeley (2012), the central executive is responsible for allocating resources toward the two limited capacity, short-term buffers: the phonological loop and the visuospatial sketchpad. The central executive is based on the “supervisory attentional system (SAS)” described by Norman and Shallice (1986) that mediates non-automatic or controlled goal-directed behaviour by selecting and maintaining task-relevant cognitions (Cieslik et al., 2015). Taken together, these models suggest the role of a domain-general executive cognition that allocates mental resources toward task-relevant and goal-directed behaviour, and these resources are then used to fuel the cognitive processes necessary for the successful attainment of goals. Executive cognition or executive functions have additionally been described as being measured by “frontal lobe cognitions” (Focker et al., 2019; Gazzaley & Nobre, 2012; Martinez et al., 2013; Moisala et al., 2017; Nikolaidis et al., 2014; Zhang et al., 2017).

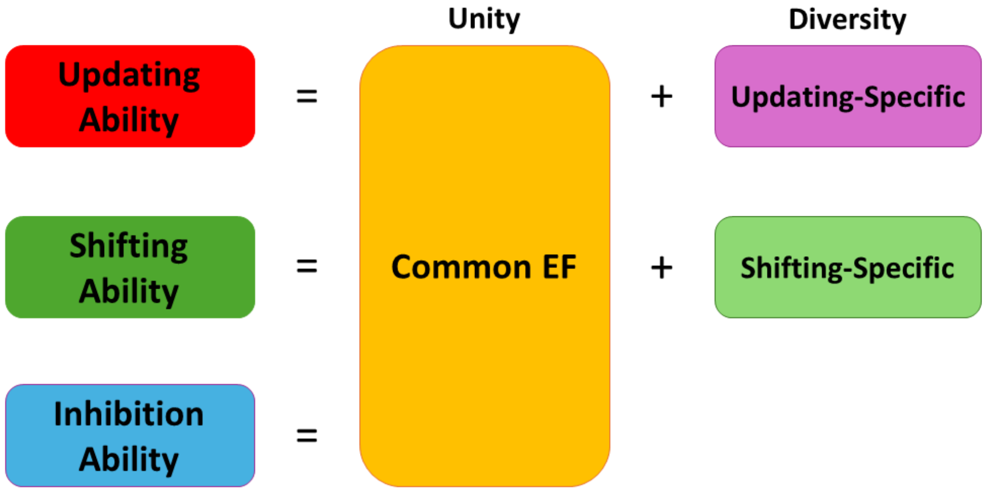
Perhaps the most influential conceptualisation of a domain-general executive of attention resources is that of Miyake et al. (2000), who identified the need for a clear conceptualisation of executive functions and their contributions to frontal lobe tasks (Friedman et al., 2008; Miyake et al., 2000). Miyake et al. (2000) used a battery of tasks intended to measure executive functions to test their contributions empirically. They identified three distinguishable components of executive function: shifting of mental set, monitoring and updating of working memory, and inhibition of automatic responses. The authors also found that the functions are not completely independent and share an ‘underlying commonality’, indicating both unity and diversity of executive functions.

The hypothesised structure of unity and diversity of executive functions continued to be developed (Friedman et al., 2011; Friedman et al., 2008). Friedman et al. (2008) conducted a twin study utilising three executive functions: inhibition of prepotent responses, updating of working memory, and switching between task sets. The longitudinal study recruited monozygotic and dizygotic pairs to determine the heritability and environmental contributions of executive functions. Moreover, to determine if genetic influences are domain-general or specific to each of the three executive functions. The authors replicated the findings of Miyake et al. (2000) in identifying three correlated (unity) but distinct (diversity) and extending the understanding of unity by developing a common executive function (Common EF) factor that underlies all three domain-specific functions. Common EF was found to be highly heritable, as were domain-specific executive functions to a lesser extent, and individual differences in EF are largely the result of genetic factors. Of note is that inhibition is identified to be shared completely with the common variance of the other domain-specific executive functions and that independent variance would be small. Friedman et al. (2011) continued the line of enquiry of the genetic and environmental contributions of EF in a longitudinal study correlating self-restraint in childhood with later executive function performance.

The hypothesised structure of executive functions continued to be developed. In their review of latent variable analyses of three executive functions, shifting, updating and inhibition, Miyake and Friedman (2012) developed the nature and organisation of executive function's unity and diversity theory further. In their findings, the results for tasks measuring inhibition were correlated almost perfectly with the latent variable Common EF, suggesting that inhibition is a common facet of all the distinctive executive functions. In the latent variable analysis, there was additional unexplained variance in the shifting- and updating-specific tasks, hence the unity and diversity of executive functions. Figure 1 is adapted from Miyake and Friedman (2012) and displays a schematic of their unity and diversity of executive functions.

Figure 1

A Schematic Representations of the Unity and Diversity of Executive Functions



Note: This figure was adapted from Miyake and Friedman (2012) and depicts the *unity/diversity* framework. Each ability can be decomposed into domain-general executive functions (Common EF or unity) and what is domain-specific for that particular ability.

As shown in Figure 1, Miyake and Friedman (2012) found no remaining inhibition-specific variance in their latent variable analysis results. While Figure 1 depicts the framework of unity and diversity in executive functions, it is not the only way the authors have depicted their findings. Figure 2a shows the higher-order common factor model adapted from Friedman et al. (2008) and Friedman and Robbins (2022). While there is an almost perfect overlap between inhibition and the latent variable of Common EF, inhibition-specific executive functions still exist. There are two potential accounts for this finding. The first interpretation is that inhibition is a fundamental ability that is utilised by all other executive functions. This interpretation requires that inhibition be conceptualised as sharing variance with the interference-control related abilities that updating- (deletion of items held in working memory) and shifting- (resistance of distractors in irrelevant set) specific functions utilise.

An alternative interpretation, and one which is favoured by Friedman and Miyake, is that inhibition is a multidimensional construct with statistically dissociable functions (Friedman & Miyake, 2004). As such, the reason for finding that inhibition loads onto the latent variable Common EF is that inhibition relies on functions that Common EF reflects: the active maintenance of task goals and goal-related information, which is required by all executive function tasks. This interpretation notes that Common EF and inhibition ability are isomorphic, having the same form and similar relations with the domain-specific cognitive functions. It is in this conceptualisation of Common EF that we observe Common EF acting toward the 'overall' responsibility of the Prefrontal Cortex (PFC) in maintaining goal-directed behaviours (Friedman & Robbins, 2022; Zhang et al., 2017), much like the previously proposed SAS (Norman & Shallice, 1986)

As executive functions are responsible for allocating resources for goal-directed behaviour, it is logical that any investigation into the ability of a behaviour to modulate and improve cognition be done on an understanding of the effect of that behaviour on executive function. The nature of improvements in various components of attention detailed above may reflect an abundance of executive function resources in VGP compared to NVGP. Diamond (2013) noted that executive functions consist of two hierarchies: higher-order executive functions and core executive functions. Higher-order executive functions include reasoning, problem-solving, and planning. Core executive functions include inhibition, interference control, working memory, and cognitive flexibility. Diamond (2013) noted the ability to train executive functions to improve performance on tasks measuring components of executive function. However, Diamond (2013) posits that the demands of tasks accessing executive function must be continually increased or there is difficulty in realising the difference between the executive function between groups, with a potential explanation that a task in which the level of difficulty remains stable may prove boring for groups which are not using their entire executive function capabilities. Moreover, differences in executive function tasks between groups are typically only observed in the most demanding task and task conditions (Diamond et al., 2007).

As previously discussed, early evidence for the notion that video game play can improve spatial attention came from Dye et al. (2009a), who employed the Attention Network Task (ANT) and compared performance between VGP and NVGP. The ANT (Fan et al., 2002) was developed based on the executive control attentional network described by Posner and Petersen (1990) and can be assumed to measure the same executive functions noted by Miyake et al. (2012) and core execution functions identified by Diamond (2013). Executive control taps the same essential functions as updating, shifting, inhibition and Common EF overall. Both Petersen and Posner (2012) and Friedman and Robbins (2022) underline the importance of inhibition within the executive control / Common EF components and the functions of shifting/ orienting and working memory/ updating. Within the ANT, the component where it was observed that VGP is linked to improved performance was the flanker interference effect dependent variable, the measure of executive control (Dye et al., 2009a).

Research investigating interference, for example, resistance to interference theory (Dempster & Corkill, 1999) argues that inhibition is a fundamental and unifying aspect of executive functions. Resistance to interference theory (Dempster, 1992) is based on classical interference theory (Jenkins & Dallenbach, 1924) which posits that later learning interferes with the recall of previously learnt material (retroactive interference) and information learnt earlier interferes with information learnt later (proactive interference). Resistance to interference theory builds upon this theory, utilising previous developments in neuroscience and understanding neurotransmitters' effects on post-synaptic receptor membranes. That is, to either cause excitation and reduce the action potential threshold and increase the likelihood of neuronal cell firing or inhibition that raises the threshold and reduces the probability of firing (Ferre et al., 2007).

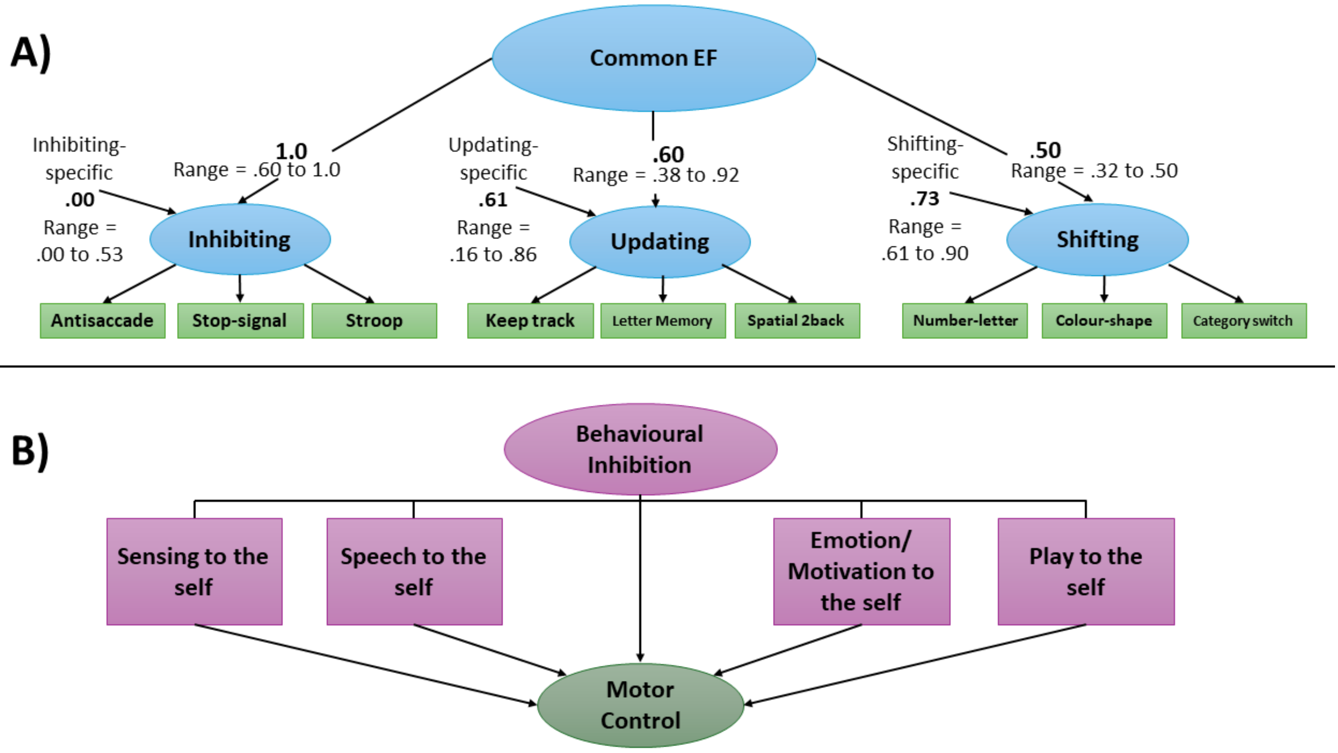
In resistance to interference theory, the importance of inhibition at the neuronal level is that it is the primary means of control in the nervous system (Dempster & Corkill, 1999). This is in line with neuropsychological models of cognition and attention and the role of inhibition (Grange et al., 2013; Tiego et al., 2018; Walley & Weiden, 1973) with arguments made that a link can be established between inhibition in interference in learning (and forgetting) and executive control (Anderson, 2003). The strength of these parallels is used to argue that inhibition is perhaps the most influential and important concept in executive function. Individual differences in the resistance to interference model reflect the ability to resist interference, which is dependent on the efficiency of the frontal lobes that are responsible for deploying inhibition, which shares similarities with more recent understandings of frontal lobe tasks (Focker et al., 2019; Gazzaley & Nobre, 2012; Martinez et al., 2013; Moisala et al., 2017; Nikolaidis et al., 2014; Zhang et al., 2017).

Barkley (1997) developed a hybrid neuropsychological model of executive function and self-regulation, where behavioural inhibition is characterised by delaying prepotent responses, interrupting ongoing responses, and interference resolution. Here, too, inhibition is observed to be a common executive function across four distinct self-regulatory executive functions (EF). The four self-regulatory EFs are nonverbal working memory (sensing to the self), verbal working memory (speech to the self), self-regulation of affect/motivation/arousal (emotion/ motivation of the self) and Reconstitution (Play to the self). Inhibition allows the four EFs to occur by permitting a delay in the decision to respond, in which the self-regulatory EFs exert control over the eventual response generated. Barkley (2001) considers inhibition an executive function as it is a form of self-directed behaviour that alters a later action. Inhibition and the four self-regulatory EFs are distinct but interact and operate toward a common goal (much akin to the unity and diversity model of executive function).

The hybrid model of self-regulation and executive function developed by Barkley (1997) and extended in Barkley (2001) is presented in Figure 2b alongside the higher-order common factor model conceptualisation of the unity and diversity of executive functions by Friedman et al. (2008). In this depiction, the theoretical overlap of the function of inhibition between the two models is apparent. While Common EF in the unity and diversity appears to take the place of behavioural inhibition in the hybrid self-regulatory model, inhibition is *almost* perfectly correlated with Common EF, and there is very little to no inhibition-specific variation accounted for in this model; inhibition forms the unity of this model. In the same vein, in the hybrid self-regulation model, inhibition is common to all EFs and part of their interaction, directing behaviour towards the common goal.

Figure 2

Conceptualisations of the Role of Inhibition in Miyake and Friedman's (2008) "Unity and Diversity Higher-Order Common Factor Model" and Barkley's (1997) "Hybrid Neuropsychological Model of Executive (Self-Regulatory) Functions"



Note: **A)** The figure and description presented are the higher-order common factor model adapted from the model presented by Friedman and Robbins (2022), it has been edited to include the original terminology of Executive Function (EF) from Friedman et al. (2008), replacing Cognitive Control (CC). In ellipses are the latent variables (executive functions) that predict performance on tasks chosen to measure those abilities (in rectangles), such as the Stroop (Stroop, 1935). The correlations between functions are depicted, with the higher order factor predicting lower order factors, and they correlate to the degree to which they are predicted by the common factor. The numbers shown are the average (in bold) and range of factor loadings for the Common EF and the residuals for domain-specific functions. **B)** The figure presented a schematic of the hybrid neuropsychological model of executive function (Barkley, 1997), and the description is adapted from Barkley (2001)Behavioural inhibition is linked to four executive functions, which together bring behavioural (motor) control under the control of internally represented information. Each executive function is covert behaviour with overt manifestations suppressed.

There has been limited direct experimental analysis of the effect of video game use on executive function as a whole (Andrews & Murphy, 2006; Schubert & Strobach, 2012;

Strobach et al., 2012) Boot et al. (2008) was unable to replicate the findings of Green and Bavelier (2003) when employing a wider range of cognitive tasks but notably did observe improvement in executive control. However, there have been investigations into the individual components that make up executive functions, assessing the ability of video game use to improve these cognitions, such as inhibition, particularly response inhibition (Argyriou et al., 2017; Azizi et al., 2018; Chaarani et al., 2022; Colzato et al., 2013; Deleuze et al., 2017; Gobet et al., 2014; Huang et al., 2017; Hutchinson et al., 2016; Latham et al., 2018; Paap et al., 2020; Steenbergen et al., 2015; Unsworth et al., 2015).

Response Inhibition; Subprocesses and Measurement

Response inhibition is a key part of the cognitive control system and is instrumental in selecting the appropriate response in a range of cognitive tasks and task settings (Mostofsky & Simmonds, 2008). Response inhibition is typically measured experimentally utilising three experimental paradigms, the Go No-go (Azizi et al., 2018; Berwid et al., 2005; Cieslik et al., 2015; Deleuze et al., 2017; Ding et al., 2014; Hummer et al., 2019; Ko et al., 2014; Kraplin et al., 2020; Leblanc-Sirois et al., 2018; Metcalf & Pammer, 2014; Noreen & MacLeod, 2015; Oei & Patterson, 2014; Raud et al., 2020; Yao et al., 2015), the Simon effect/ Spatial Stroop (Bialystok, 2006; Cieslik et al., 2015; Hutchinson et al., 2016; Latham et al., 2018; Lu & Proctor, 1995; Weinstein & Lejoyeux, 2015), and the stop signal tasks (Argyriou et al., 2017; Boecker et al., 2007; Choi et al., 2014; Colzato et al., 2013; Congdon et al., 2012; Friehs et al., 2020; Irvine et al., 2013; Kim et al., 2017; Kuhn et al., 2017; Schachar et al., 2011; Schall et al., 2017; Smittenaar et al., 2015; Song et al., 2018; van Muijden et al., 2012; Verbruggen & Logan, 2008), with meta-analyses and systematic reviews investigating response inhibition function typically reviewing research utilising these paradigms as they each represent different aspects of inhibitory processing (Argyriou et al., 2017; Bediou et al., 2018; Mostofsky & Simmonds, 2008). Specifically, each of these tasks measures a different component of response inhibition, action cancellation (Stop signal task, Logan (1994)), action withholding (Go No-go, Donders (1969)) and interference resolution (referred to as interference inhibition measured by the Simon task ((Simon, 1969) or spatial Stroop (Wuhr, 2007)) (Sebastian et al., 2013). Other components of response inhibition have been identified, such as resistance to distractor interference (Paap et al., 2020). However, action cancellation, action withholding, and interference resolution as components of response inhibition are thought to correlate with higher-order executive functions and goal-directed behaviour directly (Chan et al., 2008; Diamond, 2013).

The Go No-Go is a measure of action withholding where participants are required to respond to frequent "Go" signals on Go trials while not responding to infrequent "No-go" stimuli in No-Go trials (Gomez et al., 2007). The ability to withhold the prepotent response, developed through the predominant need to respond, in No-go trials is the measure of interest in a Go No-go task and the response times in Go trials. The difficulty of the task is modulated by manipulating the reaction time deadline (Benikos et al., 2013) or manipulating prepotency by increasing the ratio of Go trials to No-Go trials. Responding becomes more or less habitual, dependent on the manipulation, and withholding of a prepotent response more difficult (Lindqvist & Thorell, 2008). Lastly, difficulty can be moderated by manipulating the event rate (Raymaekers et al., 2004; Wessel, 2018).

The Simon task and spatial Stroop are visual choice reaction tasks, also known as nonverbal interference effect tasks (Lu & Proctor, 1995). They both require the participant to respond to a relevant stimulus dimension while suppressing a conflicting response triggered by the same stimulus in an irrelevant stimulus dimension that is automatically elicited, typically presented on the left or right side of the visual display. In the Simon effect, the relevant stimulus dimension is classically the colour of the stimulus, whereby one colour requires the response left and another colour the response right (Hommel, 2011), while in the spatial Stoop, the symbolic stimuli, typically the direction of an arrow, is the relevant dimension with leftward facing arrows requiring a response of left and likewise rightward facing arrow requiring a response of right (Viviani et al., 2023). When the relevant dimension and irrelevant dimension are congruent, there is a facilitation leading to faster response times; this is known as the stimulus-response compatibility effect. Alternatively, when the relevant dimension and the irrelevant dimension are incongruent, there is a stimulus-response incompatibility effect and invoked interference as the irrelevant dimension interferes with the processing of the relevant dimension needed to produce an accurate response (Lu & Proctor, 1995; Shi & Wang, 2022). The difference in response times between the congruent and incongruent is the variable of interest in the Simon and spatial Stroop tasks, termed the interference effect, congruency cost, and other synonyms.

The Stop-signal task (Logan, 1994) requires participants to suppress proponent motor responses to meet the task's demands in a function of action cancellation. In a stop signal task, participants perform a “Go” task whereby they produce a speeded response to a target stimulus. In some trials, a “Stop” signal is presented after a Go target, which tells the participant to stop their response to the “Go” target. The ability of the participant to stop is the variable of interest and a marker of response inhibition. The ability to inhibit responses is probabilistic and dependent on the duration of the stop signal delay (SSD) (Schall et al., 2017). The SSD is the time available to detect a stop signal and override the response before execution. The measure often reported here is the stop-signal reaction time (SSRT), which is a reliable measure of inhibitory control (Congdon et al., 2012). The SSRT is calculated by subtracting the SSD from the Go response time (Band et al., 2003). Alternative methods of identifying the SSRT can be deployed, such as the SSD at which performance falls below a certain threshold, also known as the probability to inhibit response or proportion of successful stop-signal trial (Ramautar et al., 2006). Increasing task difficulty on the stop signal task is typically undertaken by manipulating SSD or prepotency by increasing the ratio of Go trials relative to Stop trials (Lindqvist & Thorell, 2008).

Deficits in response inhibition have been implicated in a range of neuropsychological disorders such as substance abuse (Smith et al., 2014), gambling disorder (Billieux et al., 2012) and excessive internet use (Dong et al., 2012). Moreover, there have been numerous investigations into the effects of problematic video game use as well as internet gaming disorder on response inhibition (Argyriou et al., 2017; Chen et al., 2015). However, non-problematic video game play has been implicated as a potential remedy for deficits in response inhibition as previous research has suggested that video game players (VGPs) outperform non-video game players (NVGPs) on tasks assessing response inhibition, namely nonverbal response interference via Simon task (Hutchinson et al., 2016; Latham et al., 2018), Go No-Go (Huang et al., 2017) and Stop signal task (Chaarani et al., 2022), although these effects are not consistently observed, particularly in nonverbal interference tasks (Gobet et al., 2014; Paap et al., 2020; Unsworth et al., 2015). Colzato et al. (2013) and Steenbergen et al. (2015) found no significant difference in stopping performance in a stop-signal task between VGP and NVGP. Paap et al. (2020) found no significant difference between VGP and NVGP on flanker tasks, spatial Stroop, Simon task, or vertical Stroop after controlling for sex, age, and IQ in their regression model.

However, as previously discussed, Diamond (2013) stated that tasks assessing executive functions, of which response inhibition and its components are, must be sufficiently demanding in order to observe the effects of training. Moreover, only in the most cognitively demanding tasks and task conditions are differences in executive functioning commonly observed(Brown, 2006; Diamond, 2013; Diamond et al., 2007). This is borne out by evidence in video game play research where Dye et al. (2009a) observed additional attentional performance in VGP on the Attention Network Test (ANT; Fan et al. (2002) compared to

NVGP only when the task was sufficiently demanding. The same finding was observed in a visual search task, with superior capabilities of VGP over NVGP only observed in the most cognitive demanding condition (Hubert-Wallander, Green, Sugarman, et al., 2011), while Gobet et al. (2014) concluded that a potential explanation for their lack of observed differences between VGP and NVGP on a flanker task was due to the limited cognitive load placed on the participants by the task. Likewise, while simple individual component tasks that measure one facet of response inhibition often fail to observe a difference between VGP and NVGP (Paap et al., 2020; Unsworth et al., 2015), studies using hybrid tasks (that is tasks assessing more than one component of a cognition or having multiple response requirements) such as the ANT employed by Dye et al. (2009a) have observed differences between VGP and NVGP in conditions such as interference resolution that is not consistently observed.

As such, the aim of the current thesis is to investigate the effects of video game use on executive functions. Considering the findings in visual selective attention research (Bavelier et al., 2018; Bavelier & Green, 2019; Green & Bavelier, 2003, 2006a, 2006b, 2007, 2020), it is hypothesised that the source of improved cognition in recent frequent VGP relative to NVGP is enhanced executive function resources. Therefore, the current thesis will investigate the cognition fundamental to executive function, inhibition, according to models of executive function such as Friedman and Miyake (2004) and Barkley (2001). Moreover, the current thesis will investigate the transfer of training across other executive functions, as the potential of video games to evoke skill generalization from a trained domain to untrained domains, far transfer (Baniqued et al., 2015; Barnett & Ceci, 2002; Bavelier, Green, et al., 2012; Carroll, 1993; Duyck & Op de Beeck, 2019; Jaeggi et al., 2014; Lee et al., 2012; Lintern & Boot, 2021; Sala et al., 2019; Sala & Gobet, 2017; Sala et al., 2018; Zhao et al., 2018), is vital in understanding the limits of video game play effects. Finally, manipulations of cognitive load on an executive function task based on the Load Theory of attention (Eayrs & Lavie, 2021;

Lavie, 1995; Lavie & Cox, 1997; Lavie et al., 2004) will test the hypothesis that sufficient load is required to observe executive function performance differences (Diamond, 2013). It is hypothesised that there will be a difference in the executive function capabilities between VGP and NVGP. This will be observable in measures of the fundamental component of executive function, inhibition. It is predicted that VGP will outperform NVGP in measures of response inhibition, where there is sufficient cognitive demand for such a difference to be observed. It is hypothesised, due to the function of inhibition as a domain-general executive function in various models of executive function, that the observed enhanced response inhibition performance of VGP compared to NVGP will transfer to other executive functions such as updating/ working memory. It is predicted that recent frequent video game use will evoke far transfer, with VGP outperforming NVGP on additional measures of executive function where there is sufficient cognitive demand to observe such an effect.

Chapter 2: Video Game Use and Response Inhibition

Response inhibition is a crucial component of goal-directed behaviour and instrumental for selecting the appropriate response in a range of cognitive tasks and task settings (Mostofsky & Simmonds, 2008). It's important to note that response inhibition, the ability to suppress prepotent motor responses, is distinct from attentional control, defined as the ability to resist interference from distracting stimuli. Both are key parts of the cognitive control system, but they operate in different ways and serve different functions (Tiego et al., 2018). Response inhibition is thought to be a process in which a non-task related stimulus/inappropriate response is suppressed/withheld to prevent interference with a co-existent relevant stimulus/correct response, to ensure an appropriate action to achieve a current motor, cognitive, or socioemotional goal (Bari & Robbins, 2013). Response inhibition plays a central role in attentional control. It helps us inhibit responses to distracting stimuli, which is vital for maintaining task performance. Its significance extends beyond the realm of cognitive tasks, as it is crucial for normal functioning in our daily lives. For instance, it aids in avoiding interruptive verbal communication, patiently waiting in traffic, resisting the urge to snack unnecessarily, and even stopping that ever-so-tempting Netflix binge.

As Identified in the General Introduction chapter, the presupposed benefit of frequent recent video game use is hypothesised to be a result of increased executive function capabilities. This is due to the finding that any potential benefit is only measurable under sufficient cognitive load (Dye et al., 2009a; Gobet et al., 2014), a common finding in executive function training paradigms (Diamond, 2013). Moreover, any improvement in the executive function networks should be more readily apparent in inhibition due to its role in many conceptualisations as overlapping with other executive functions, such as Common EF in the unity and diversity model, and acting as a domain-general executive function (Dempster, 1992; Dempster & Corkill, 1999; Friedman et al., 2008; Miyake & Friedman, 2012). Response inhibition has been identified as a candidate function of inhibition, as it is a key part of the cognitive control system (Mostofsky & Simmonds, 2008) and due to its use in previous experiments assessing the potential benefit of recent frequent video game use on executive function (Argyriou et al., 2017; Azizi et al., 2018; Chaarani et al., 2022; Colzato et al., 2013; Deleuze et al., 2017; Gobet et al., 2014; Huang et al., 2017; Hutchinson et al., 2016; Latham et al., 2018; Paap et al., 2020; Steenbergen et al., 2015; Unsworth et al., 2015).

In the General Introduction, three main subcomponents of response inhibition and the tasks typically employed in literature to measure them were identified: interference resolution, action withholding, and action cancellation (Sebastian et al., 2013). To measure interference resolution, the Simon task (Simon, 1969) and the closely related spatial Stroop (Wuhr, 2007) are frequently used (Bialystok, 2006; Cieslik et al., 2015; Hutchinson et al., 2016; Latham et al., 2018; Lu & Proctor, 1995; Weinstein & Lejoyeux, 2015). To measure action withholding, the Go No-go task (Donders, 1969) is often used to assess the ability to inhibit a prepotent response (Azizi et al., 2018; Berwid et al., 2005; Cieslik et al., 2015; Deleuze et al., 2017; Ding et al., 2014; Hummer et al., 2019; Ko et al., 2014; Kraplin et al., 2020; Leblanc-Sirois et al., 2018; Metcalf & Pammer, 2014; Noreen & MacLeod, 2015; Oei & Patterson, 2014; Raud et al., 2020; Yao et al., 2015). Lastly, the stop signal task (Logan, 1994) is typically employed to measure action cancellation (Argyriou et al., 2017; Boecker et al., 2007; Choi et al., 2014; Colzato et al., 2013; Congdon et al., 2012; Friehs et al., 2020; Irvine et al., 2013; Kim et al., 2017; Kuhn et al., 2017; Schachar et al., 2011; Schall et al., 2017; Smittenaar et al., 2015; Song et al., 2018; van Muijden et al., 2012; Verbruggen & Logan, 2008).

Action cancellation is typically measured using Stop Signal Reaction Time (SSRT) developed from the independent race model (Verbruggen & Logan, 2008), which posits that stop signal tasks are a race between the go and stop process. Two separate and independent processes are involved in a stop signal task: a Go and a Stop process. Once the Go signal is perceived, the cognitive and motor actions are initiated to execute the required response. The Stop process is initiated once the Stop signal is perceived; this signal is presented after the stop signal delay (SSD). The Stop processes initiate the executive functions required to inhibit or cancel an initiated response that was prepared by the Go process. In failed inhibition, the Go process finishes before the Stop process, while in successful inhibition, the Stop process wins the race. The Go process is comprised of sensory processing, decision-making, and motor execution, while the Stop process is comprised of initiation inhibitory control. Both of these processes are random in nature, and their finishing times are probabilistic. Stop Signal Reaction Time (SSRT) is a measure derived from this model, predicated on the distribution of response times and the probability of successfully inhibiting response at various SSDs (Congdon et al., 2012).

As detailed in the General Introduction, these tasks have been utilised in previous attempts to assess the differences between VGP and NVGP on components of response inhibition, nonverbal response inhibition through the Simon task (Hutchinson et al., 2016; Latham et al., 2018). The ability to suppress a prepotent response, action withholding, using the Go No-go (Azizi et al., 2018; Huang et al., 2017), and the ability to stop an already initiated response, action cancellation in stop signal task paradigms (Chaarani et al., 2022; Colzato et al., 2013; Deleuze et al., 2017; Irvine et al., 2013).

Previous investigations have found that VGP outperforms NVGP in Simon effect tasks. However, they have also underlined the importance of conceptualising video game play experience, in addition to recent frequent video game use. Latham et al. (2018) observed that experienced-VGP (a result of playing video games before the age of ten) were faster than NVGP in incongruent conditions. Specifically, experienced-VGP could resolve the stimulus-response conflict faster than NVGP. Ridderinkhof et al. (2004) developed the activation-suppression hypothesis of selective response inhibition. Within this hypothesis, it is predicted that there is a compounding effect of stimulus-response incompatibility. Slower responses exhibit more interference effects over time, while faster responses are less impacted by congruency and spared this additive trend (Ridderinkhof et al., 2004). The pattern of results observed by Latham et al. (2019) suggests the potential for VGP to be less impacted by stimulus-response incompatibility initially, potentially to a limited extent, but that this exacerbates over the time course of the experiment due to compounding congruency effects.

Hutchinson et al. (2016) trained NVGPs on either a first-person shooter video game or a control visual training game and compared their performance pre- and post-training on a Simon task. Post-training participants trained on the first-person shooter game were observed to have reduced response time and reduced stimulus-response incompatibility cost. Meanwhile, control participants trained on a control visual training game were observed as having no improvement on the post-training Simon task. Finding a causal link between recent frequent video game play leads to transfer effects that improve interference resolution.

Unsworth et al. (2015) treated video gameplay as a continuous variable and were unable to find evidence that video game play predicted the flanker effect or spatial Stroop task performance. Employing a similar design to Unsworth et al. (2015), Paap et al. (2020) investigated the effect of the frequency of video game use as a continuous variable. They observed that as the frequency of video game use increased, a composite measure of interference effects on the Simon task, the spatial Stroop, and the vertical Stroop reduced. However, once impulsivity, sex, IQ, and self-control were entered into the model the correlation became not significant. Likewise, the frequency of video game use did not significantly predict interference effect scores in any of the individual tasks. In a different executive function, shifting, it has been observed that age of onset of video game use is an important factor in establishing the effect of video game use (Hartanto et al., 2016). This stresses the importance of incorporating more characteristics of video game use, such as experience, into methodologies assessing the effect of video game use.

In a Go No-go task, Azizi et al. (2018) observed faster but more impulsive responses in VGP compared to NVGP. VGP were reported as having a significantly faster response time and a higher false alarm rate. SDT identified more impulsive responses in terms of a high risk-taking bias in VGP than NVGP. However, speed was emphasised during task description, and across the entire sample, there was a negative correlation between response time and false alarm rate, suggesting a speed-accuracy trade-off across all participants.

Irvine et al. (2013), when comparing problematic VGP to healthy NVGP controls on the stop signal task, found no group differences in stop signal reaction time (SSRT). However, a linear regression implicated the genre of video game use to mask any potential differences between groups. It was noted that strategy genre VGP was associated with reduced action cancellation performance. However, Nuyens et al. (2018), in their meta-analysis, found that once problematic levels of VGP were accounted for, only minimal positive effects remained on components of executive control. Colzato et al. (2013) found that VGP were faster and more accurate in a measure of working memory, the *n*-back, but that action cancellation performance in a stop-signal task did not differ from NVGP. VGP were faster in responding to Go trials, and there was no difference between the two groups in overall accuracy. However, once SSRT had been computed on a 50% accuracy staircase procedure, the difference between the two groups on performance was not significant.

Incorporating three major subcomponents of response inhibition identified within one hybrid task paradigm should impart the sufficient cognitive demand required to observe differences in executive function due to training, as observed in previous hybrid paradigms (Dye et al., 2009a). A previous hybrid Stop/ Go No-go task (Deleuze et al., 2017), combined two response inhibition components of action withholding and action cancellation in the

Go/No-go and SST. The aim of Deleuze et al. (2017) was to compare the effects of the video game genre on the ability of video game use to evoke changes to response inhibition. As such, no NVGP condition was included. Instead, the authors grouped participants based on the genre of video games they played, identified by three genres: first-person shooter (FPS), massive multiple online role-playing game (MMORPG), and multiplayer online battle arena (MOBA). While controlling for potential confounds such as the number of hours played and trait impulsivity using the UPPS-P impulsive behaviour scale (Cyders et al., 2007) Deleuze et al. (2017) found a significant difference between VGP of each genre. FPS demonstrated reduced action cancellation performance compared to both MMORPG and MOBA. Moreover, FPS players had faster reaction times than MOBA but not MMORPG, and no differences were observed between groups on action withholding.

As such, the present study aims to use a hybrid response inhibition task (HRIT) paradigm developed by Sebastian (Sebastian et al., 2013) to potentially evoke sufficient cognitive demand to observe the differences between VGP and NVGP in interference resolution, action withholding, and action cancellation, all of which the HRIT measures.

Additionally, impulsivity has been implicated in inhibitory control, specifically that participants with higher levels of reported urgency are slower to respond to Stop signals, an inability to inhibit prepotent responses (Wilbertz et al., 2014). Paap et al. (2020) indicated that controlling for impulsivity reduced the effects of video game use on interference resolution. Higher levels of self-reported impulsivity are associated with increased congruency cost and longer time to overcome stimulus-response incompatibility in nonverbal interference tasks (Enticott et al., 2006). Higher self-reported impulsivity also correlates with worse action cancellation on a stop signal paradigm (Portugal et al., 2018). In particular, negative urgency, the tendency to act impulsively in response to negative affect, from the

UPPS-P Cyders et al. (2007) has been observed to positively predict stop signal reaction time (SSRT), with higher urgency resulting in worse stopping performance (Wilbertz et al., 2014).

Likewise, some findings suggest that VGP and NVGP differ in their self-reported impulsivity (Azizi et al., 2018; Billieux et al., 2011; Deleuze et al., 2017; Ding et al., 2014; Nuyens et al., 2016). Ding et al. (2014) demonstrated that individuals with internet gaming disorder (IGD) were more impulsive than recreational gamers, and this correlated with worse action withholding as measured by the Go No-go task. Azizi et al. (2018) found that non-problematic VGPs were more impulsive than NVGPs, exhibiting faster response times, higher error rates, and riskier decision-making on a Go No-go task.

To that end, the current study will employ a measure of self-report impulsivity that measures negative urgency, by Cyders et al. (2007) and Cyders and Smith (2007) (Negative) Urgency, Premeditation (lack of), Perseverance (lack of), Sensation seeking, Positive Urgency (UPPS-P) or its short-form alternative developed by Cyders et al. (2014), which is utilised here, the SUPPS-P.

The aim of the current experiment is to assess the effect of video game use on response inhibition in a task measuring the three main components of response inhibition: interference resolution, action cancellation, and action withholding. This, in turn, fulfils a broader aim of investigating the effect of video game play on a key executive function and informs the wider video game play and executive function inquiry. Moreover, the present study aims to identify the relationships between video game play and impulsivity and the relationship between impulsivity and response inhibition performance. Understanding the nature of these relationships will inform upon the nature of the influence of video game play on executive functions.

It is predicted that VGP and NVGP will differ on the HRIT in interference resolution, action cancellation, and action withholding measures based on skill generalisation and transfer effects of training (Barnett & Ceci, 2002), as observed in visual attention research (Bavelier et al., 2018; Bediou et al., 2018; Castel et al., 2005; Chisholm et al., 2010; Chisholm & Kingstone, 2012, 2015; Dye et al., 2009a, 2009b; Green & Bavelier, 2006a), where the task is sufficiently demanding (Diamond, 2013; Diamond et al., 2007; Dye et al., 2009a; Gobet et al., 2014; Hubert-Wallander, Green, Sugarman, et al., 2011). Any hypothesised increased executive function performance as a result of frequent recent video game play should be readily apparent in inhibition; this cognition is hypothesised to interact with all over executive functions or act as a domain-general executive function, in various conceptualisations of executive functions (Dempster, 1992; Dempster & Corkill, 1999; Friedman et al., 2008; Miyake & Friedman, 2012). Additionally, the current study aims to investigate the relationship between self-reported impulsivity and response inhibition on the HRIT and the relationship between self-reported impulsivity and video game play.

Methods

Participants

Seventy-two (M_{age} = 20.82, SD_{age} = 2.70, 74% female) participants were recruited online via Gorilla using the Swansea University SONA participant pool. 19 males (M_{age} = 20.89, SD_{age} = 3.15) and 53 females (M_{age} = 20.79, SD_{age} = 2.48) took part in this experiment. Exclusion criteria included neurological and cognitive issues that are known to influence response inhibition, such as attention-deficit/ hyperactivity disorder (Coutinho et al., 2017), and taking over 24 hours to complete participation upon accessing the Gorilla website (gorilla.sc; Anwyl-Irvine et al. (2020)). The inclusion criteria were participants between the ages of 18 and 35 years old.

The age criteria were established based on executive function developmental trajectories and ageing research investigating the effect of ageing on executive function. Filippi et al. (2020); McCabe et al. (2010) investigated developmental trajectories of executive function and used the following age classifications: children (7-12 years old), young adults (18-35 years old), middle-aged adults (36-55 years old) and older adults. Filippi et al. (2020) and McCabe et al. (2010) differed in their definitions of older adults, with McCabe et al. (2010) further categorising ages 56 and up as younger-old (56-70 years old) and older-old (71-90 years old), whereas Filippi et al. (2020) used a single older adult group (56-80 years old).

Fillipi et al. (2020) observed that executive function performance, as measured by the Simon and Tower of London tasks, peaked in young adulthood. McCabe et al. (2020) found a similar pattern of results with executive function performance following the same inverted *U* shape with age; the peak of the inverted U shape (and, as such, peak performance) was observed in the young adulthood group. Young adulthood is most readily sampled in a university/student population. Sampling this population avoids the inclusion of other age groups, which may differ in their executive function performance and introduce a confounding variable.

Participants obtained from the Swansea University SONA participant pool were compensated with 15 SONA credits, and Call for Participants recruited participants were offered the opportunity to be entered into a raffle for £15 Amazon gift vouchers. In total, 87 participants were recruited; however, 9 were excluded due to taking more than 24 hours to complete participation, and 6 were excluded due to incomplete datasets. All participants provided signed, informed consent to participate in the study, which was approved by the School of Psychology Ethics Committee, Swansea University.

Participants were later separated into VGP and NVGP conditions for analysis based on their responses to the covert video game experience questionnaire (CVGEQ). Participants were separated based on the recommendations set by Green et al. (2012) and those typically observed in this area of research (Bavelier et al., 2018; Bavelier & Green, 2019). Participants reporting more than 6 hours of video game play per week over a period of 6 months are considered VGP (while those that report > 1 hour per week on average are NVGP) In the current study, the limit of video game play with a frequency of once a month or less are considered NVGP, five participants were included in the NVGP group despite reporting a frequency of more than once a month as the average number of hours of video game play did not meet the requirement for inclusion in the VGP group.

Materials

Short Urgency, Premeditation (lack of), Perseverance (lack of), Sensation seeking, Positive Urgency (SUPPS-P; Cyders et al., 2014)

The original Urgency, Premeditation, Perseverance, Sensation Seeking (UPPS) scale was developed by Whiteside and Lynam (2001) and was adapted to include a fifth trait of Positive Urgency by Cyders et al. (2007), and Cyders and Smith (2007), culminating in an impulsive behaviour scale measuring five traits (Negative) Urgency, Premeditation (lack of), Perseverance (lack of), Sensation seeking, Positive Urgency (UPPS-P). This adaptation was published as the English 59-item version (Lynam et al., 2006) and has satisfactory convergent and discriminant validity (Cyders & Smith, 2008; Cyders et al., 2007; Smith et al., 2007). There is a consensus that the UPPS-P measures five separate but related first-order factors in young undergraduates (Cyders et al., 2007) with three second-order factors: emotion-based dispositions, sensation seeking, and lack of conscientiousness (Cyders, 2013; Cyders et al.,

2007) as well as producing a total impulsivity score which is the total response to items assessing the five previously mentioned factors.

The self-report UPPS-P was modified to the 20-item scale short UPPS-P (SUPPS-P); Cyders et al. (2014) validated the SUPPS-P against the UPPS-P and determined that it is valid to the full-form version based on the methodology proposed by Smith et al. (2000). SUPPS-P subscales were observed to be strongly correlated with UPPS-P subscales (r = >.7, across all subscales); with a loss of variance of no more than 6.4% (5.4% in negative urgency, 3.1% in positive urgency, .6% in lack of perseverance, 0% in lack of premeditation, and 6.4% in sensation seeking) with 66% of administration time saved when the SUPPS-P is used in place of the UPPS-P. The 20 items are measured on a four-point Likert (1-4) scale ranging from "*Strongly Agree*" (1) to "*Strongly Disagree*" (4).

Positive urgency is the tendency to act impulsively as a result of positive affect; four items contribute to this subscale with questions such as "*I tend to lose control when I am in a great mood*". Cronbach's alpha was used to determine the internal consistency of this subscale (in addition to the remaining four sub-scales and total score) on the sample of 72 participants. It demonstrated acceptable internal consistency (α = .76, 95% CI [.60, .86]). Negative urgency is a four-item measure of the tendency to act impulsively due to negative affect; questions posed include "*When I am upset I often act without thinking*" and demonstrated acceptable internal consistency (α = .73, 95% CI [.57, .82]). Lack of premeditation is measured by four items refers to the tendency to act rashly without first reflecting upon the decision to act, an example of an item "*My thinking is usually careful and purposeful*", and demonstrated acceptable internal consistency (α = .76, 95% CI [.61, .85]). Lack of perseverance is a four-item subscale and refers to a tendency to leave projects incomplete. An example of a question measuring lack of perseverance is "*I finish what I start*". In the current sample, it demonstrated a questionable internal consistency (α = .62, 95% CI [.42, .74]). Sensation seeking is a four-item measure of motivation to experience novelty. An example of a sensation-seeking item is “*I quite enjoy taking risks*”. In the current sample, it demonstrated a borderline acceptable internal consistency (α = .69, 95% CI [.54, .79]). The total impulsivity score demonstrated an acceptable internal consistency (α = .76, 95% CI [.61, .84]). The SUPPS-P took approximately five minutes to complete.

Covert Video Game Experience Questionnaire (CVGEQ; Sobczyk et al., 2015)

The CVGEQ (Sobczyk et al., 2015) was developed to address a common criticism in the area of video game research around participant recruitment and the development of demand characteristics. In addition to offering a covert method for obtaining video game experience information, it provides an in-depth and granular assessment of the nature of a participant's video game experience. While previous studies have underlined the importance of covert recruitment and group allocation in video game research (Boot, 2015; Boot et al., 2011), Schubert and Strobach (2012) highlight that there is no evidence for a motivational effect as a result of recruitment strategies on cognitive performance of VGP and NVGP in video game literature; however, Sobczyk et al. (2015) still recommend a covert approach to minimise demand characteristics.

For use in the current study, and due to the nature of the larger study this experiment forms a part of, the CVGEQ was modified to remove irrelevant dimensions, thus nullifying the covert nature of the questionnaire. This was primarily undertaken to reduce task fatigue and was presented as part of a battery of 5 questionnaires, potentially mitigating some of the negative effects of removing the covert nature of this questionnaire and minimising the potential for demand characteristics while preserving the key metric of the questionnaire. The original CVGEQ is 28 items and includes dimensions measuring internet usage, TV use, sports, and physical activities (none of which were of interest regarding the current research question). The modified CVGEQ employed in this study removed these irrelevant dimensions and is 10 items. Initially, participants are asked their gender and date of birth. Then, participants are asked how often they play video games (*once a month or less, more than once a month, more than once a week, once a day, more than once a day*). This initial filtering question was presented individually; the following questions are only presented if the participant frequently participates in the activity. If the participant responded "*once a month or less*" or "*More than once a month*", they proceeded to the end of the questionnaire as it was determined a priori that there would be limited video game experience to be measured from participants who do not reach the required limit observed in video game research to be deemed a video game player (6 or more hours per week on average consistent for six months)(Bavelier et al., 2018; Bavelier & Green, 2019). Additionally, Sobczyk et al. (2015), in the original CVGEQ, recommend the filtering question be set to responses of "*more than once a week*" or higher frequencies, in line with the current approach here to the modified CVGEQ, where participants answering "*more than once a week"* or more frequent would continue as normal and answer all items of the CVGEQ.

Additionally, the device used, the number of hours per week on average over the last six months, and subjective experience level on a seven-point Likert scale (1 – *Not at all experienced* to 7- *Very experienced*) were questions posed. The number of years of video game experience the participant has playing video games is also recorded, with an internal rule present in the questionnaire that would not allow answers that exceeded the participant's age.

The video game genre played were recorded by this questionnaire with 16 response options: Adventure, fighting, first-person shooters, logic/puzzle, multiplayer online battle arena, open-world action-adventure, platform, racing, real-time strategies, role-playing games, simulation, sport, third person shooters, turn-based strategies, vehicle simulation, and other. All response options include examples of prevalent titles within that genre. Participants are asked to record the three video game titles they have played the most often in the past six months and their rating of how “good” they are in the genres they selected on a seven-point Likert scale (1-7, 1- *Not good at all* to 7 – *Very good*). Participants were also asked to record in the past six months the average hours per week spent on average playing each genre and each device. The amount of time allowed to be allocated to each genre or device is capped to a total of the average number of hours spent gaming per week over the last six months, as recorded earlier in the CVGEQ. Participants are shown the number they reported as the total average number of hours spent gaming to enable them to allocate time to each genre accurately. Participants are asked to distribute this time between answers with intervals of 30 minutes using sliders. As the covert element has been removed from this measure, the name Video Game Experience Questionnaire (VGEQ) will be used instead of CVGEQ.

Hybrid Response Inhibition Task (HRIT; Sebastian et al., 2013)

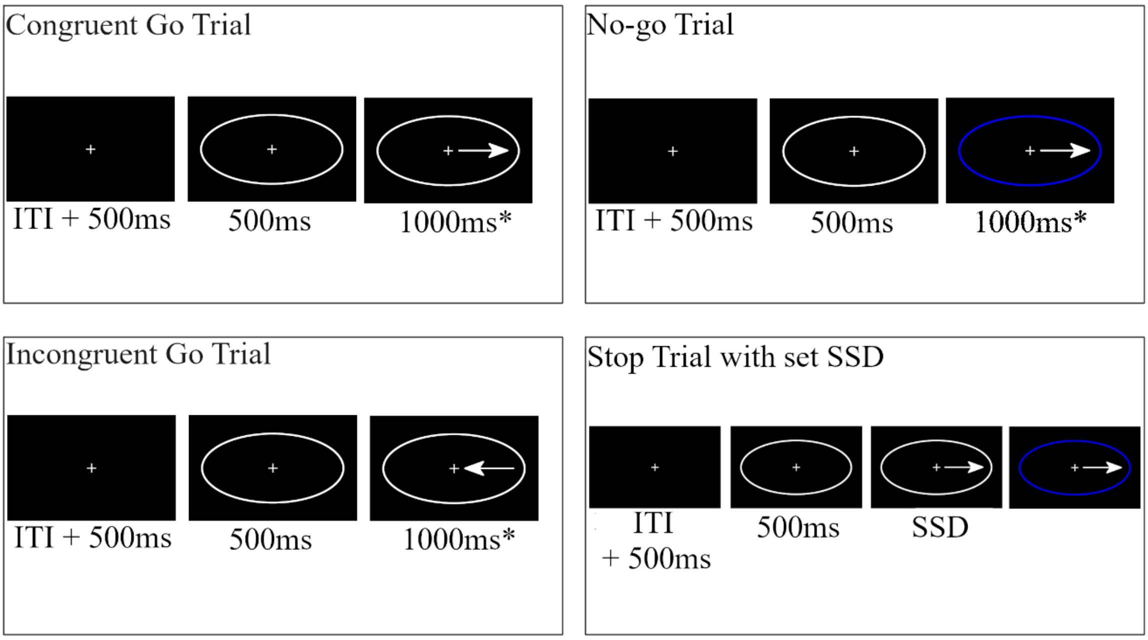
The Hybrid Response Inhibition Task (HRIT; Sebastian et al. (2013)) used in this study was programmed and presented on Gorilla (gorilla.sc; Anwyl-Irvine et al., 2020). has previously been employed in functional magnetic resonance imaging (fMRI) studies and is an established task to investigate response inhibition subcomponents in neuroscientific paradigms (Gerhardt et al., 2021; Sebastian et al., 2013). Within the HIRT, performance on three major components of inhibition, interference resolution, action withholding, and action cancellation, are assessed, which enhances task complexity and hence demands on the executive functions (Sebastian et al., 2013). The stimulus conditions included in the HRIT resemble interference inhibition as measured by the Simon Task, action withholding as implemented in the Go/No-go task, and action cancellation based on the Stop Signal Task. A schematic of the HIRT trial types is presented in Figure 3.

Before each trial, an intertrial interval (ITI) was presented to the participants. The ITI was a fixation cross in the centre of the screen presented for an average of 1500ms (jittered by randomised values *m*=1500ms*, SD*=372ms). During each trial, the fixation cross from the ITI remains on screen and is presented for 500ms, followed by 500ms of the fixation cross surrounded by an ellipse, and then the response screen is presented. During the response screen, an arrow surrounded by an ellipse is shown for 1000ms or until a response is made. The arrows were presented equally often on either the left or the right side of the fixation cross and pointed equally often to either the left or the right side of the screen. Across 200 experimental trials, four different stimulus conditions were presented in a pseudo-randomised order: congruent Go condition (62.5% of trials), incongruent Go condition (12.5), congruent No-go condition (12.5), congruent Stop condition (12.5%). Simon Task-associated trials were either Incongruent (e.g. arrow is presented left of the fixation cross but points towards the right) or Congruent (e.g. arrow is presented left of the fixation cross and points towards the left) Go trials. The colour of the ellipse around the response screen was used to either indicate No-go trials (blue ellipse as soon as arrows are presented) or Stop trials (ellipse turned blue after a specified Stop Signal Delay, SSD), of which both were Congruent and required no button press. The SSD in this design was fixed and each SSD appeared equally often throughout the experiment: 35ms, 85 ms, 135 ms, 185 ms, 225 ms. These SSDs were in line with the possible SSDs observed in the stepwise procedure employed in previous research on the hybrid response inhibition task (Gerhardt et al., 2021; Sebastian et al., 2013).

Participants were instructed to respond as quickly and accurately as possible to the direction the arrow points towards (e.g., if the arrow points to the right, perform a button press with the right index finger). Participants responded by pressing a keyboard button with either the right index finger (letter J on the keyboard for arrows pointing to the right) or their left index finger (letter F on the keyboard for arrows pointing to the left). When the arrow was surrounded by a blue ellipse (No-go trial), participants were instructed to withhold their button press, and participants were told that on some trials, the blue ellipse could appear after a delay (Stop trial). Before the experimental trials, participants performed 34 practice trials of the task components with feedback. The first practice block consisted of spatially congruent and incongruent Go stimuli and No-go trials. The second block of practice then additionally introduced the Stop Signal trials. This was followed by another set of 17 practice trials without feedback during which minimal performance criteria needed to be met (50 % accuracy; met by all participants).

Figure 3

Hybrid Response Inhibition Task (HRIT) Trial Schematic



Note: Shown is a schematic representation of HRIT trial types. The Simon task-related trials (interference inhibition) included Congruent and Incongruent go arrow and location pairings (e.g. Incongruent: an arrow presented to the right of the fixation cross that is pointed towards the left). The No-go (action withholding) and Stop conditions (action cancellation) consisted of congruent trials only and were indicated by a blue ellipse either appearing at the same time as the arrow (No-go trial) or after a set Stop Signal Delay (SSD; Stop Signal trial, ITI; Inter-Trial Interval). Participant must respond to the direction of the target arrow “F” for leftward facing, “J” for rightward facing in Go trials but not in No-go or Stop trials. For Stop Trials, the length of the blue ellipse lasted 1000ms – SSD duration, if SDD was 135ms the blue ellipse lasted 865ms. * Indicates ‘or until key press’.

Design

A between-subjects experimental design was employed for this experiment. The independent variable of video game play was measured by the VGEQ and used to quantify video game use and experience. The dependent variable was response inhibition, with the variables of interference resolution, action cancellation, and action withholding measured by the hybrid response inhibition task. The response time and proportion correct responses were recorded for congruent go, incongruent go, and no-go trials. Response time and proportion correct was recorded for congruent Go and incongruent Go trials as a measure of interference resolution. The difference between the incongruent Go and congruent Go was calculated as the interference effect (incongruent RT – congruent RT = interference effect). Action withholding was measured by the proportion of false alarms calculated for the no-go trials (ultimately, this measure was not computed due to performance being at ceiling for the entire sample). Action cancellation was measured by For stop trials, the proportion of successful stopping at 5 different stop timings was calculated. Using individual slope and intercept values produced on the proportion correct at each time point for each individual, the stop timing for 75% accuracy, termed stopping performance (SP) was calculated. Impulsivity was recorded by the SUPPS-P, and the measures of the subscales and the total score were included in the analysis as dependent variables to correlate with measures of response inhibition on the HRIT and measures of video game play from the VGEQ.

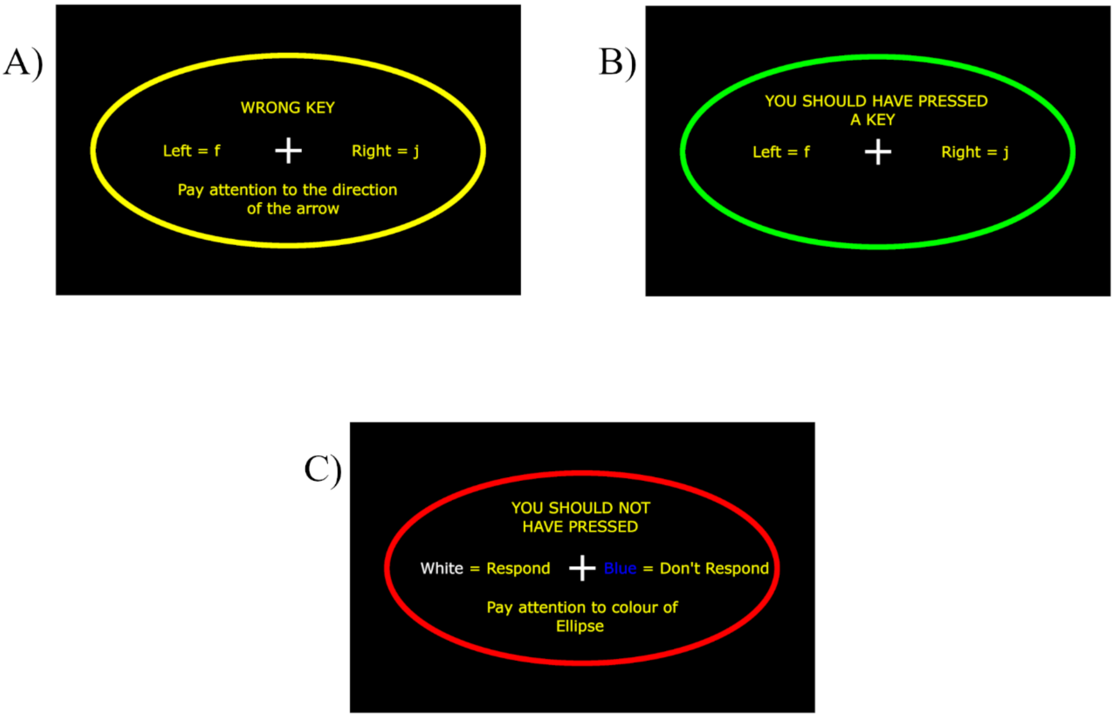
Procedure

Participants were recruited through a SONA participant pool advert in which they were given an overview of the experiment and directed to an experiment and questionnaire hosting website, Gorilla. There participants were presented with a full detailed information sheet and were asked to consent to take part in the study. After which pre-screening forms which did not form part of this experiment were completed. The participants were then directed to an introduction to the two questionnaires, informing the reader of the response requirements. The SUPPS-P was presented in Gorilla (gorilla.sc ; Anwyl-Irvine et al. (2020)), and Qualtrics (Qualtrics, 2023) hosted the VGEQ. Once the participants had completed these questionnaires, they were presented with an introduction to the HRIT. This detailed the practice and task requirements to the participant and gave an overview of how the second half of the HRIT would progress. Participants were told they were allowed breaks but to stay at the computer.

The HRIT has a duration of 9 minutes. Participants were instructed to respond as quickly and accurately as possible before undertaking the task or practice; this was also displayed in the instructions presented on the screen. Participants were instructed to fixate on the fixation cross in the centre of the screen throughout the task. For training, the HRIT was broken down into the components identified by Sebastian et al. (2013) to allow the participants to familiarise themselves with the response requirements of each component of response inhibition. For each practice task (and the HRIT itself), participants were presented with detailed instructions with no time limit. Participants were able to take as long as needed to understand the instructions. All the initial practice tasks were presented with detailed feedback, as demonstrated in Figure 4. If participants responded to No-go trials, timed out (or did not respond to Go trials), or responded in the wrong direction, they were presented with the relevant feedback required to understand the cause of their error.

Figure 4

Feedback Presented to Participants During Practice Trials



Note: A) Incorrect key press during congruent or incongruent trial. B) No key press during Go trials. C) Keypress during No-go or Stop trials. The Simon task practice presented A and B feedback. Go/No-go and HRIT practice presented A, B, and C feedback.

Participants were initially presented with instructions regarding the Simon effect practice task and subsequently completed 17 practice trials. Following this, the Go No-go were built into the Simon effect practice task, with the ellipse around the right or left-facing arrows now changing to blue to identify a No-go trial and white for Go trials. The ellipse would change colour at the same time as the arrows were displayed to participants. The participants completed 17 practice trials. Once these practice tasks were completed, participants progressed to the full HRIT task with a stop-signal trial condition included. In the stop-signal trials, the white ellipse would turn blue once the arrows had been presented after a predetermined delay period, 225, 185, 135, 85, and 35 msec. This was adapted from the paradigm reported by Anderson and Carnagey (2009); Gerhardt et al. (2021); Sebastian et al.

(2013). As previously, participants were presented with detailed instructions and feedback. Participants completed 17 trials before progressing to a final practice with the same response criteria without feedback, again 17 trials. Here, if participants did not score above 50% accuracy in Go trials, they were instructed to repeat the practice. After the second no-feedback practice, participants who still scored below 50% accuracy were removed from the study and were informed that this was not a reflection of their ability, but rather the demands of a difficult task (no participants were withdrawn based on this criteria).

Lastly, the participants progressed to the full HRIT task, with 200 trials. The task consisted of 5 blocks of 40 trials, with the order of Go, No-go, and stop-signal trials pseudorandomised to allow for habituation. Four different stimulus conditions were presented in a pseudo-randomised order: a congruent Go condition (62.5%; a left-pointing arrow in the left hemisphere of the ellipse and vice versa), an incongruent Go condition (12.5%; a right-pointing arrow in the left hemisphere of the ellipse and vice versa), a No-go condition(12.5%; a congruent condition with a change from a white ellipse to a blue ellipse on the onset of arrow presentation), and a stop condition (12.5%; a congruent condition with a change of white to blue ellipse after a delay): the predetermined delay period, 225, 185, 135, 85, and 35 msec.

Each trial followed the schematic presented in Figure 3 and described in the HRIT subsection of *Materials*. In brief, after the ITI a fixation cross appeared on the screen for 500ms followed by a white ellipse that circled the fixation cross for 500ms, after which a white arrow appeared inside the ellipse (for 1000ms or until a key was pressed) either on in the left or right hemisphere. Participants responded by pressing a keyboard button with either the right index finger (letter J on the keyboard for arrows pointing to the right) or their left index finger (letter F on the keyboard for arrows pointing to the left). When the arrow was surrounded by a blue ellipse (No-go trial), or the white ellipse turned blue after a delay (Stop trial, SSD), participants were required to withhold their button press. Once 200 trials were completed, participants had completed their participation, thanked, and debriefed. Once the task was completed, participants were provided with a full debrief and the contact information for the researcher and project supervisor.

Results

It was predicted that VGPs would outperform NVGPs on the HRIT in accuracy, response times (RT), and successful stopping. Additionally, it was predicted that there would be a relationship between impulsivity and VGP and NVGP status. Lastly, it was predicted that impulsivity would correlate with performance on measures of the HRIT.

Prior to analysis, the data were assessed for outliers to ensure that it conformed to the assumptions of parametric analysis. As previously reported, 15 participants were removed from the current sample due to incomplete datasets or taking longer than the maximum allowed participation time and being subsequently removed from the analysis. As part of the a priori restrictions placed on data regarding the identification of outliers, any participant with an average RT or accuracy that was more than 3 SD away from the group mean was deemed an outlier and removed from the analysis. Two NVGP participants were observed to have an average performance that was more than 3 SD from the mean on most variables of interest in this study and, as such, were removed from the analysis. The updated sample ($n = 70$; $M_{\text{age}} = 20.95$, $SD_{\text{age}} = 3.69$) included 19 males ($M_{\text{age}} = 19.89$, $SD_{\text{age}} = 5.83$) and 51 females ($M_{\text{age}} = 20.84$, $SD_{\text{age}} = 2.51$). No other participants or data points were identified as outliers.

VGP were identified as playing video games for more than 6 hours per week on average consistent for a period of 6 months, NVGP were identified as playing “once a month or less” on the VGEQ. In Table 1 the descriptive statistics for both VPG ($n = 20$, 15 males) and NVGP ($n = 50$, 4 males) can be observed.

Table 1

Descriptive statistics for Age of VGP and NVGP groups

		N	M	SD
Age	NVGP	50	20.78	2.59
	VGP	20	20.10	5.64
	Total	70	20.59	3.69

Note: Video Game Player (VGP), Non-Video Game Player (NVGP)

Regarding behavioural data, the No-go condition was excluded from the current analyses as the performance of participants was at ceiling (whole sample proportion correct $M = 1$, $SD = 0$). Moreover, while the proportion correct of congruent Go has been analysed, they, too, are approaching ceiling. In the whole sample proportion correct congruent go ($M = .98$, $SD = .03$) and for incongruent Go, more variation is observed ($M = .83$, $SD = .17$). Additionally, as a whole sample, each of these dependent variables were determined to be non-normally distributed by a Shapiro-Wilk test ($p<.001$). As such, while congruent go and incongruent go proportion correct will be included in subsequent analysis, a non-parametric approach will be taken to assess any significant differences. Response time was calculated for congruent Go and incongruent Go correct trials, and a measure of interference effect was computed by subtracting the average congruent reaction time from the incongruent reaction time for each participant individually.

Stop signal delays (SSD) were computed as a proportion correct for each of the time points (35ms, 85ms, 135ms, 185ms, 225ms), with correct being successfully cancelling an action to respond to stimuli in the stop signal trials. A linear regression of successful stopping was used to calculate the value of X (stop timing) when participant accuracy (proportion correct successful stopping) was at 75% as a summary statistic, using the formula [$x= (y -$

b)/m], where *m* is the slope and b is the y-intercept as indicated from the linear regression. See Appendix A for the calculation of 75% accuracy scores. The summary statistic, from here on termed Stopping Performance (SP), provides a clear picture of the performance of participants and their ability to successfully cancel an action compared to performance across the five levels of SSD. By computing a summary statistic based on performance in fixed SSD, it is possible to assess the individual level of performance by demand per participant akin to the stop signal reaction time calculated in an adaptive staircase procedure (Verbruggen et al., 2019; Verbruggen & Logan, 2008).

Behavioural - Accuracy

Presented in Table 2 are the descriptive statistics for performance on the HRIT for VGP, NVPG, and the sample as a whole. Of note is that the proportion of correct congruent and incongruent variables is titled congruent accuracy and incongruent accuracy, respectively. Violations of normality and homogeneity were observed, and as such, non-parametric analysis of longitudinal data (nparLD) is appropriate to examine the effects of VG status and congruence on accuracy in the HRIT. The nonparametric analysis has been conducted using R package nparLD (Noguchi et al., 2012) version 2.2 using RStudio (RStudio Team, 2022) version 2022.7.2.576 running R programming language version 4.2.1.

NparLD is based on nonparametric models of *Fx-LD-Fy*, where *x* and *y* represent the number of "whole plot" or between-subjects and "sub plot" or within-subjects factors, respectively (Brunner & Puri, 2001). Brunner and Puri (2001) focus on longitudinal data; however, there is no distinction between repeated measures data and longitudinal data in factorial designs without any assumption of the covariance matrix structure. This package includes a rank-based non-parametric method, which utilizes estimators of relative treatment effects. ANOVA-type statistics are provided for the examination of the hypotheses. As the data are transformed into ranks, conventional degrees of freedom based on the assumption of homoscedasticity cannot be produced. Box-type approximations can be applied to approximate the distribution of the ANOVA-type statistics.

As described in the appendix of Marmolejo-Ramos et al. (2013) and in their use of the nparLD package, and Brunner and Puri (2001) when developing the methods of nonparametric analysis for longitudinal data, for within-subject or sub-plot factors and their interactions, the numerator degrees of freedom are approximated while the denominator degrees of freedom are assumed to be infinity. The numerator and denominator degrees of freedom approximations can be applied to produce more accurate results for between-subject or whole-plot factors and their interactions. As such, the approximated degrees of freedom are given instead of the conventional degrees of freedom reported when conducting repeated measures ANOVA. However, when using a 2x2 design with no missing observations, nparLD will return approximated degrees of freedom for both within and between subjects' factors, as well as a p-value approximated by Student's t distribution using the approximated degrees of freedom.

An F1 LD f1 analysis was conducted with one whole plot factor of video game play status with two levels, VGP and NVGP, and one subplot factor of accuracy with two levels, congruent and incongruent trial type on the dependent variable of proportion correct. There was a significant main between-subjects effect of video game status $F\,(1, 36.10) = -2.87$, $p = .007$, a significant main within-subjects effect of congruency $F\,(1, 28.06) = 5.3$, $p < .001$; but the interaction of video game status and congruency was not statistically significant $F\,(1,28.06)=1.86$, $p=.073$).

Table 2

Descriptive Statistics for the HRIT

		N	M	SD
Congruent Accuracy	NVGP	50	.97	.04
	VGP	20	.99	.01
	Total	70	.98	.03
Incongruent Accuracy	NVGP	50	.81	.17
	VGP	20	.90	.13
	Total	70	.84	.17
Congruent RT	NVGP	50	506.08	60.08
	VGP	20	505.44	79.91
	Total	70	505.90	65.74
Incongruent RT	NVGP	50	647.40	70.50
	VGP	20	602.64	64.23
	Total	70	634.61	71.28
Congruency Cost	NVGP	50	141.31	50.22
	VGP	20	97.20	45.19
	Total	70	128.71	52.50
SP	NVGP	50	1.60	3.62
	VGP	20	2.68	3.18
	Total	70	1.91	3.51

Note: Hybrid Response Inhibition Task (HRIT); Video Game Player (VGP); Non-video Game Player (VGP); Response Time (RT); Stopping Performance (SP); Mean (M); Standard Deviation (SD).

The distribution of the difference between congruent and incongruent accuracy was asymmetric, as such a Wilcoxon Signed Rank test would not be appropriate and a sign test was conducted between the two levels of congruency accuracy, congruent (median (*m*)= .99, Interquartile Range (*IQR*)= .02) and incongruent (*m*= .88, *IQR*= .21), there was a significant difference between congruent and incongruent trials ($T = 11$, $Z = -5.21$, $p < .001$) where the proportion of correct response to incongruent trials (m=.88) was lower than congruent correct responses (m=.99). There was a significant effect of congruency on proportion correct responses, as anticipated by the HRIT paradigm.

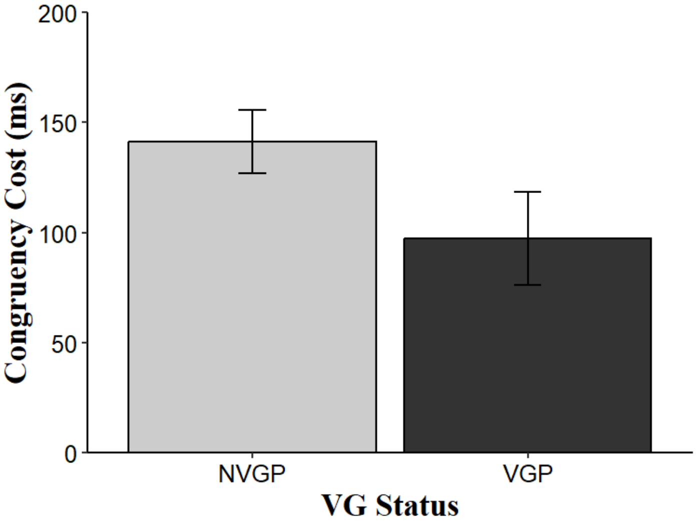
To investigate the effects of congruent and incongruent accuracy and measures of video game experience, a set of Spearman rank correlations were conducted to assess the relationship between SP and video game measures in VGP participants only. For congruent accuracy and subjective rating (*r* (18) =.08, *p*=.751), years of experience (*r* (18) =.01, *p*=.973). There was no significant relationship between measures of video game experience and performance on congruent trials. For incongruent accuracy and subjective rating (*r* (18) =.42, *p*=.068), years of experience (*r* (18) =.08, *p*=.735). There was no significant relationship between measures of video game experience and accuracy on incongruent trials.

Behavioural - Response Time

Response time for correct responses was recorded for congruent and incongruent trials, and the average response time of congruent was subtracted from incongruent to produce a measure of interference effects (congruency cost), which is reported in Table 2. On average, it appears that VGPs exhibit less congruency cost compared to their NVGP counterparts. To investigate the nature of the effect of VG status on congruency, an inferential analysis was conducted to examine the differences in congruency cost on response times in VGP and NVGP. Figure 5 displays a bar chart of the mean congruency cost by group.

Figure 5

Bar Chart of Mean Congruency Cost by VG Status



Note: Error bars represent 95% Confidence Interval. VG: Video Game; VGP: Video Game Players; NVGP: Non-Video Game Players; MS: Milliseconds

As can be observed, VGP has a lower congruency cost (incongruent response time minus congruent response time) than NVGP. A Levene's test was conducted (*F* (1,68) =1.51, *p* =.224), and the assumption of homogeneity of variances was met. However, the data were not normally distributed. As such, a Mann-Whitney U was conducted as a non-parametric alternative. The results of the analyses are that there is a significant difference between VGP (*m* =95.30, *IQR* =73.35) and NVGP (*m* = 141.62, *IQR* = 87.23) on congruency cost (*U* = 256, *Z* =-3.16, *p* =.002). These results suggest there is a difference between VGP and NVGP in the interference effect on response times between congruent and incongruent conditions.

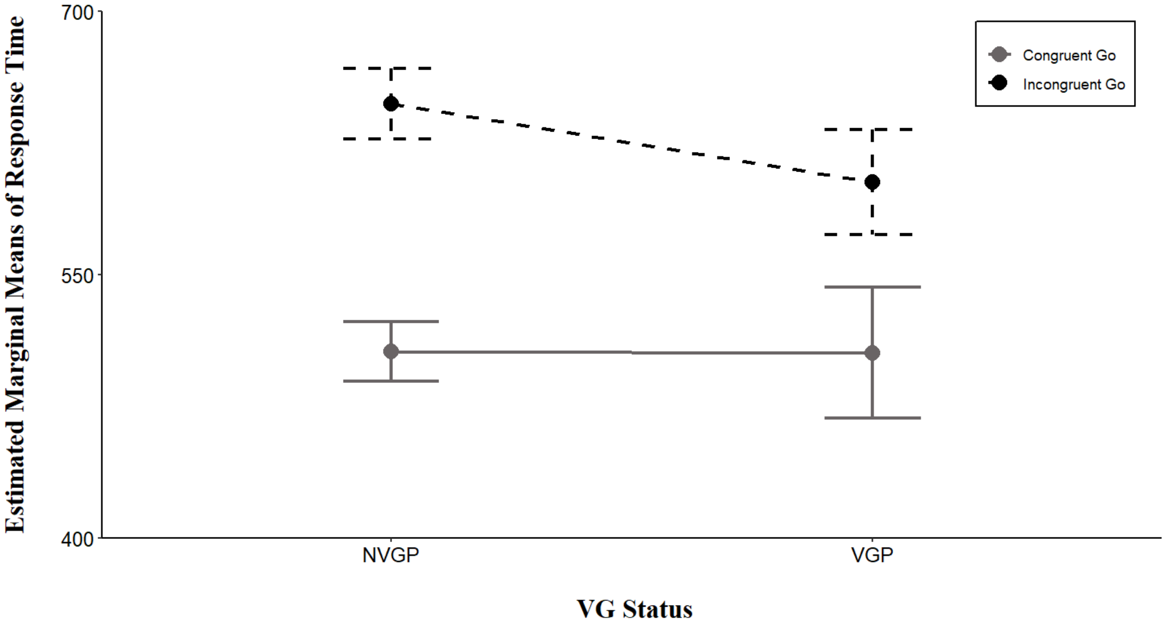
To investigate the nature of this difference further, the RT for each group was compared across the two levels of congruency. Table 2 presents the descriptive statistics for congruent and incongruent RT across the entire sample; congruent trials appear to have a shorter average response time than incongruent trials. A line graph representing the estimated marginal means for VGP and NVGP on congruent and incongruent response times is depicted in Figure 6. By VG status, VGP appears to be faster on average in responding to incongruent trials compared to NVGP, with comparable variability. On congruent trials, there appears to be little meaningful difference between the two groups in average response time, with more variability in the VGP group. To investigate this trend, a mixed 2x2 ANOVA was conducted with the between-subjects factor of VG status, with two levels (VGP and NVGP), and the within-subjects factor of congruency with two levels (congruent and incongruent) on average response time.

The between-subjects factor of VG status was not significant (*F* (1,68) = 1.86, *p*=.177, *ηp2*=.03), the within-subjects factor of congruency was significant (*F* (1,68) = 340.31, *p*<.001, *ηp2*=.83); likewise, the interaction between congruency and VG status was significant (*F* (1,68) = 11.64, *p*=.001, *ηp2*=.15). The interaction and main effect of congruency were analysed further, Bonferroni corrections were applied to alpha levels for four comparisons (.05/3=.0167).

To investigate the effect of congruency on reaction time, a paired samples t-test was conducted on incongruent (*M* = 634.61, *SD* = 71.28) and congruent (*M* = 505.90, *SD* = 65.74) response time, incongruent response time was observed to be significantly longer than congruent response time (*t* = 20.51, *df* = 69, *p* <.001, *d* = 2.45) with a mean difference of 128.71ms (*SD* difference of 52.50ms). This suggests there was a significant difference between congruent and incongruent response times, with incongruent trials prompting longer response times. This is in line with the expected effects of the HRIT and interference resolution and suggests a successful interference effect. Additionally, a line graph representing the estimated marginal means for VGP and NVGP on congruent and incongruent response times is depicted in Figure 6.

Figure 6

Estimated Marginal Means of Average Response Time by Congruency for VGP and NVGP



Note: Error bars represent a 95% confidence interval. VG: Video Game; VGP: Video Game Players; NVGP: Non-Video Game Players.

Additionally, an independent samples t-test was conducted on incongruent response time between NVGP (*M* = 647.40, *SD* = 70.50) and VGP (*M* = 602.64, *SD* = 64.23) and a significant difference was observed (*t* =2.46, *df* = 68, *p* = .016 two-tailed, *d* = .65) with a mean difference of 44.76ms (SD difference 6.27ms) with NVGP producing longer response times than VGP on incongruent trials, on average.

An independent samples t-test was conducted on congruent response time between NVGP (*M* = 506.08, *SD* = 60.08) and VGP (*M* = 505.44, *SD* = 79.91) and a non-significant difference was observed (*t* =.04, *df* = 68, *p* = .971 two-tailed, *d* = .01) with a mean difference of .65ms (SD difference 19.83ms) suggesting the difference between response times did not significantly differ between NVGP and VGP. These results suggest that the interaction observed in the 2x2 mixed ANOVA above is driven by the difference in VG status on incongruent trials, with VGP overcoming interference conflicts faster than their NVGP counterparts. However, there is no difference between groups in the congruent condition, suggesting that the advantage observed in the VGP condition is driven by response inhibition capabilities as opposed to an overall decreased response time across trial types.

VGP exhibits a reduced congruency cost, with significantly faster response times on incongruent trials but not congruently with NVGP. Likewise, VGP and NVGP significantly differ in their performance on Go trials, but this does not interact with congruency, while the main effect of congruency was significant. Taken together it can be confirmed that there is the typical finding of a significant effect of congruency has been produced by the HRIT, and there is a differential effect on incongruent trials dependent on VG status, but not congruent trials. This suggests that VGP are not simply faster or more accurate overall, but they exhibit improved interference resolution capabilities over their NVGP counterparts.

Lastly, Pearson correlations were conducted between measures of VG experience (subjective rating and year experience in VGP group only) congruent response time and incongruent response time. For congruent reaction time and measures of VG experience, there was no significant correlation with subjective experience (*r* (18) =-.20, *p* = .395) or years of experience (*r* (18) =.18, *p* = .460). Suggesting no relationship between performance on congruent trials and the observed video game play demographics.

For incongruent response time and measures of VG experience, there was no significant correlation with subjective experience (*r* (18) =-.26, *p* = .265) or years of experience (*r* (18) =.20, *p* = .393). Suggesting that, experience or rating did not significantly correlate with response time on incongruent trials,

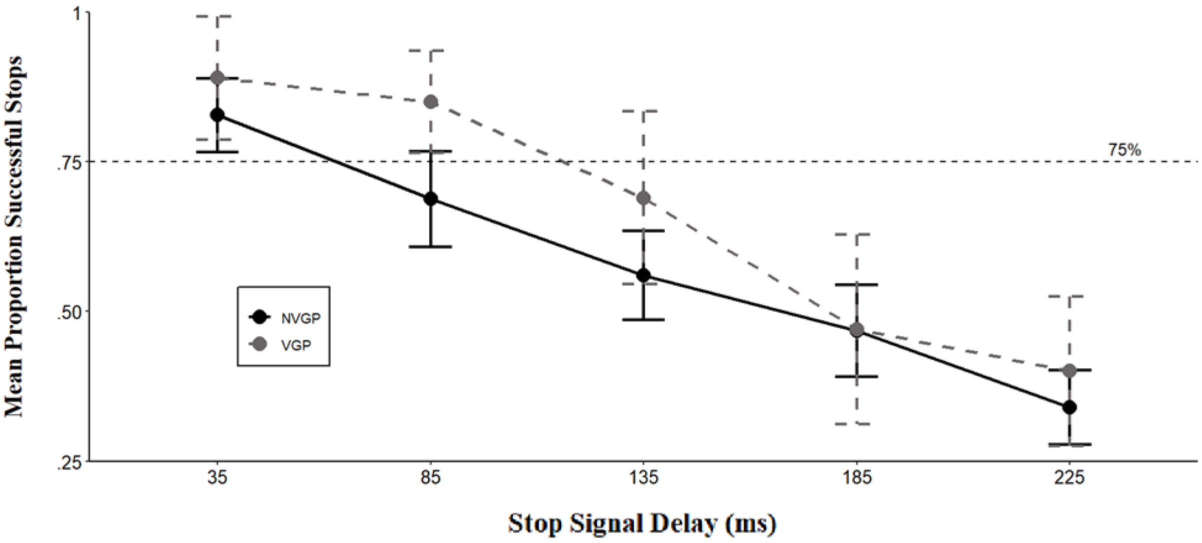
For congruency cost, Spearman's correlations were produced with measures of VG experience; there was no significant correlation with subjective experience (*r* (18) = -.01, *p* = .979) or years experience (*r* (18) = .03, *p* = .906). Suggesting no significant relationship between the amount of congruency cost and experience playing video games. Therefore, it appears that there is no relationship with the experience of video game play to drive the observed effect of VGP exhibiting reduced congruency cost and faster response on incongruent trials, simply frequent recent video game use.

Behavioural - Stop Delay

Figure 7 presents a visualisation of the summary statistic developed for the value of Stopping Performance (SP) at 75% accuracy where SP is the stop timing value. A larger value of SP is a larger stop value and represents better stopping performance. This is because a longer SP demonstrates a longer stop-signal delay (SSD) before performance falls below the 75% accuracy threshold. The ability to cancel an action at longer delays (i.e. longer into the action execution processes) is thought to be representative of more successful action cancellation. Descriptive statistics for the summary statistic can be observed in Table 2. In Figure 7, it can be observed that the VGP group, on average, had a longer stop timing than the NVGP. The NVGP appears to fall below 75% accuracy at around a 50ms stop delay, whereas the VGP group falls below 75% at 100ms (please refer to Appendix A for more data on the creation of the summary statistic). Appendix B presents the supplementary analyses for the original SSD. To investigate these trends further, the SP for the VGP and NVGP groups will be inferentially analysed. Prior to analysis, the data were checked to ensure that it conformed to parametric analysis. Upon inspection via the Wilk-Shapiro test of normality, the data violated the assumption of normal distribution (p <.05). As such, the non-parametric alternative to one-way ANOVA was used, a Kruskal-Walis was conducted between NVGP (m = 1.84, *IQR* = 2.23) and VGP (m = 2.48, *IQR* = 2.81). The differences between the rank totals were significant, H (1, n = 70) = 4.77, p = .029. Therefore, it can be concluded that the NVGP and VGP do significantly differ in their ability to stop, or action cancel, with VGP able to perform to a sufficient level until a longer stop delay, as opposed to the NVGP condition which falls below this threshold at a shorter stop delay demonstrating a shorter SP.

To analyse the results in SP further, Spearman rank correlations were conducted to assess the relationship between the summary static and video game measures in VGP participants only: subjective rating (*r*(18)=-.12, *p*=.615) and years of experience (r(18)=-.05, p=.839). As such, no significant relationship between VG experience or subject perceived skill and ability to stop effectively was observed.

Figure 7
Proportion of Successful Stopping at Stop Signal Delay by Video Game (VG) Play Status



Note: Error bars displayed represent a 95% confidence interval. VGP: Video Game Player; NVGP: Non-Video Game Player.

SUPPS-P & Video Game Play

Descriptive Statistics are presented in Table 3 for the measures of trait impulsivity obtained from the SUPPS-P. Namely, lack of premeditation, lack of perseverance, sensation seeking, positive urgency, and negative urgency. It can be observed that NVGP appear to report higher levels of negative urgency, positive urgency, and lack of perseverance. Meanwhile, VGP reports higher levels of lack of premeditation and sensation seeking, with the total scores largely equal. Prior to analysis, it was identified that SUPPS-P total score, Positive Urgency scores, and Lack of Premeditation were not normally distributed in addition to the previously identified variables of incongruent accuracy, congruent accuracy, and SP, which measure 75% stop timing accuracy. As such, they will be correlated using Spearman rank correlation. Sensation Seeking, Negative Urgency, Lack of Perseverance, incongruent response time, congruent response time, years of video game experience, and subjective rating of video game skill will be correlated parametrically with Pearson correlation (unless correlated with a variable that does not conform with parametric assumptions.

Table 3

Descriptive Statistic of Impulsivity Traits

	Video Game Play Status			
	NVGP		VGP	
	M	SD	M	SD
Lack of Perseverance	2.01	.48	1.94	.44
Lack of Premeditation	1.95	.47	2.05	.64
Negative Urgency	2.45	.63	2.07	.66
Positive Urgency	2.00	.52	1.86	.77
Sensation Seeking	2.51	.61	2.72	.73
SUPPS-P Total	8.7	1.2	8.5	1.6

To first investigate the hypothesis of the relationship between VG status and impulsivity, point biserial correlations were conducted on VG status and SUPPS-P subscales. There was a significant negative correlation between VG status and negative urgency (pbr = -.26, p =.031), suggesting that NVGP is associated with higher negative urgency and VGP with less. There were no other significant correlations.

To further investigate the effects of video game experience and subjective rating of skill, Pearson correlations were produced for the VGP group only on years of experience and sensation seeking (*r*= -.17,*p*=.478), negative urgency (*r*=.07,*p*=.769), and lack of perseverance (*r*= -.25,*p*=.29). Additionally, Spearman correlations were conducted between years of experience and lack of premeditation (*r*= -.19, *p*=.413), positive urgency (*r*=-.23, p=.338) ¸and SUPPS-P total scores (*r*=-.31, p=.185).

Likewise, Pearson correlations were conducted for subjective rating of skill and sensation seeking (*r*=-.15, *p*=.541), negative urgency (*r*=.13, *p*=.574), and lack of perseverance (*r*= -.26, p=.275). Finally, Spearman correlations were conducted between years of experience and lack of premeditation (*r*=-.27, *p*=.258), positive urgency (*r*=.05, *p*=.835) and SUPPS-P total scores (*r*= -.24, p=.319). As such, there were no significant correlations between measures of VG experience or skill and impulsivity traits, with the exclusion of allocation to VGP being associated with a higher rating of negative urgency and NVGP associated with lower scores on said trait.

SUPPS-P & HRIT

To test the hypothesis that response inhibition performance would be related to trait impulsivity, correlations were produced between response to the SUPPS-P and traits of impulsivity observed, and measures of performance on the HRIT, including congruent and incongruent accuracy and response time, as well as stop signal performance. As detailed above, Pearson and Spearman's correlations were conducted based on the results of assumption checks of each variable. Pearson correlations are presented in Table 4, and Spearman correlations, including all variables, are included in Table 5. Of note in Table 4 is the significant moderate positive correlation between negative urgency, the tendency to act impulsively due to negative affect, and incongruent response time (*r*= .34, *p* = .004). The correlations presented in Table 5 show a trend between incongruent accuracy and negative urgency (*r*= -.40, *p* <.001), and incongruent accuracy and positive urgency (*r* = -.26, *p* = .032), the tendency to act impulsively as a result of positive affect, with a moderate to weak significant negative correlation with incongruent accuracy. Taken together with the weak significant positive correlation between positive urgency and incongruent response time (*r* = .26, *p* = .028), it suggests that as the urgency of any kind increases, incongruent performance worsens, longer response times and less accurate responding. Meanwhile, no equivalent relationships were observed on congruent measures. This suggests that higher trait urgency is associated with worse interference resolution.

Positive urgency and congruency cost have a significant weak positive correlation (*r* = .30, *p*= .012), suggesting that higher levels of positive urgency are associated with higher congruency cost; positive urgency is noted as being the trait of acting more rashly in response to positive emotions is related to worse interference resolution. Lastly, the total mean score on the SUPPS-P, a measure of overall impulsivity, has a significant weak negative correlation with incongruent accuracy (*r* = -.34, *p* = .004), meaning that higher levels of impulsivity are related to decreased accuracy on incongruent trials.

Table 4

Whole Sample Pearson Correlations Impulsivity and Behavioural Variables

		Incongruent RT	Congruent RT
Sensation Seeking	*R*	-.230	-.084
	p	.056	.488
Negative Urgency	*R*	.342**	.211
	p	.004	.080
Lack of Perseverance	*R*	.018	-.107
	p	.882	.376

**. Correlation is significant at the 0.01 level (2-tailed).

Table 5

Whole Sample Spearman Correlations Impulsivity and Behavioural Variables

			Congruent Accuracy	Incongruent Accuracy	Incongruent RT	Congruent RT	Congruency Cost	SP
Spearman's Rho	Lack of Perseverance	*R*	-.044	-.073	.011	-.137	.161	-.081
		p	.720	.547	.926	.257	.183	.505
	Lack of Premeditation	*R*	-.106	-.131	.140	.007	.073	-.004
		p	.382	.281	.249	.951	.548	.972
	Negative Urgency	*R*	-.147	-.404	.379	.169	.197	-.088
		p	.226	<.001	.001	.162	.102	.469
	Positive Urgency	*R*	.020	-.257	.262	.022	.299	-.177
		p	.871	.032	.028	.855	.012	.143
	Sensation Seeking	*R*	-.011	.085	-.188	-.033	-.172	-.073
		p	.925	.482	.119	.788	.155	.549
	SUPPSP Total	*R*	-.126	-.340	.202	-.010	.232	-.198
		p	.299	.004	.093	.931	.053	.101

Correlation is significant at the 0.01 level (2-tailed). **
Correlation is significant at the 0.05 level (2-tailed). *

The same Spearman correlations were produced for NVGP and VGP groups separately. In the NVGP, there was a weak significant negative correlation between negative urgency and incongruent accuracy ($r = -.29, p = .041$) and SUPPS-P total and incongruent accuracy ($r = -.29, p = .041$). For the VGP group, there was a significant moderate negative correlation between negative urgency and incongruent accuracy ($r = -.57, p = .008$). In VGP and NVGP no impulsivity traits significantly correlated with SP, congruent RT, incongruent RT, or interference effect/congruency cost. Suggesting the relationship observed in the whole sample is maintained, at least regarding incongruent accuracy and negative urgency when observing each group individually.

Discussion

The present study aimed to investigate the effects of video game play on response inhibition as part of a larger investigation into the effects of video game play on executive functions. Additionally, the current study aimed to investigate the relationship of impulsivity with response inhibition and video game play. By utilising and modulating a novel paradigm which incorporates three well-established response inhibition assessments: Go No-Go, Simon effect, and stop signal task, the Hybrid Response Inhibition Task (HRIT) allowed for the assessment of three core response inhibition functions. However, while interference inhibition, action cancellation, and action withholding are all assessed by the HRIT, only interference resolution and action cancellation were analysed in the current results. This is due to performance on No-Go trials being at the ceiling for the current sample, which prevents the construction of a No-Go proportion correct or false alarm variable and a measure of action withholding.

Regarding interference resolution, the findings support the ability of the HRIT to demonstrate a congruency effect, with significantly different performance on congruent and incongruent conditions in regard to both the proportion of correct responses and response time for correct responses. These findings partially replicate the results presented by Gerhardt et al. (2021) and, in particular, Sebastian et al. (2013), validating the HRIT. It was observed that there were low error rates in incongruent trials in both the HRIT and Simon task (<2.0%). The present study did not replicate this trend, as there were significant errors in incongruent trials (19-10%). Moreover, Sebastian et al. (2013) report low error rates in all tasks (HRIT and the Simon task, Go No-Go, and Stop sign administered within the same testing session as part of validation). Likewise, findings here demonstrate low error rates on congruent trials (1-3%). However, the authors produced commission error rates based on No-go and Stop errors in their calculations. The present study treated these two variables separately in favour of hits, misses, correct rejection, and false alarms (of which only hits and misses, i.e. proportion correct, could be calculated). This difference in analytical approach disallows the opportunity to compare performance solely on No-Go trials. Additionally, a staircase procedure was used for the calculation of SSRT in Sebastian et al. (2013), while the present study opted for set stop signal delay (SSD) and the production of a summary statistic of SP where performance falls below a 75% threshold as SSD increases. Yet, the findings converge on similar trends, an interference effect as a result of congruency, and a manipulation of action cancellation. More data is needed to assess the ability of this task to measure action withholding, as there is limited evidence of its ability to produce a stimulus-response effect with regard to withholding a prepotent response.

The independent variable of video game play status demonstrated a clear trend: VGP outperformed their NVGP counterparts in incongruent conditions. In terms of reaction times, there is a clear delineation in performance whereby VGP exceed that of NVGP. Moreover, this effect is not observed in congruent trials, suggesting that this is not the result of a general improvement in motor or processing speed. Additionally, analysis of congruency cost (also termed interference effect), found VGP to have significantly reduced congruency cost compared to NVGP. Findings also suggest that VGP have a better SP than their NVGP counterparts; that is, they are able to effectively undertake action cancellation at longer stop delay periods, whereas NVGP demonstrates a short SP. VGP SP did not correlate with years of video game play experience or participant subjective rating of video game play skill. This suggests that the relationship is more exclusively defined by the frequency of video game play in the past 6 months. This reflects the trends observed in congruent and incongruent variables as well as congruency cost where accuracy or response time was not significantly correlated with measures of video game play years of experience or subjective rating of video game skill. This again suggests that the main driver of this effect is the recent (within the last

6 months) frequency of video game play, and it is not significantly related to the number of years that an individual has played video games.

Previous research into interference effects, particularly nonverbal interference tasks and video game play, has observed similar findings from both observational group-based comparisons and training methodologies (Hutchinson et al., 2016; Latham et al., 2018; Paap et al., 2020). Previous investigations using group-based comparisons of VGP and NVGP participants have found that VGP outperform NVGP in Simon effect tasks. Latham et al. (2018) observed that experienced-VGP (termed as a result of playing video games prior to the age of ten) was faster in incongruent conditions. Specifically, experienced-VGP could resolve the stimulus-response conflict faster than NVGP, but only when the conflict arose on the right-side of space, not the left. The present study found a reduced conflict effect, as observed by Latham et al. (2018), but did not investigate the potential for a left/right bias in responding. Future investigations utilising the HRIT could increase the number of trials to allow for the power to produce these comparisons, as 200 trials with 12.5% of them incongruent Go (Simon effect) split 6.5% between each direction limits the possibility of making meaningful claims on this matter. Moreover, in the present study, there was no observable significant relationship between years of video game play experience and measures of response inhibition performance, suggesting that the effects observed by Latham et al. (2019) may not be a result of "experience" VGP but simply *video game players*.

Evidence from training paradigms has suggested a causal link between video game play and reduced congruency cost on a Simon effect task (Hutchinson et al., 2016). Training on a first-person shooter led to a reduction in response time and a reduced cost of stimulus-response incompatibility, suggesting video game play leads to plastic changes in inhibitory control systems and improves goal-directed action. Likewise, the current findings follow this trend with reduced congruency cost to response time in the VGP condition but not NVGP.

The reduced congruency cost expands observed in this study expands upon previous findings as participants in the current sample reported a range of video game genres, undermining the potential suggestion that the difference between pre-and-post training performance is genre specific. Taken together, it can be suggested that the improved performance in VGPs is not simply the result of improved reaction time or quicker responding, but rapid resolving stimulus-response conflicts. Video game use may have the potential to improve response selection during planning and execution of goal directed behaviour.

However, there continues to be discrepancies between particular nonverbal interference tasks and the effect of video game use. The spatial Stroop task and flanker tasks within the nonverbal interference task category and have been utilised in interference effect paradigms assessing the performance of video game players (Dye et al., 2009a; Paap et al., 2020; Unsworth et al., 2015). Perhaps the most influential video game experience findings in the domain of nonverbal interference effect is that of Dye et al. (2009a) utilising the attention network test (ANT) developed by Fan et al. (2002). The ANT is a computerised testing measure designed to assess the three networks of attention, orienting, alerting, and executive control as identified by Posner and Petersen (1990). The ANT includes flankers designed to provide a measure of executive control (via nonverbal interference effects) and Dye et al. (2009a) observed that VGP responded faster than and as accurately as NVGP while also demonstrating larger flanker effects. Flanker tasks are thought to be a measure of resistance to distracter interference within the nonverbal interference task paradigms (Paap et al., 2020) with the flanker compatibility effect being the difference between congruent and incongruent flanker condition response time (Sanders & Lamers, 2002). In Dye et al. (2009a) the flanker compatibility effect was calculated on normalised response times, and incongruent flankers' effects were more pronounced than congruent flankers. As previously stated, VGP were faster than NVGP in incongruent trials and as accurate but exhibited a greater flanker interference effect.

The interpretation of findings from Dye et al. (2009a) was that VGP are able to distribute their attentional resources across a wider visual field and processes flankers and the central target. Yet, traditionally, processing of congruent flankers provides limited benefit, and processing of incongruent flankers incurs a heavy stimulus-response cost (Sanders & Lamers, 2002). This was taken as an enhanced ability in VGPs, and that VGP perform even better in incompatible circumstances, where the additional executive resources allow for processing of incongruent flankers and still outperform NVGP. While the findings of the current study did not observe an increased congruency effect in VGP relevant to NVGP, in fact, the opposite was observed; it was found that VGP had reduced congruency cost and that this effect was driven by faster responding in incongruent conditions. There was a significant main effect of video game player status in accuracy, but this did not interact with congruency. Moreover, It is possible that we observed a more direct improvement in response inhibition and executive function more generally due to the demands of the task. VGP were able to be faster on incongruent trials compared to their counterparts while maintaining accuracy across levels of congruency, suggesting no speed-accuracy trade-off.

Previous research by Green and Bavelier (2007) and Bavelier, Achtman, et al. (2012) has found that there needs to be sufficient cognitive load placed upon VGP for their additional attentional to be apparent. It is possible that the additional demands placed upon participants by the HRIT were sufficient cognitive load to reflect this finding. Participants in both groups may have biased goal-directed behaviour towards successfully undertaking the Go No-go component, or action cancellation, as observed by their perfect No-go responding, and the additional executive resources available to VGP “spilled over” to the incongruent conditions and resolving stimulus response conflicts. To investigate this potential account further, measurements of cognitive load for the HRIT and ANT should be taken using a measure such as the NASA task load index (NASA TLX) (Hart, 2016; Hart & Staveland, 1988), comparing the demands placed upon participants by the respective tasks should allow for a greater understanding of the benefits of cognitive demand in VGP for the recruitment of additional attentional resources.

Unsworth et al. (2015) treated video gameplay as a continuous variable and was unable to find evidence that video gameplay predicted the flanker effect or spatial Stroop task performance. Employing a similar design to Unsworth et al. (2015), Paap et al. (2020) investigated the effect of the frequency of video game use as a continuous variable on a composite interference score constructed from the interference effects in the Simon task, the spatial Stroop, and the vertical Stroop and found a significant negative correlation. The negative correlation observed suggests that as video game play became more frequent in the sample, the effects of interference became smaller.

However, once impulsivity, sex, IQ, and self-control were entered into the model the correlation became not significant. Likewise, the frequency of video game use did not significantly predict interference effect scores in any of the individual tasks. While the present study did not treat video game play as a continuous variable, the present results likewise did not find a significant correlation between measures of VG experience and interference effects. This suggests that there may be a potential confounding variable driving the observed effects in VGP and nonverbal interference tasks, particularly stimulus-response compatibility tasks. For instance, the belief of expertise alone is sufficient to improve performance on tasks assessing visual attention (Langer et al., 2010), Boot et al. (2011) provide a compelling review of the dangers of cross-sectional research in video game effects and attention methodologies.

Contrary to this point, blind recruitment has been employed in a number of studies and have still observed the typical attentional benefit of VGPs versus NVPG (Clark et al., 2011; Dye & Bavelier, 2010; Dye et al., 2009a), albeit not consistently (Gobet et al., 2014). Training studies such as Hutchinson et al. (2016) and Wang et al. (2014) provide a direct causal link of improved stimulus-response conflict resolution. An argument can be made that participants in training methodologies may expect to perform better on measures related to their training, results of experiments investigating this prediction have not found support in the data obtained (Boot et al., 2011). Participants have improved in measures they did not expect to improve in. Taken together, the limited potential for recruitment strategy to impact results or for demand characteristics in the form of expected expertise. Moreover, subjective rating of video game skill, a measure of a VGP's personal perceived expertise, did not significantly correlate with any measure of performance. NVGP did not produce such a measure, as it is assumed that their subjective rating of skill would be essentially 0 as they do not play video games. As such, it is unlikely that confounding effects of expected expertise could produce the differences observed between VGP and NVGP, as observed in visual attention tasks by Langer et al. (2020).

The potential for cognitive load to be a critical factor in utilising the additional executive function resources in VGP (Green & Bavelier, 2007) returns here again as the simple single-component tasks to assess individual facets of response inhibition, such as those in Paap et al. (2020), fail to observe improved performance consistently. Yet the current findings here, as well as Dye et al. (2009a) using the ANT suggest that tasks with multiple goal demands are sufficiently demanding. However, there is still limited evidence to support this hypothesis, as experiments involving hybrid response inhibition tasks are limited, and even fewer employ a cross-sectional design comparing VGP and NVGP. Deleuze et al. (2017) employed a hybrid response inhibition paradigm utilising Go No-go and stop-signal conditions; however, comparisons were not made to NVGP, only different players' video game genres.

It is possible that training paradigms such as Hutchinson et al. (2016) and Wang et al. (2014) are able to report significant improvements in VGP condition as the limited training is sufficient to provide improved executive functioning to outperform NVGPs in low and relatively normal cognitive loads. Particularly in tasks designed to measure one facet of response inhibition. Yet, when (to use the terminology from Latham et al.) experience-VGPs undertake tasks, additional cognitive load is required to observe the additional executive resources, else performance is NVGP equivalent. It should be reiterated that in the current finding, years of video game play experience did not correlate with performance on response inhibition measures. nonetheless, a replication with a larger sample size, larger age range (the current study being predominately student population age range), and a more varied range of video game use history may be able to explore this hypothesis further. Further support for this hypothesis comes from the older age group in Wang et al. (2014), where no effect of training was observed in a flanker task, with the flanker effect remaining stable pre and post-training, with the prediction for this lack of effect being insufficient training time, suggesting simply that more training results in a compounding effect on executive function. In turn, this would suggest a positive relationship between the more cognitively demanding the task, the better VGP performs due to a surplus of executive resources compared to NVGP.

Regarding the activation-suppression hypothesis of selective response inhibition, it is hypothesised that faster responses will exhibit less of an interference effect, while slower responses are more impacted by congruency, suggesting a compounding effect (Ridderinkhof et al., 2004). It is possible that VGP is faster in responding more regardless of congruency initially and is spared the compounding congruency effects. This then presented as reduced interference effects, faster responding on incongruent trials, but the same level of stimulus-response compatibility benefit experienced by NVGP. Alternatively, there is the potential that the reduced interference effect is a result of the observed improved top-down attentional control, where VGP exhibit flexible control over stimulus-drive attention (Cain et al., 2014) utilising useful congruent stimulus to guide responses and overriding the saliency from incongruent stimuli.

The spatial Stroop, which can be argued the present HRIT paradigm draws upon, places minimal demands on the participant as the symbolic cues tell the participant the required response direction, unlike traditional Simon tasks (Diamond, 2013). Diamond (2013) posits that the demands of tasks accessing executive function must be continually increased or there is difficulty in realising the difference between the executive function between groups, with a potential explanation that a task in which the level of difficulty remains stable may prove boring for groups which are not using their entire executive function capabilities. Moreover, typically, differences in executive functions tasks between groups are only observed in the most demanding task and task conditions (Diamond et al., 2007). This could also explain the ceiling effect in No-go conditions and the potential for a masked difference due to task difficulty. Perhaps, increasing difficulty by increasing prepotency of response (increasing Go trials relative to No-go and stop), reducing the reaction time deadline, or increasing the event rate (Benikos et al., 2013; Lindqvist & Thorell, 2008; Raymaekers et al., 2004; Wessel, 2018), would allow a difference to be observed.

Previous research has not always demonstrated improved inhibitory control as measured by the stop signal task in VGP observed in the current findings. The frequency of video game use has been observed to have a negative linear relationship with stop signal reaction time (SSRT), suggesting worsening inhibitory control as time spent playing video games per week on average increases (Irvine et al., 2013). While Irvine et al. (2013) recruited problematic VGP with minimum average hours per week of video game play of more than 20 hours, the current findings observed an opposite effect, that frequent video game play in the past 6 months is associated with better stopping performance and improved inhibitory control. Steenbergen et al. (2015) adopted a stop-change paradigm, which measures the ability to cancel a prepared response as well as change to a new response after stopping. They found there was no difference in response inhibition and that stopping performance remained the same between NVGP and VGP. However, VGP did outperform NVGP in action cascading efficiency and were faster in swapping to a new response. Concerning the independent race model of stop signal task performance (Verbruggen & Logan, 2008), while SSRT was not utilised in the current study in favour of the summary measure of SP, insights from the race model can still be applied. To achieve optimum performance, the participant must balance the competing demands of the two processes, stopping and going. The current study observed a difference in this optimum performance, and Steenbergen et al. (2015) did not.

However, the additional cognitive demand placed on the participants by the inclusion of a *change* condition in Steenbergen et al. (2015) may have resulted in an adapted biasing of the competing demands. Hypothetically, sufficient minimal resources were allocated to stopping and going processes to enable relatively acceptable performance. In contrast, additional executive function resources were allocated to the change processes, resulting in improved performance relative to NVGP. This may demonstrate an improved ability of VGP to determine the expected value of control based on the current demands of the task and to update response strategies and allocation of control process resources in order to perform at their optimum level (Shenhav et al., 2013). Future research should investigate the anterior cingulate cortex (ACC) in a cross-section VGP and NVGP paradigm to implicate the potential difference in the expected value of control functioning, as the ACC is hypothesised to be the locus of the expected value of control cognitions. According to Shenhav et al.

(2013), the expected value of control theory is the role of the ACC in undertaking a cost-benefit analysis of exerting control in a situation. In evaluating and optimising the allocation of executive control resources, task performance is maximised while cognitive effort is minimised, ensuring efficiency of executive functioning (Shenhav et al., 2013).

Regarding the observed relationships between video game play and impulsivity, whereby there were significant moderate negative correlations between urgency (both positive and negative) and incongruent accuracy and a significant yet weak positive correlation between positive urgency and incongruent response time. Similarly, there was a positive correlation between response time congruency cost and positive urgency, although this is potentially due to the positive correlation between positive urgency and incongruent response time. These findings suggest that incongruent performance worsens as the urgency of any kind increases, correlated with longer response times and less accurate responses. Meanwhile, no equivalent relationships were observed on congruent measures. This suggests that higher trait urgency is associated with poor interference resolution. Additionally, the total score on the SUPPS-P, a measure of overall impulsivity, has a significant weak negative correlation with incongruent accuracy, meaning that higher levels of impulsivity are related to decreased accuracy on incongruent trials. Irvine et al. (2013) observed that VGP, pathological at least (>20 hours per week of video game play), are more impulsive than NVGP as measured by the total UPPS-P score, current findings could not support the hypothesis that VGP are more impulsive than NVGP, where no significant relationship between group membership and scores on any measure of impulsivity except negative urgency. Negative urgency was negatively correlated with VG membership suggesting that NVGP are observed as having higher negative urgency scores and VGP lower. Nuyens et al. (2016) likewise employed SUPPS-P to measure impulsivity in VGP and found no significant relationships. However, there was a weak, not significant trend between negative urgency and hours per week of video game play. The tendency for VGP to react rashly is an important facet of understanding the nature of response inhibition performance relative to NVGP and one that warrants further exploration.

Previous research has suggested that higher levels of self-reported impulsivity is associated with increased congruency cost and longer duration to overcome stimulus response incompatibility in nonverbal interference tasks (Enticott et al., 2006), and higher self-reported impulsivity is correlated with worse action cancellation on a stop signal paradigm (Portugal et al., 2018) in particular negative urgency from the UPPS-P has been observed to positively predict SST, with higher urgency resulting in worse stopping performance (Wilbertz et al., 2014). While the current study was unable to replicate both of these effects, it is observed that negative urgency appears related to congruency cost and increased interference effect. There is, however, research suggesting that there is no correlation between impulsivity scores and response inhibition (Aichert et al., 2012; Reynolds et al., 2006). These inconsistent findings underline the need for more research in this area, in particular tasks assessing response inhibition. As failures in response inhibition is hypothesised to predict behavioural impulsivity, tasks typically used to assess response inhibition fail to reliably demonstrate the relationship between poor task performance and trait impulsivity (Paap et al., 2020). Our findings to suggest that urgency is related to interference resolution performance, and to the best of the authors knowledge is the first to do so in a hybrid response inhibition paradigm. van Eijk et al. (2015) approached the same trends observed in the current study in measures of stop performance and interference effects but failed to find significance. Future replications should employ additional measures of self-reported impulsivity, such as the Barratt Impulsiveness Scale (Enticott et al., 2006) with hybrid response inhibition paradigms to explore this trend further.

Lastly, in the NVGP participants, there was a weak, significant negative correlation between negative urgency and incongruent accuracy and SUPPS-P total and incongruent accuracy. For the VGP group, there was a significant moderate negative correlation between negative urgency and incongruent accuracy. Suggesting that regardless of video game play status, negative urgency is related to a larger stimulus-response incompatibility effect in nonverbal interference tasks. Ding et al. (2014) compared participants with internet gaming disorder (IGD) and healthy controls on a Go No-Go task. They found worse accuracy but faster responding in No-Go trials in IGD compared to NVGP; importantly, they observed larger BOLD responses in the dorsolateral prefrontal cortex (DLPFC) and ACC in No-Go trials, which correlated positively with impulsivity scores and that higher impulsivity scores correlated with more severe IGD. These results suggest that there is an underlying relationship between video game play and interference resolution performance that is associated with concurrent impulsivity. Further studies are needed to elucidate this trend and assess the involvement of urgency and action cancellation in this pattern of findings.

The current study may have been limited in its ability to fully explore the effects of the video game play genre and reliably provide support for patterns of results observed in genre research due to an imbalance in VGP and NVGP groups. While this cross-sectional study sampling issue is not uncommon in this area of research (Boot et al., 2011) every effort should be made to rectify this issue in future samples.

To conclude, frequent video gameplay is associated with improved interference resolution and action cancellation compared to infrequent or no video gameplay. There is no effect of the frequency of video game play on the ability to withhold a prepotent response, as this measure observed a clear ceiling effect across both groups. However, this effect is hypothesised to be masked by the need for increased cognitive load to observe the benefit of additional executive function resources. Video game play is related to larger negative urgency scores. Positive and negative urgency is correlated with worse response interference resolution, although this trend is true for both VGP and NVGP. Further investigations are indeed to identify the role of cognitive load in observing the executive function benefit of VGP (Chapter 4).

Additionally, the role of the ACC in the expected value of control in response inhibition is an area warranting further exploration. The frontal networks responsible for response inhibition performance, as observed by Sebastian et al. (2013) and Zhang et al. (2017), are also worthy of further investigation to identify the regions in this network that are manipulated by recent frequent video game use and responsible for the observed benefit in the VGP group. This will be the aim of the next study, to investigate the impact of video game play on neurotransmitters in the fronto-parietal network, as recent research has shown the importance of the relationship between the concentration of γ-aminobutyric acid (GABA) and glutamate/ glutamine in this network on response inhibition (Weidacker et al., 2020). Using the same HRIT, designed to assess neural regions active during the three major components of response inhibition, will also allow for the opportunity to replicate the pattern of results obtained here.

Chapter 3: Magnetic Resonance Spectroscopy: Video Game Use and Response Inhibition

Response inhibition and interference task performance are assumed to depend on optimally balancing excitatory and inhibitory neurometabolites (Krause et al., 2013; Weidacker et al., 2022). γ-aminobutyric acid (GABA) is a well-known neuro-metabolite and is involved in maintaining optimal behavioural performance. GABA is the main inhibitory neurochemical in the human brain (Li et al., 2022). In contrast, Glutamate is a major excitatory transmitter in the brain (Zhou & Danbolt, 2014). In healthy functioning neurotypical individuals, the mechanism of efficient information transfer in neural circuits relies upon a balance of cortical inhibition and excitation (Haider et al., 2006). An interplay between the inhibitory GABAergic interneurons and the excitatory Glutamatergic synapses achieves inhibitory and excitation balance (Grent-'t-Jong et al., 2022; Whittington et al., 1995).

Numerous studies have linked magnetic resonance spectroscopy (MRS) assessed GABA levels at rest, referred to as baseline GABA levels, to performance on various task types (Boy et al., 2010; Dyke et al., 2017; Hermans et al., 2018; Li et al., 2022; Prena et al., 2020; Silveri et al., 2013; Weidacker et al., 2020; Weidacker et al., 2022; Yoon et al., 2016). MRS is a technique used to study the endogenous metabolites in the human brain non-invasively in vivo. This technique has traditionally been used in a clinical setting (Barker et al., 1994; Weinberg et al., 2021; Yurista et al., 2022), but there has been an increase in research applications of MRS to understand the neurochemical determinants of behaviour, including the neurometabolites GABA and glutamate due to their antagonistic roles in inhibition and excitation. However, it is of note that due to the similarity of the molecular structure of Glutamate and Glutamine and the resulting similarity in spectral profile, Glutamate is often reported pooled together with glutamine as ‘Glx’ (Grent-'t-Jong et al., 2022; Ramadan et al., 2013; Weidacker et al., 2020; Weidacker et al., 2022). Improvements, including higher magnetic field strength scanners and acquisition techniques, have allowed for investigations of neurometabolites that formally constituted a unitary pool due to structural similarity within the human brain and resultant spectra similarity, such as GABA and Glx (Ramadan et al., 2013; Steel et al., 2020).

Specifically, GABA has traditionally been difficult to measure with MRS methods at 3T due to the relatively low concentrations in the human brain and overlap with compounds that have more intense signals, such as water (Rowland et al., 2013). One particular advancement in spectral-editing methods that has allowed for the investigation of GABA is the "MEGA-PRESS" editing sequence (Marjanska et al., 2013; Mescher et al., 1998). In short, MEGA-PRESS is a sequence that can resolve the GABA component in difference spectra obtained by subtracting the spectra obtained. In 3T MEGA-PRESS, GABA is typically resolved at 3.00 parts per million (ppm), while Glx is resolved at 3.75ppm (Bell et al., 2021; Deelchand et al., 2021; Harris et al., 2017).

Understanding the assessed levels of GABA and Glx in key regions in the fronto-subcortical network (Orth et al., 2022) such as the dorsolateral prefrontal cortex (DLPFC), supplementary motor area (SMA), and anterior cingulate cortex (ACC) and their relationship to cognitive process, in particular response inhibition tasks (Chambers et al., 2009), can provide valuable insights into the underlying mechanisms of executive control and behavioural regulation and their relationship to excitatory and inhibitory processes.

In a functional magnetic resonance imaging (fMRI) study, Chen et al. (2015) employed a Go No-go task to measure activation in neural regions associated with inhibitory control. Chen et al. (2015) recruited participants who met the criteria for, and were diagnosed with, internet gaming disorder (IGD), to investigate a loss of control of addictive behaviours as a result of a deficit in inhibitory control over responses. Deficits in response inhibition associated with the frontal cortex and a comorbid development of addictive behaviours have led some authors to term drug addictions as ‘the syndrome of impaired response inhibition’ (Goldstein & Volkow, 2002), and the development of the impaired response inhibition and salience attribution model of drug seeking and taking (Zilverstand et al., 2018).

Chen et al. (2015) compared problematic VGPs (with IGD diagnosis) with matched controls; control participants underwent psychiatric interviews to confirm they did not meet the diagnosis of IGD. Chen et al. (2015) observed that problematic VGPs and controls had no significant accuracy or reaction time differences. Additionally, in VGP, there was no significant activation of the DLFPC or SMA for response inhibition (determined by subtracting Go block contrasts from No-go blocks). In control participants, the DLPFC and SMA did show significant activation during response inhibition as part of the frontostriatal circuit (Chambers et al., 2009). No significant activation of the DLPFC or SMA during the Go No-go task is hypothesised to demonstrate that the frontostriatal network for response inhibition is altered compared to the control group without a detriment to performance. This suggests that playing video games can alter behaviour, neuronal activation, and chemistry. Further research on the neurocognitive effects is warranted to understand the impact of video game play fully.

DLPFC in Response Inhibition

The DLPFC is known to be involved in higher-order cognitive function and appears to be associated with working memory, controlling executive function (Barbey et al., 2013), the monitoring of ongoing operations and inhibition of prepotent responses (Jahanshahi et al., 1998). These responsibilities have been characterised as a set of related but independent functions, specifically forming a crucial component of Miyake et al. (2000) frontal lobe tasks in developing the unity and diversity model of executive functions.

Non-invasive brain stimulation (NIBS) techniques such as transcranial Direct Current Stimulation (tDCS) can offer insight into the function of cortical regions by either increasing or decreasing cortical excitability (Lefaucheur et al., 2017). For example, in the motor cortex, tDCS alters the resting membrane potential of neurones towards depolarization in cathodal stimulation or hyperpolarization in anodal stimulation (Nitsche & Paulus, 2000). tDCS has also been evidenced to affect the local concentration of neurotransmitters; anodal tDCS was shown to reduce the concentration of GABA, while cathodal stimulation reduced both GABA and Glx (Stagg et al., 2009). While it is counterintuitive that cathodal tDCS would decrease GABA, it is explained by the biochemical relationship between GABA and Glx, in that glutamine is essential to the synthesis of both Glutamate and GABA (Archibald et al., 2020; Rae, 2014).

Cathodal stimulation over the DLPFC is hypothesised to decrease cortical excitability and interfere with inhibitory control. Cathodal tDCS during a battery of tasks measuring working memory and executive functions, titled the Cognitive Reflection Test (CRT) resulted in incorrect and impulsive responses compared to sham (control) and anodal tDCS (Oldrati et al., 2016). However, Oldrati et al. (2016) observed no differences between performance following anodal tDCS or sham.

Chen et al. (2021) likewise utilised a tDCS paradigm to investigate the role of the DLPFC in action cancellation. Specifically, they employed a between-subjects anodal, cathodal, and sham tDCS during a stop signal paradigm to measure SSRT (mean stop signal delay (SSD) plus correct Go RT), and signal detection theory measures of discrimination and decision bias (Stanislaw & Todorov, 1999). Chen et al. (2021) found that compared to sham, SSRT difference (pre-stimulation SSRT minus post-stimulation SSRT) was longer in anode and cathode conditions, but no significant difference in SSRT difference between the two stimulation conditions. Likewise, discrimination was improved in the anode and cathode groups post-stimulation but not in the sham group. There was an increase in decision bias following anodal stimulation compared to baseline, but a decrease was observed in the cathode group (sham showed no effect). Overall, the results demonstrate the capability of tDCS modulation of the DLPFC to affect response inhibition performance in participants, shedding light on the role of neuronal synapse activation within the DLPFC. In cathodal stimulation, there is resultant impulsive responding. In the stop signal task, this manifested with concurrent improvement in performance, while in CRT detrimental effects were observed. Conversely, anodal tDCS appears to improve action cancellation (SSRT, discrimination and decision bias) but not affect the deleterious effect of impulsive response, as the improvement in response inhibition was not observed in CRT.

Additionally, Aron et al. (2004) recruited patients with discrete DLPFC lesions. They observed larger task-switching costs, increased Stoop-like interference effects, and poorer action withholding performance compared to neurotypical controls. In patients with right frontal damage, reduced performance compared to neurotypical controls was hypothesized to be a result of impaired inhibition of inappropriate responses, as evidenced by large SSRT and high failure to stop (in stop trials). Meanwhile, in left frontal damage patients, weak top-down control was thought to be the cause, with larger stimulus-response compatibility effects and larger task-switching costs. Moreover, damage to the DLPFC has been implicated in an inability to provide top-down facilitatory input in endogenous attention, to switch to new rule sets in task-switching paradigms, and to update items held in working memory (Szczepanski & Knight, 2014). Taken together these results have implicated the role of the DLPFC in executive functioning and inhibitory control.

Concerning the in-vivo neurochemistry of the DLPFC, Boy et al. (2011) correlated GABA levels in the DLPFC with trait impulsivity. A higher concentration of GABA predicted a facet of the impulsivity construct related to lower urgency scores, suggesting a link between GABAergic neurotransmission and impulsivity. Impulsivity has been repeatedly linked to response inhibition (Bari & Robbins, 2013; Chamberlain & Sahakian, 2007; Horn et al., 2003) with Silveri et al. (2013) noting a link between GABA in the frontal regions and impulsivity and response inhibition. Silveri et al. (2013) reported a positive correlation between impulsivity and cognitive control and frontal region GABA. However, the authors chose the ACC as a region of interest over the DLPFC due to the findings of Boy et al. (2010) and Boy et al. (2011).

Boy et al. (2011) did not find a relationship between impulsivity and response inhibition, nor did levels of GABA in the DLPFC correlate with response inhibition performance on a stop-signal paradigm. Yet, previous research has shown lower DLPFC Glx/GABA ratios have correlated with better inhibitory control in Go No-go paradigms, with lower action withholding related error rates in No-go trials (Koizumi et al., 2018), although it is not clear if GABA or Glx was driving this association, underlying the importance of more research into Glx/GABA ratios in the DLPFC and the correlation of that with inhibition performance.

Evidence from functional Magnetic Resonance Imaging (fMRI) research has identified activation of the DLPFC in response inhibition judged to be predominately a means of exerting executive control, ensuring goal-directed behaviour and that task “rules” are followed (Horn et al., 2003). The DLPFC appears to be recruited in response inhibition tasks as a function of executive control and maintenance of task performance (Bari & Robbins, 2013). Additionally, as previously described, it has been observed that there is altered activation of the DLPFC and SMA in response inhibition in a Go No-go task in video game-playing populations, with higher impulsivity being associated with reduced activation of the SMA (Chen et al., 2015). Game-playing participants in this study were diagnosed with problematic video game play termed Internet Gaming Disorder (IGD). fMRI of VGP during the response inhibition task showed that there was no significant activation of the DLFPC or SMA. No significant activation of the DLPFC or SMA during the Go No-go task is hypothesised to demonstrate that the frontostriatal network for response inhibition (Chambers et al., 2009) is altered in comparison to the control group without a detriment to performance. VPG and controls were observed to have no significant differences in accuracy or reaction time.

The roles of the DLPFC and SMA within the prefrontal-striatal network, as discussed by Chen et al. (2015), are based on components of frontostriatal circuity implicated in undertaking response inhibition (Chambers et al., 2009). In a systematic review by Orth et al. (2022), frontostriatal circuitry was identified as having a three-part organisation: limbic, associative, and motor subsystem. The DLPFC is the critical node of the associative subsystem. The DLPFC is considered responsible for selecting sensory information, responses and executive function, while the associative subsystem is involved in monitoring and updating. The motor subsystem engages in planning, preparing, and executing motor responses, of which the SMA and pre-SMA form a part. The limbic system, including the ACC (which is also involved in the associative subsystem), is responsible for emotion regulation, action selection, and reward-based learning. The limbic, associative, and motor subsystems project to various striatal structures, including the ventral striatum, caudate nucleus, and caudate putamen, respectively.

The findings of Chen et al. (2015) have been extended by Chen et al. (2020) who observed that participants who were suffering from internet gaming disorder (IGD) exhibited higher impulsivity and reduced inhibition performance on the Stoop task (longer reaction time and reduced accuracy) compared to non-problematic video game players (VGP), with an associated disruption of the prefrontal-striatal network. In non-patient populations with typical prefrontal-striatal networks, the DLPFC is activated during response inhibition

(Crockett et al., 2013; Morein-Zamir & Robbins, 2015). Chen et al. (2020) observed dysfunctional prefrontal-striatal networks in IGD participants resulting in the dorsal striatum suppressing the left DLPFC activation. In contrast, activation of the DLPFC was observed in the VGP group.

The findings of Chen et al. (2020) and Chen et al. (2015) highlight the role that the DLPFC plays in response inhibition and modulation to networks, including the DLPFC, as a result of video game play. The ability for our behaviour to change as a result of our experiences, such as video game play, is reliant on modulations of the inhibitory and excitatory balance (Haider et al., 2006) and subsequent neuroplastic changes to the brain (Chapman et al., 2022) Therefore, as behaviour and cognition change in relation to experience, there should be an observable difference in GABA and Glx.

The effect of video game play on prefrontal neural circuitry, particularly at a neurochemical level, is unclear. It is, therefore timely to investigate this using a novel task that can assess DLPFC function, such as the stop-signal task and the Go No-go, which will allow for comparison to previous research and a deeper understanding of the executive function component of DLPFC processes on response inhibition performance, in line with Miyake and Friedman (2012) understanding of updating and inhibition in executive function on frontal lobe tasks and prefrontal-striatal networks (Chen et al., 2015; Chen et al., 2020; Morein-Zamir & Robbins, 2015).

Additionally, the use of MRS will allow for correlations of measures of response inhibition under different executive function demands with Glx and GABA concentrations in the DLPFC. Evidence from fMRI research, namely Criaud and Boulinguez (2013) and Mostofsky et al. (2003), has shown that the activation of the DLPFC, and more generally activation of the prefrontal-striatal response inhibition network, fluctuates with the executive function load exerted by response inhibition tasks. The activation of the DLPFC in high load finding was reported in a meta-analysis of fMRI research using a Go No-go paradigm by Criaud and Boulinguez (2013), with activation of the right DLPFC specifically activated when the task was complex. Activation of the right DLPFC was consistent across all metrics of complexity: No-go frequency, stimulus complexity, and executive function load.

To observe the difference between high and low load activation, Mostofsky et al. (2003) employed two versions of a Go No-go task, one simple (low load) and one complex, exerting a high executive function demand. Executive demand was manipulated by making the No-go trials conditional, in that if they were preceded by an even number of Go trials, No-go trials required a response. In contrast, an odd number of Go trials preceding a No-go trial required participants to inhibit a response. Using event-related fMRI, they observed that there was no difference in activation of frontal or motor regions in response to Go trials in high or low load. However, activation was localised in the pre-SMA in low-load No-go trials, whereas high-load No-go was observed to recruit the DLPFC.

These findings suggest a functional dissociation in the roles of these two regions, SMA and DLPFC within response inhibition (in action withholding, to be precise), depending on the involvement of updating and executive function demand.

SMA in Response Inhibition

The SMA is a region involved in the control of action, motor preparation and execution, as well as reactive control and proactive inhibitory control of movement initiation (Picard & Strick, 2001; Wardak, 2011). The SMA is situated in the dorsomedial frontal cortex, which is composed of two functionally distinct regions relevant to response inhibition. First is the SMA, a complete somatotopic representation of body movement (Kim et al., 2010). Second, the pre-SMA is responsible for preparing movement and motor selection in the performance of complex cognitive tasks and is, as such, associated with cognitive control (Nachev et al., 2008). As described in the previous section, the prefrontal-striatal network is hypothesised to be instrumental in response inhibition; the SMA and pre-SMA circuits are critical to the functioning of this network (Mostofsky & Simmonds, 2008) as part of the motor subsystem (Orth et al., 2022).

A cognitive behavioural therapy (CBT) intervention utilising resting-state fMRI on Internet Gaming Disorder (IGD) patients has observed reduced coactivation of sites within the prefrontal-striatal subsystems and associated impulsivity linked to impaired inhibitory control compared to matched healthy controls (Han et al., 2018). Han et al. (2018) observed amplitude of low-frequency (ALFF) values (regarded here as a measure of spontaneous neural activity) and functional connectivity (FC) in the orbitofrontal cortex (OFC), SMA, and ACC in IGD patients and healthy matched controls pre- and post-CBT. CBT significantly reduced hours spent on internet gaming per week, as well as scores on the Chen Internet Addiction Scale (CIAS; Chen et al. (2003)) and the Barratt Impulsiveness Scale 11 (BIS-11; Patton et al. (1995)).

Post-CBT SMA ALFF and FC values are not compared to pre-CBT values in the IGD group, nor post-CBT healthy control values. While the lack of a reported significant difference may suggest that no differences were observed pre- and post-CBT in the SMA, Han et al. (2018) do not explicitly state this. However, there is evidence of a relationship between problematic video game use, alterations to the function of the SMA, and associated impulsivity. There is also the potential that once this video game use is reduced to non-problematic levels, alterations in the function of the SMA are still observed with concurrent reduced behavioural impulsivity.

Further clarifying the role of the SMA in response inhibition, clinical studies have observed the effect of damage to the SMA in patients with discrete lesions. Right superior medial frontal region lesions, including the SMA and pre-SMA, impair response inhibition on a stop signal task (Floden & Stuss, 2006). Specifically, there was a detrimental effect on action cancellation but not action execution in a stop signal paradigm, eliminating the possibility for general motor slowing. This suggests that the role of the SMA is closer related to inhibition than motor preparation in stop-signal tasks. However, given previous research demonstrating that pre-SMA is more closely linked to cognitive control, there remains the possibility that damage to the pre-SMA was the causal effect observed in action cancellation, as opposed to other interpretations of these results inferring a clear implication of the SMA (Verbruggen & Logan, 2008).

Transcranial magnetic stimulation (TMS) offers a non-invasive tool that complements lesion studies by temporarily activating or inhibiting specific brain regions (Hallett, 2007), indeed, when used to inhibit a cortical area, TMS is often referred to as a temporary or 'virtual' lesion (Pascual-Leone et al., 2000; Weissman-Fogel & Granovsky, 2019). This technique enables researchers to probe the spatial and temporal dynamics of cognitive functions precisely, mainly when used in conjunction with neuro-imaging methods (Nieminen et al., 2022). By comparing the outcomes of TMS-induced modulation with observations from lesion research, it is possible to gain insight into the roles of brain regions, such as the SMA, in health and clinical populations.

A review of recent non-invasive brain stimulation research on response inhibition has implicated the crucial role that the SMA (and IFG) plays in response inhibition (Borgomaneri et al., 2020). Of particular relevance, a stop signal task paradigm conducted by Obeso et al. (2013) used offline inhibitory TMS (before the task) over the inferior frontal gyrus (IFG) and online inhibitory TMS (during the task) over the pre-SMA, along with a sham offline condition and control online TMS over the vertex. Obeso et al. (2013) observed that online stimulation over the pre-SMA, with sham offline stimulation, exclusively altered stopping performance, resulting in prolonged SSRT. As such, replicating the findings of Floden and

Stuss (2006) in healthy populations and isolating the impact of disruption to the pre-SMA and worsening of stopping performance.

Regarding action withholding, Liddle et al. (2001) observed increased activation of the SMA and pre-SMA in Go trials in a Go No-go task, while the DLPFC and ventrolateral prefrontal cortex were more active in No-go trials. This suggests that the SMA is involved in making and monitoring responses while the DLPFC has a specific response inhibition function (Rubia et al., 2003).

The hybrid response inhibition task was developed by Sebastian et al. (2013) for identifying the neural links between three primary subcomponents of response inhibition, namely, action cancellation, as measured by the Go No-Go; interference inhibition, as measured by the Simon effect task (and spatial Stroop); and action withholding, as measured by the stop signal task. Its principal use is to identify neural subcomponents of these three separable cognitive subcomponents of response inhibition (action cancellation, action withholding, and interference resolution) within a single task. Activations common to all tasks were found (of which there was overlapping activation of the pre-SMA). However, discrete patterns were also evident for each inhibition task, and contrasts were produced to isolate unique activation patterns in each of the three subcomponents. They found that interference inhibition engages fronto-parietal-pre-motor circuits while action cancellation/ withholding relies strongly on the fronto-striatal-network. Moreover, interference inhibition compared to action cancellation/withholding revealed activation in the pre-SMA, suggesting involvement in response selection within interference inhibition.

In regards to MRS paradigms investigating the role GABAergic transmission has in the SMA, Hermans et al. (2018) found that in older adults, there were higher levels of GABA in the pre-SMA, and these correlated with better stopping performance in a stop-signal ask but the same trend was not observed in younger adults or the left sensorimotor cortex, bilateral striatum, and occipital cortex. Moreover, no relationship between GABA/Glx ratios in the SMA and performance was found on a Go No-go task, where the lack of relationship was assumed to suggest a role of the SMA in implicit control as opposed to explicit control in response inhibition (Kim et al., 2010) which corresponds to the medial/lateral distinction of the pre-motor cortex. Supporting this view are the results from Boy et al. (2010), where responsiveness of subconscious motor mechanisms is related to GABA concentrations in the SMA. Subconscious motor mechanisms were assessed through manipulation of the duration between prime and target presentation in a reverse masked prime task. In a reverse masked prime task, participants respond to the direction of a leftward or rightward-facing target arrow with either a left or right response. Before each target arrow, there is a backward-masked prime. Masking refers to the obscuring of a signal when the signal and masker are not present simultaneously, typically with a difference in presentation onset of a number of milliseconds; backward masking is when the masker follows the signal (in the case of Boy et al. (2010) a prime) as opposed to preceding it (known as forward masking) (Elliott, 1971). Prior to the reverse masked prime task, a staircase discrimination task was used to ensure the primes were below the threshold for conscious perception (Boy et al., 2010).

When the duration between subliminal primes and targets is short (21ms) and the prime and target are congruent, there is subliminal activation by the prime, known as the positive compatibility effect. If the duration between the congruent prime and the target is increased (26ms), responses are delayed as a result of automatic inhibitory mechanisms triggered to override the initial subliminal activation by the prime; this is the reverse masked prime effect and is known as the negative compatibility effect. Higher concentrations of GABA in the SMA positively correlated with negative compatibility effects, the automatic inhibition mechanism that overrides the initial subliminal activation by the masked prime. Thus, the role of the SMA is suggested in the production of inhibition rather than implementation. However, there was no relationship observed between levels of GABA in the SMA on Simon effect tasks and the stop signal paradigm, suggesting that levels of GABA in the SMA are not significantly related to Stop or No-go responses, which appears at odds with the observed inhibitory function of the SMA in the reverse masked prime task. Moreover, MRS investigations of the SMA undoubtedly include measurements of pre-SMA due to voxel size restrictions and regional architecture which makes delineating the GABAergic and Glutamatergic functions of the pre-SMA and SMA difficult.

To investigate the observed contradictory findings of GABA levels in the SMA and correlated response inhibition performance, further, the relationship of levels of GABA in the SMA to response inhibition will be measured in this study. Considering neuroimaging studies implicating the SMA as part of a fronto-parietal-pre-motor network, levels of GABA and Glx in the SMA will be investigated in the three major subcomponents of response inhibition, action cancellation, action withholding, and interference resolution. Results here could elucidate the inconsistencies observed in the role of the SMA and clarify the relationship between levels of GABA and Glx and response inhibition performance. It would be expected that there would be a correlation between levels of GABA or Glx abundance in the SMA and performance in a response inhibition task.

ACC in Response Inhibition

The ACC is a region implicated in cognitive control, outcome evaluation, conflict monitoring, and inhibition (Albert et al., 2012; Liddle et al., 2001; Stevens et al., 2011). In a Go/No-go event-related fMRI paradigm by Liddle et al. (2001) the ACC was observed to be active in both Go and No-go trials, suggesting a similar role in decision formation and monitoring, which are required for both response execution and response inhibition.

Resolving response interference and appropriate selection in tasks such as the Stroop or Simon tasks have routinely been linked to the function of the ACC in a range of review articles focusing on evidence from healthy populations (Hung et al., 2018; Isherwood et al., 2023; Nachev et al., 2008; Wiecki & Frank, 2013). Moreover, in disorders with impaired impulse control, such as addiction, ADHD and OCD, the ACC has routinely been associated with response inhibition performance; see Chambers et al. (2009) for a review of literature in this area. Given this, in response inhibition tasks such as the Hybrid Response Inhibition Task (HRIT), it would be expected that a relationship between levels of GABA in the ACC with action cancellation (Stop response) and action withholding (No-go response) would be observed as these are both cognitions closely related with decision formation, with the ACC observed as having a "top-down" response inhibitory role (Dalley et al., 2011).

In regard to clinical evidence of the role of the ACC in inhibition, Decary and Richer (1995) assessed patients with excised dorsomedial prefrontal cortex, including the ACC and SMA/pre-SMA, on a battery of tasks, including the Go No-go, to measure response inhibition and response interference. They found that participants produced more errors as response selection difficulty increased when patients presented with frontal lesions, but only where decisional difficulty was manipulated but not where perceptual difficulty was manipulated. As previously stated, the SMA plays a pivotal role in response inhibition and selection so findings here cannot fully implicate the role of the ACC, potentially the ACC works as part of a network to enable successful conflict resolution and the individual role of the ACC is unclear, nevertheless, the authors state that observed effects cannot be the result of motor problems as all responses were executed easily and that there was no general slowing as response times were similar to controls and errors were produced as quickly as correct responses. This again supports the top-down control effect of ACC in response interference and response selection.

Shenhav et al. (2013) reviewed literature relevant to the ACC in response inhibition. They developed a theory to account for the diverse role of the ACC in a myriad of tasks, attempting to unify the associated functions such as reward processing, performance monitoring, execution of action, and action selection. Termed the expected value of control (EVC), which represents the net value associated with allocating control to a given task. The ACC then calculates the EVC and determines if it is worth investing control resources in the current task, how much should be invested, and in dual-task or multi-tasking paradigms, which task should be given preferential treatment and bias control resources towards it. As such, in decision-making and likewise response inhibition, the ACC monitors control relevant information and uses this to decide how much control is given to a task, selecting an optimum signal and sending this to regions responsible for control regulation, such as the DLPFC (Brockett et al., 2020; MacDonald et al., 2000). Moreover, the authors suggest in their EVC model that the ACC decided not only the processes that should be prioritised for control but also the balance between controlled and automatic processes by way of monitoring the intensity of control processes.

Silveri et al. (2013) measured levels of GABA in a developmental study sampling adolescents (12-14 years old) and emerging adults (18-24 years old); lower concentrations of ACC GABA were associated with greater impulsivity and lower cognitive control as measured by reduced accuracy on a Go No-go task. This demonstrates the link between ACC GABAergic contributions and specific response inhibition tasks, as other impulse control indices did not show a correlation. Koizumi et al. (2018) employed an auditory Go No-go with task-irrelevant face distractors. They observed higher GABA/Glx, an index of inhibition vs. excitation, ratios in the ACC produced faster responses when distractors were present as opposed to no distractor conditions, suggesting faster and perhaps impulsive responses. This increased difficulty may have exceeded the EVC threshold; as a result, the ACC emitted more control signals to control regulation systems, such as the DLPFC, via GABAergic transmission. Moreover, the abundance of GABA/Glx in the DLPFC only correlated to performance in no-distractor conditions and not distractor conditions, furthering support for the hypothesis that once the task exceeds the EVC threshold, it becomes sufficiently demanding or requires more controlled responding to achieve successful goal-directed behaviour, the ACC sends signals to the DLPFC that more control processes are needed. Alternatively, when the requirements of the task are below the EVC threshold and task requirements can be achieved without additional control processes initiated by the ACC, the local GABAergic processes within the DLPFC are allowed to dictate the level of control regulation. Overall, higher GABA/Glx ratios in the ACC were correlated with more accurate Go responses and implicated the excitatory and inhibitory ratios in the ACC in interference resolution.

To investigate this trend further and the relationship of the level of GABA in the ACC to response inhibition, in particular, interference resolution and how this relationship is modified by video game play. As video game play is hypothesised to improve executive control processes, the ACC will be identified as a region of interest and concentration of resting state GABA and Glx. The levels of GABA and Glx in the ACC will be investigated in the three major subcomponents of response inhibition using the HRIT.

GABA, Glx, and Video Game Play

At the time of writing, there has been limited research utilising MRS procedures to measure baseline GABA and Glx in video game research of healthy adults (and non-problematic video game play), with the neural region of interest almost exclusively hippocampal (Prena et al., 2020). As such, there is limited understanding of the nature of the relationship between video game play and measures of in vivo assessed GABA and Glx in the DLPFC, ACC, and SMA. However, Prena et al. (2020) observed no difference between VGP and non-VGP (NVGP) in hippocampal GABA concentrations, pre- or post-video gameplay. Additionally, the concentration of GABA in the hippocampus was not predicted by performance in a digit span task, a measure of working memory (Baddeley, 2012; Baddeley et al., 1999) and executive function via updating (Miyake & Friedman, 2012; Miyake et al., 2000). Broadly, this suggests that in current MRS research, there is no significant difference between VGP and NVGP in GABA.

While the hippocampus region of interest in Prena et al. (2020) has some relevance to the current aims of this study, as the hippocampus is part of a frontal-midline network responsible for the detection and resolution of goal conflict in goal-directed behaviours (Huster et al., 2013), a higher order executive function (Diamond, 2013), it cannot be reliably used to inform the current hypotheses concerning response inhibition. Evidence from fMRI research shows that the hippocampus is activated in a stop signal task and that this effect is moderated by age (Hu & Li, 2020). Additional evidence from a meta-analysis of neuroimaging studies has shown the contribution of the hippocampus in tasks assessing executive function more generally (Parro et al., 2018). However, this is likely due to the retrieval of stimulus-response sequences from memory and connections with frontal regions (Jiang et al., 2020). Evidence from fMRI and MRS research has also suggested a fronto-hippocampal network associated with inhibition of thought and emotional inhibition (Anderson & Floresco, 2022; Dillon & Pizzagalli, 2007; Friedman & Robbins, 2022; Schmitz et al., 2017), suggesting a potential role in inhibitory processes, but limited support for the argument of involvement in response inhibition processes such as interference resolution and action withholding. Despite clear indications of the DLPFC, ACC, and SMA in response inhibition and evidence that their activation as part of the fronto-parietal network is altered as a result of recent frequent video game use, there is no literature on the ability of video game play to affect changes in the concentrations of GABA and Glx in these regions.

The aim of this chapter is to investigate any differences in the concentration of neurometabolites associated with neuronal excitation and inhibition (GABA and Glx, respectively) in regions associated with the components of response inhibition, interference resolution, action withholding, and action cancellation. A secondary aim is to replicate the behavioural findings of Chapter 2 and establish a relationship between observed differences in performance between VGP and NVGP and concentrations of GABA and Glx in the ACC, SMA, and DLFPC. Due to the limited established evidence on the relationship between MRS measures and video game play, research questions are favoured over specific hypotheses. To that end, the present study aims to answer the question, is there a relationship between the abundance of GABA and Glx in established regions of interest, namely the DLPFC, ACC, and SMA and performance on response inhibition measures in the HRIT and do levels of GABA and Glx in these regions correlate with video game play and video game experience.

Additionally, as the current study uses the same paradigm as Chapter 2, albeit with the inclusion of in-vivo resting state MRS, the previous research questions and predictions are of interest here again. Namely, there is a significant difference in the performance of VGP and NVGP on the HRIT as measured by interference resolution and action cancellation. Given previous findings of a ceiling effect in action withholding condition of the HRIT, the current research question remains: Is there a difference between VGP and NVGP in this condition? Regarding impulsivity, the aim of the current study is to replicate the findings from Chapter Two in the relationships observed between impulsivity and response inhibition and measures of video game use.

Methods

Participants

Forty right-handed males were recruited to participate in this study; however, n=1 participants were dropped due to incomplete data, resulting in a sample of 39 participants (M_{age} = 23.79; SD_{age} = 7.96). The sample predominately consisted of White European ethnicity participants (76.9%), with the remaining participants British Indian (12.8%) or

Asian (10.3%). Participants were compensated for participation with either a voucher worth £20 or SONA participant pool credits, which was the participant's choice. Inclusion criteria were that participants were right-handed males with no contraindications that precluded entering a highly magnetic environment. Handedness was included as an eligibility criterion to control for potential confounds as a result of differences in the lateralisation of functions and asymmetry in brain morphology due to handedness (Good et al., 2001; Kang et al., 2017; Panta et al., 2021; Sun & Walsh, 2006). Likewise, sex was included as an eligibility criterion as evidence suggests fluctuations in resting state GABA and Glx during the menstrual cycle in various brain regions (De Bondt et al., 2015; Harada et al., 2011; Sailasuta et al., 2008). Therefore, recruiting only right-handed participants controlled for this potential confound and was in line with sampling practices in recent comparable studies (Bell et al., 2021; Prena et al., 2020; Weidacker et al., 2020; Weidacker et al., 2022). Any potential contraindications that precluded entering a highly magnetic environment were determined by a completed MR screening questionnaire reviewed by an MR-responsible person at Swansea University Clinical Imaging Facility; Appendix C presents the MR questionnaire. Exclusion criteria consisted of factors that would prevent the participant from undergoing MR scanning, such as metal in the body. All participants provided signed, informed consent to participate in the study, which was approved by the Department of Psychology Ethics Committee, Swansea University.

Participants were later separated into VGP and NVGP conditions for analysis based on their responses to the covert video game experience questionnaire (CVGEQ; Sobczyk et al. (2015)), which was adapted to be the Video Game Experience Questionnaire (VGEQ) as described in Chapter 2 Methods Materials. Participants were separated based on the recommendations set by Green et al. (2012) and those typically observed in this area of research (Bavelier et al., 2018; Bavelier & Green, 2019). Participants reporting more than 6 hours of video game play per week over a period of 6 months are considered VGP (while those that report < 1 hour per week on average are NVGP). In the present study, the frequency of video game play, once a month or less, is considered NVGP. Five participants were included in the NVGP group despite reporting a frequency of more than once a month, as the average number of hours of video game play did not meet the requirement for inclusion in the VGP group. In this sample we observed 15 NVGP (M_{age} = 21.53; SD_{age} = 2.33) and 24 VGP (M_{age} = 25.21; SD_{age} = 9.80).

Materials

The behavioural measures and questionnaires employed in this study replicate those in Chapter 2, with the exception of the (Negative) Urgency, Premeditation (lack of), Perseverance (lack of), Sensation seeking, Positive Urgency (UPPS-P). In Chapter 2, the Short UPPS-P (SUPPS-P) was employed; however, the full form UPPS-P was utilised in the present chapter. The experiment described in this chapter formed part of a larger study, and as such, other tasks, measures, and questionnaires were employed that are outside the scope of this report. However, the aims of the larger study necessitated the use of the UPPS-P, and to reduce participant fatigue, the decision was made not to include the SUPPS-P. As a result, the UPPS-P will be described in this materials subsection. Details of the Hybrid Response Inhibition Task (HRIT) and the Video Game Experience Questionnaire (VGEQ) are reported in Chapter 2, Methods, Materials.

(Negative) Urgency, Premeditation (lack of), Perseverance (lack of), Sensation seeking, Positive Urgency (UPPS-P; Cyders et al. (2007))

The original Urgency, Premeditation, Perseverance, Sensation Seeking (UPPS) scale was developed by Whiteside and Lynam (2001) and was adapted to include a fifth trait of Positive Urgency by Cyders et al. (2007) culminating in an impulsive behaviour scale measuring the five traits: (Negative) Urgency, Premeditation (lack of), Perseverance (lack of), Sensation seeking, Positive Urgency (UPPS-P). This adaptation was published as the English 59-item version (Lynam et al., 2006) and has satisfactory convergent and discriminant validity (Cyders & Smith, 2008; Cyders et al., 2007; Smith et al., 2007). The 59 items are measured on a four-point Likert (1-4) scale ranging from “Strongly Agree” (1) to “Strongly Disagree” (4). There is a consensus that the UPPS-P measures five separate but related first-order factors of impulsivity in young undergraduates (Cyders et al., 2007) with three second-order factors of emotion-based dispositions, sensation seeking, and lack of conscientiousness (Cyders, 2013; Cyders et al., 2007) as well as producing a total impulsivity score, which is the sum of scores for items assessing the five previously mentioned first-order factors.

Positive urgency is the tendency to act impulsively as a result of positive affect, 14 items contribute to this subscale with questions such as “When I am very happy, I can’t seem to stop myself from doing things that can have bad consequences”. Cronbach’s alpha was used to determine the internal consistency of this subscale (in addition to the remaining 4 sub-scales and total score), on the sample of 39 participants. It demonstrated excellent internal consistency ($\alpha = .90$, 95% CI [.83, .94]). Negative urgency is a 12-item measure of the tendency to act impulsively due to negative affect; questions posed include “I have trouble controlling my impulses” and demonstrated acceptable internal consistency ($\alpha = .71$, 95% CI [.51, .81]). Lack of premeditation is measured by 11 items, which refers to the tendency to act rashly without first reflecting upon the decision to act; an example of an item is “I have a reserved and cautious attitude toward life” and demonstrated good internal consistency ($\alpha = .83$, 95% CI [.73, .88]). Lack of perseverance is a 10-item subscale and refers to a tendency to leave projects incomplete. An example of a question measuring lack of perseverance is “I generally like to see things through to the end”. In the current sample demonstrated an acceptable internal consistency ($\alpha = .71$, 95% CI [.55, .80]). Sensation seeking is a 12-item measure of a motivation to experience novelty. An example of a sensation-seeking item is “I generally seek new and exciting experiences and sensations”. In the current sample, it demonstrated a good internal consistency (α = .85, 95% CI [.79, .81]). The total impulsivity score demonstrated an excellent internal consistency (α = .90, 95% CI [.83, .93]).

Design

An individual differences experimental design was employed for this experiment. The independent variable of video game play was measured by the VGEQ and used to quantify video game use and experience. The dependent variable was response inhibition, with the variable’s interference resolution, action cancellation, and action withholding measured by the hybrid response inhibition task. The response time and proportion correct responses were recorded for congruent go, incongruent go, and no-go trials. Moreover, response time was calculated for congruent go and incongruent go trials, and the difference between the two was calculated as the interference effect (incongruent RT – congruent RT = interference effect). For stop trials, the proportion of successful stopping at 5 different stop timings was calculated. Using individual slope and intercept values produced on the proportion correct at each time point for each individual, the stop timing for 75% accuracy, termed stopping performance (SP) was calculated. The creation and interpretation of the summary statistic SP were detailed in Chapter 2, Results.

Additionally, MRS sequencing was used to observe the abundance of neuromatabolites GABA and Glutamate/Glutamine (Glx) in the DLPFC, ACC, and SMA. This will be covered in the procedure's MR acquisition and spectral quantification subsections. The metabolite concentrations of each neurometabolite will be correlated with behavioural measures of interest for each brain region.

Procedure

Participants were initially pre-screened to determine eligibility using the magnetic resonance exclusion criteria. On meeting the inclusion criteria (right-handed and safety criteria for scanning), participants were sent an invite link to an information sheet and provided informed consent. They were given instructions to complete the questionnaires; the UPPS-P was hosted on Gorilla (gorilla.sc ; Anwyl-Irvine et al. (2020)) and Qualtrics (Qualtrics, 2023) hosted the VGEQ. Additional questionnaires formed part of a larger study and were not included in the current analysis.

Once the participants completed the questionnaires (the duration of which, including the questionnaires that formed part of the larger study, took 1 hour), they were invited to the Clinical Imaging Facility at Swansea University, where spectroscopy and behavioural assessments took place. Participants completed MR pre-screening upon arrival at the facility to ensure congruency with previously obtained information. In the absence of technical difficulties, spectroscopy assessments were undertaken first upon arrival (duration of 1 hour 30 minutes). Upon the conclusion of spectroscopy assessments, participants were removed from the MRI machine and taken to the behavioural testing lab to complete behavioural tasks the same day (approximately 1 hour 30 minutes). Additional behavioural tasks formed part of a larger study, including the attentional blink, the balloon analogue risk task, a time perception and estimation task, and a Stroop task, and were not analysed as part of this experiment. The HRIT was the last task of the battery for all participants; the order of task presentation was not counterbalanced between participants.

The procedure of the HRIT replicated that of the procedure employed in Chapter 2. Once all trials were completed, participants had completed their participation, thanked, and debriefed.

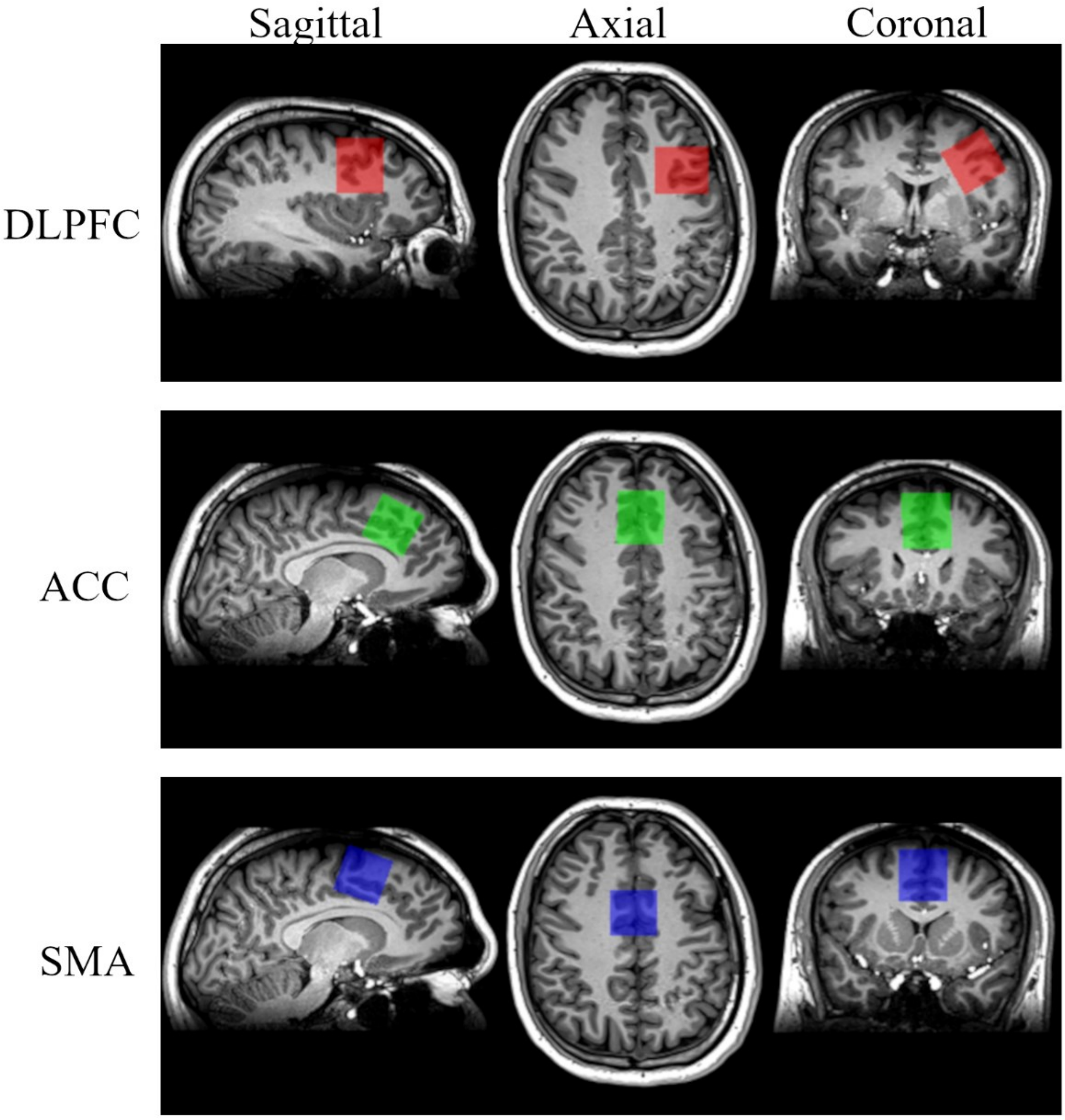
MR acquisition

The minimum reposting standard for in-vivo magnetic resonance spectroscopy checklist (MRSinMRS; Lin et al. (2021)) has been completed as per the recommendations of Lin et al. (2021) and is supplied in Appendix D. For MR acquisition, a 3-T Siemens Magnetom Skyra scanner (Siemens Medical Solutions, Erlangen, Germany; software version XA30) was used in combination with Siemens 1H (transmit/receive), 32-channels head coil. A T1-weighted image was obtained using the MP1Rage sequence: repetition time (TR=1900ms), echo time (TE= 2.54ms), inversion time (TI=900ms), flip angle (9°), 176 slices, 1mm per slice.

Single voxel MRS was conducted using the MEGA-PRESS MRS package developed by Marjanska et al. (2013) and provided by the University of Minnesota under a C2P agreement. GABA-edited MEGA-PRESS sequence parameters: TR=2000ms, TE=68ms, 150 averages (150 per on and 150 per off), 16 averages without water suppression, 2000Hz, 2048 complex data points, offset frequency set to -1.70ppm. Editing pulses: edit-on 1.9, edit-off 7.5ppm. Block-wise averaging (gannet default) was used. Water suppression was achieved using VAPOR. Automatic shimming using FASTEST map. Shimming was performed to reduce local field inhomogeneities in each voxel of interest (VOI), with a <15 threshold for acceptance of shim. VOIs were placed in the right DLPFC (30x30x30mm), the ACC (30x30x30mm), and the SMA (30x30x30mm) without outer voxel suppression. Figure 8 presents the VOI locations for the DLPFC, ACC, and SMA.

Figure 8

Localisation of Voxels of Interest in the DLPFC, ACC, and SMA Across Sagittal, Axial, and Coronal MRI Planes



Note: A representative participant from the current sample displays MRS voxel placement on the Dorsolateral Prefrontal Cortex (DLPFC), Anterior Cingulate Cortex (ACC) and the Supplementary Motor Area (SMA).

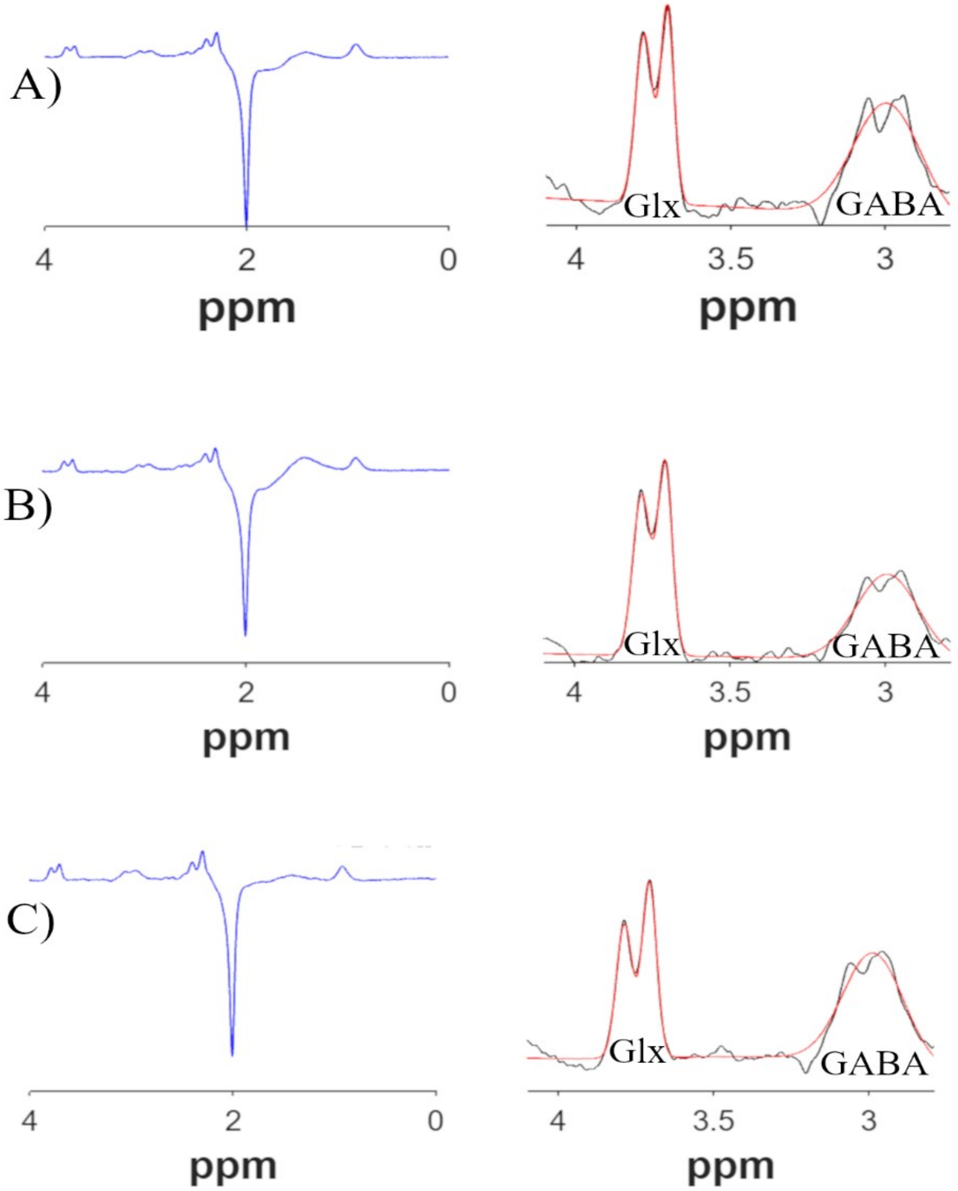
Spectral Quantification

Exemplar MRS spectra from the voxels of interest (DLPFC, ACC, SMA) from the present sample have been produced and are depicted in Figure 9. The MRS data was quantified using GANNET 3.0 (Baltimore, MD, USA), a MATLAB-based toolbox for the analysis of GABA data derived from the MEGA-PRESS sequence, using the standard processing steps, inbuilt models and assumptions for this software (details can be found at http://gabamrs.com). Given the absence of macromolecule suppression, GABA + was utilised as an estimate of GABAergic concentration, which is referred to as GABA from here on. Following phase and frequency correction, the 'ON' and 'OFF' spectra were subtracted to retrieve the edited spectrum for the quantification of GABA. Glx was estimated using the 'OFF' spectra. GANNET models the GABA peak as a single Gaussian, Glx as a doublet, and the water reference as a singlet. Measures of GABA and Glx are shown and analysed in institutional units (i.u.) and referenced to water.

The concentrations are corrected for relaxation times and tissue composition using the relaxation and tissue correction method described by Gasparovic et al. (2006). For the participants reported here, at least one of the neurotransmitters, GABA or Glx, was successfully fit, according to visual inspection and FWHM of the respective molecule falling within 3 SDs from the group mean.

Figure 9

Exemplar MRS Spectra from the DLPFC, ACC, and SMA



Note: Depicted in A), B), and C) are the spectra for the Dorsolateral Prefrontal Cortex (DLPFC), Anterior Cingulate Cortex (ACC) and Supplementary Motor Area (SMA), respectively. In the left column are the fitted exemplar spectra, and in the right column is an example model fit spectrum overlaid on top in red. The neurometabolite γ-aminobutyric acid (GABA) is resolved at 3.00 ppm, and the combined measure of glutamine and glutamate (Glx) is resolved at 3.75 ppm. Magnetic Resonance Spectroscopy (MRS). Parts Per Million (PPM).

Results

It was predicted that VGPs would outperform NVGPs on the HRIT in accuracy, response times (RT), and successful stopping. In addition to this, there was a research question to investigate how the concentrations of GABA would predict performance on the HRIT measures and whether there was further difference between VGP vs NVGP in each brain region (SMA, ACC, DLPFC) and impulsivity as measured by the UPPSP. Additionally, it was predicted that there would be a difference in the impulsivity outcomes in VGP and NVGP. Lastly, it was predicted that impulsivity would correlate with performance on the HRIT.

Data was checked for outliers before analysis to ensure that data conformed to the assumptions of parametric analysis. As previously reported, one participant was removed from the current sample due to an incomplete dataset. Moreover, three participants were removed from the analysis of SMA MRS data due to being determined outliers (>3 Z score). Additionally, there were violations of normality across GABA data in the ACC, Necessitating the use of non-parametric stats when examining the role of ACC GABA on behavioural performance.

The following analysis includes whole sample analyses of individual differences and analyses of group effects between VGP and NVGP groups. Group allocation was determined based on data extracted from the VGEQ. Participants are categorised as VGP if they report ≥6 hours of video game play per week on average in the past 6 months (n=24), and NVGP are participants that report a frequency of video game play of "once a month" or less (*n*=10), or more than once a month with the average hours reported not meeting the threshold for VGP group allocation (*n*=5) for a total of 15 NVGP.

Regarding behavioural data, the No-go condition was excluded from the current analyses as participants' performance was at ceiling (whole sample proportion correct *M* = 1, *SD* = 0). Moreover, while the proportion correct of congruent go has been analysed, they, too, are approaching ceiling. In the whole sample, proportion correct congruent Go (*M* = .99, *SD* = .01) and for incongruent Go, more variation is observed (*M* = .95, *SD* = .10). As such, while congruent go and incongruent go proportion correct will be included in subsequent analysis, they will be non-parametrically analysed, and caution should be applied to interpreting the results. Response time was calculated for congruent Go and incongruent Go correct trials, and a measure of interference effect was computed by subtracting the average congruent reaction time from the incongruent reaction time.

Stop signal delays were computed as a proportion correct for each of the timepoints (35ms, 85ms, 135ms, 185ms, 225ms), with correct being successfully cancelling an action to respond to stimuli in the stop signal trials. The calculation of the summary statistic stopping performance (SP) is described in Chapter 2 Results, and the same procedure for producing SP was followed in the current analyses.

Behavioural

Presented in Table 6 are the descriptive statistics for performance on the HRIT for VGP, NVGP, and across the entire sample. Of note is that the proportion correct in congruent and incongruent go trials named congruent and incongruent accuracy, respectively. A 2x2 mixed ANOVA was conducted to examine the effects of VG status and congruency on accuracy in the HRIT. The within-subjects factors were Congruent and Incongruent in Go Conditions in the HRIT. Violations of normality and homogeneity were observed, and as such, non-parametric analysis of longitudinal data nparLD is more appropriate (See Chapter 2: Results, Behavioural for a description of the nparLD package). Data used to create the summary statistic SP are presented in Appendix E.

Behavioural - Accuracy

An nparLD F1 LD f1 analysis was conducted with one whole plot factor of video game play status with two levels, VGP and NVGP, and one subplot factor of accuracy with two levels, congruent and incongruent trial type on the dependent variable of proportion correct. There was no significant main between-subjects effect of video game status *F* (1, 27.86) = -.93, *p* = .36, no significant main within-subjects effect of congruency *F* (1, 30.31) = 1.93, *p* = .063; and the interaction of video game status and congruency was not statistically significant *F* (1, 30.31)=-.19, *p* =.853).

Table 6

Descriptive Statistics for the Hybrid Response Inhibition Task

		N	*M*	*SD*
Congruent Accuracy	NVGP	15	.99	.02
	VGP	24	1.00	.01
	Total	39	.99	.01
Incongruent Accuracy	NVGP	15	.96	.05
	VGP	24	.95	.12
	Total	39	.95	.10
Congruent RT	NVGP	15	513.55	70.27
	VGP	24	509.43	72.84
	Total	39	511.01	70.96
Incongruent RT	NVGP	15	597.11	63.85
	VGP	24	609.61	79.71
	Total	39	604.80	73.39
Congruency Cost	NVGP	15	83.56	35.47
	VGP	24	100.18	58.12
	Total	39	93.79	50.75
SP	NVGP	15	2.52	2.00
	VGP	24	2.96	2.46
	Total	39	2.79	2.28

Note: Video Game Players (VGP), Non-video Game Players (NVGP), Response Time (RT), Stopping Performance (SP)

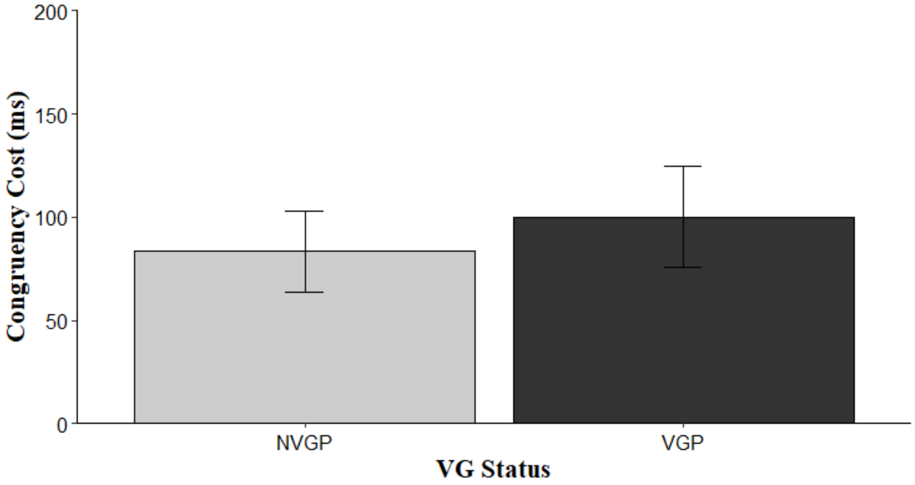
Behavioural - Response Time

Figure 10 shows the congruency effect in the reaction time data for VGP and NVGP. As can be observed, the mean congruency cost (also known as interference effect) is smaller for NVGP than VGP, suggesting that there is less difference between congruent and incongruent trials' response time on average in NVGP compared to VGP.

A one-way ANOVA was conducted to examine the differences in interference effects on response times in VGP and NVGP. A Levene’s test was conducted (F (1,37) =2.30, p =.138), and the assumption of homogeneity of variances was met. There was no significant main effect of VG status on interference effect F (1,37) =.99, p=.326, $\eta 2$ = .026. These results suggest there is no significant difference between VGP and NVGP in the interference effect on response times between congruent and incongruent conditions. To further investigate the effects of congruency, the response time in correct congruent Go and incongruent Go were compared across VGP and NVGP.

Figure 10

Mean Congruency Cost by Video Game (VG) Status



Note: Error bars represent 95% confidence intervals. Video Game Player (VGP), Non-Video Game Player (NVGP), Video Gameplay Status (VG status)

As shown in Table 6, congruent response time shows a small difference between VGP and NVGP, with VGP being slightly faster. However, this trend is reversed in incongruent trails, albeit with higher dispersion in VGP. To investigate this, a 2 [VG Status: NVGP vs VGP] x2 [Congruency: Congruent vs. Non-congruent] mixed ANOVA was conducted to examine the effects of video game status and congruence on response times on HRIT. There was a significant within-subjects effect of congruency (F (1,37) =120.98, p <.001, ηp2 = .77). The between-subjects factor of VG status was not significant (*F* (1,37) =324.04, *p* =.853, *ηp2* =.001). Likewise, the interaction between VG status and Congruency was not significant (*F* (1,37) =1288.07, *p* =.326, *ηp2* =.026).

To investigate the relationship between stimulus-response congruency in reaction time and video game usage, Pearson correlations were conducted between congruent RT, incongruent RT, congruency cost, years of experience of video game use and subjective rating of skill in VGP participants only. The Pearson correlation matrix is presented in Table 7. There was a significant positive correlation between congruent and incongruent RT *r*(22) = .71, *p* < .001 and between interference effect and incongruent RT *r*(22)=.48, *p*=.018. No other significant correlations were observed. A similar pattern of results was observed in a correlation matrix using the complete sample; for the sake of brevity, these have been presented in Appendix F. Taken together, there is support for the account that there is a typical finding of a significant effect of congruency, but this effect does not interact with VG status. VG status does not significantly alter the congruency cost experienced.

Table 7

Pearson Correlation Matrix Response Time and VGP Years Experience and Subjective Rating of Skill

		Years Experience	Subjective Rating	Incongruent RT	Congruent RT	Congruency Cost
Years Experience	Pearson Correlation	--				
Subjective Rating	Pearson Correlation	-.049	--			
	Sig. (2-tailed)	.819				
Incongruent RT	Pearson Correlation	.004	-.318	--		
	Sig. (2-tailed)	.984	.131			
Congruent RT	Pearson Correlation	.122	-.214	.713**	--	
	Sig. (2-tailed)	.570	.316	<.001		
Congruency Cost	Pearson Correlation	-.147	-.168	.478*	-.275	--
	Sig. (2-tailed)	.493	.434	.018	.193	

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

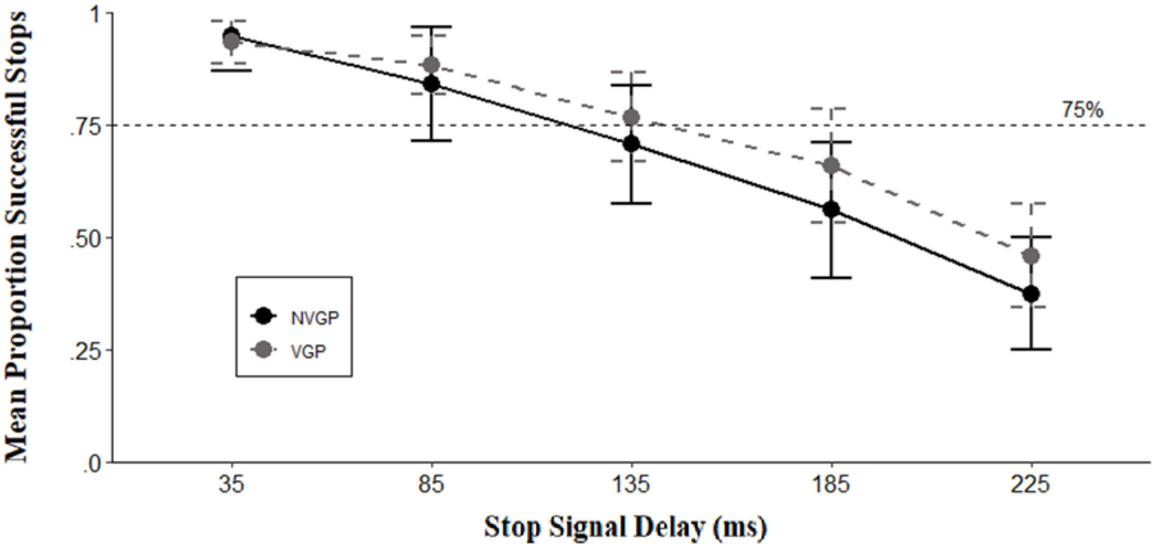
Behavioural - Stop Delay

Prior to the creation of the SP summary statistics, a 2 [VG Status: NVGP vs VGP] x 5 [SSD: 35, 85, 135, 185, 225ms] mixed ANOVA was conducted to examine the effects of VG status and stop timing, in addition to correlations investigating the same effect. This analysis will not be reported here in favour of the summary statistic of the value of stop at 75% accuracy, SP. However, the analysis has been presented in supplementary analysis in Appendix G. Figure 11 illustrates the point at which, as a group, on average, accuracy passed the 75% threshold. Higher values for SP in Table 6 demonstrate better performance, with longer periods of stop delays before participants' performance decreases to the 75% threshold.

An independent samples t-test was conducted using VG status as the grouping variable and SP to assess whether VGP had a higher value for SP, demonstrating a better ability to stop. The difference between groups was not significant (*t* (37) = -.58, *p* = .28). This suggests no significant difference in the stop timing in which VGP and NVGP approach 75% accuracy on average.

Figure 11

Line graph of Proportion Successful Stop per Stop Signal Delay for Video Game Players (VGP) and Non-Video Game Players (NVGP)



Note: Error bars 95% confidence interval. Video Game Player (VGP). Non-Video Game Player (NVGP). Hybrid Response Inhibition Task (HRIT). The horizontal line depicts 75% successful stopping, termed Stopping Performance (SP).

Pearson correlations were conducted to assess the relationship between the required period between the go and stop signal for 75% successful stopping to be achieved, SP, with video game measures, and are presented in Table 8. No relationships approached significance.

Table 8

Pearson Correlation of Stopping Performance and Video Game Measures

		Years Experience	Subjective Rating	SP
Years Experience	Pearson Correlation	--		
Subjective Rating	Pearson Correlation	-.049	--	
	Sig. (2-tailed)	.819		
SP	Pearson Correlation	.309	-.267	--
	Sig. (2-tailed)	.142	.207	

Table 9

Descriptive Statistics of Magnetic Resonance Spectroscopy Data

		N	*M*	*SD*
ACC GABA	NVGP	15	3.71	.44
	VGP	24	3.72	.39
	Total	39	3.72	.41
ACC Glx	NVGP	15	12.16	.92
	VGP	24	12.26	1.12
	Total	39	12.22	1.04
DLPFC GABA	NVGP	15	3.84	.44
	VGP	24	3.63	.37
	Total	39	3.71	.41
DLPFC Glx	NVGP	15	9.71	.58
	VGP	24	9.94	1.30
	Total	39	9.85	1.07
SMA GABA	NVGP	12	3.89	.55
	VGP	24	3.96	.44
	Total	36	3.94	.47
SMA Glx	NVGP	12	10.99	1.18
	VGP	24	11.14	1.45
	Total	36	11.09	1.35

MRS & HRIT

Table 9 presents the descriptive statistics for the MRS data. Three participants were removed from the SMA analyses in the NVGP group due to being determined as outliers. Overall, there appear to be limited differences between groups. VGP demonstrates a higher concentration of GABA and Glx in all brain regions apart from DLPFC GABA, but differences here are minimal. Moreover, there appears to be more variability in VGP DLPFC Glx and ACC Glx compared to other brain regions (both GABA and Glx) and NVGP overall.

Pearson correlations were run between the behavioural measures of incongruent response time, congruent response time, response time congruency cost, SP and the MRS data DLFPC and SMA Glx and GABA, and ACC Glx only, presented in Table 10. Spearman correlations were conducted for correlations including ACC GABA (Appendix H). Spearman correlations were conducted for congruent go accuracy and incongruent go accuracy (Appendix I). The Spearman correlations of ACC GABA and Accuracy (congruent and incongruent) were run due to violations of the assumptions of normality. None of these correlations were significant, and as such, they are presented in Appendix H and I, respectively.

Table 10

Pearson Correlation Matrix HRIT Behavioural Data and MRS data

		Incongruent RT	Congruent RT	Congruency Cost	SP
ACC Glx	Pearson Correlation	-.120	-.024	-.140	-.339*
	Sig. (2-tailed)	.465	.884	.394	.035
DLPFC GABA	Pearson Correlation	-.086	-.144	.078	-.445**
	Sig. (2-tailed)	.604	.381	.638	.005
DLPFC Glx	Pearson Correlation	-.042	.169	-.298	-.178
	Sig. (2-tailed)	.798	.303	.065	.279
SMA GABA	Pearson Correlation	-.021	-.223	.283	-.088
	Sig. (2-tailed)	.903	.192	.095	.610
SMA Glx	Pearson Correlation	-.287	-.360*	.091	-.218
	Sig. (2-tailed)	.089	.031	.599	.201

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

As can be observed in Table 10, there were three significant weak negative correlations; there was a weak yet significant negative correlation between SMA Glx and Congruent RT (*r* (34) = -.360, *p* = .031, *n* = 36), with an observed power of *q* =.732. Suggesting that congruent reaction time increases as the observed level of Glx (excitatory neurometabolites) decreases.

A significant negative Pearson correlation between SP and ACC Glx (*r* (37) =-.339, *p*=.035, *n*=39, *q* =.512). This suggests that as the concentration of ACC Glx decreases, SP increases. For SP, this demonstrates improved performance as longer, more successful stop timing indicates better stopping ability.

Additionally, a significant negative Pearson correlation between SP and DLPFC GABA (*r* (37) =-.445, *p*=.005, *n* =39), *q* = .527. As the concentration of DLPFC GABA decreases, the value of SP increases; larger values indicate better performance in this measure.

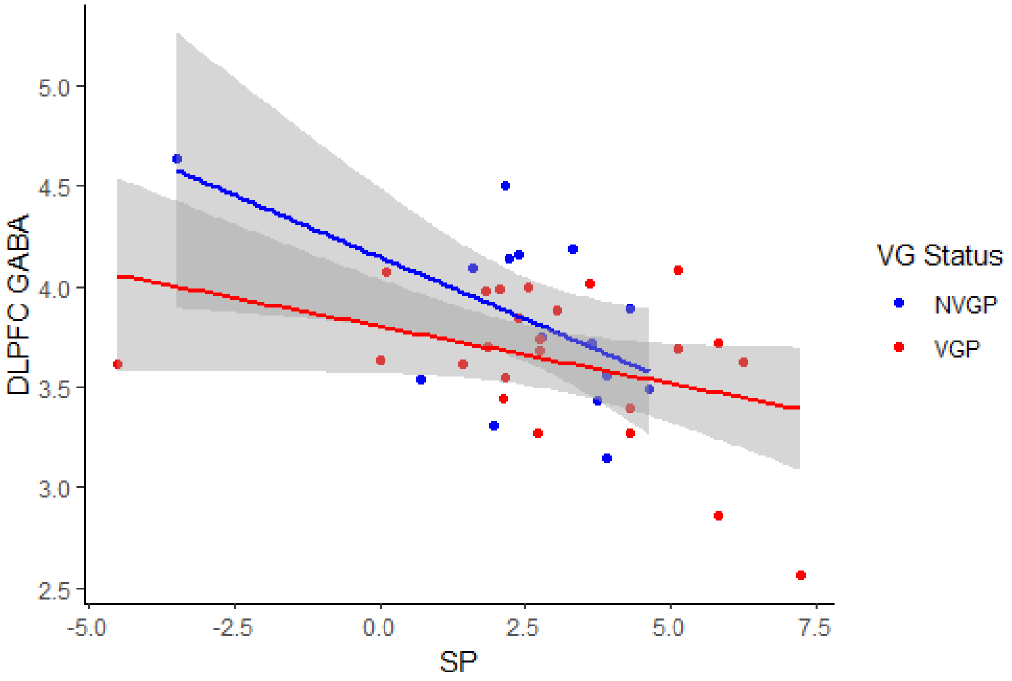
All the above effect sizes can be categorised as medium. A two-sided power analysis was conducted using the R studio package "pwr". Pwr version 1.3-0 produces power calculations based on Cohen (1988) using the same notations for effect sizes (ES) (pwr.r.test: correlation test (ES=r)).

Point biserial correlations were produced between all brain regions, GABA and Glx, on VG status; no correlation approached significance (p >.05). Results here suggest that as SMA Glx, ACC Glx, and DLPFC GABA decrease, participants respond faster and are able to stop more successfully with a shorter stop delay period. The correlations with SP are plotted in Figures 12 and 13.

The above correlations were repeated and split between NVGP and VGP. Table 11 presents the Pearson correlations for NVGP and Table 12 VGP to investigate the correlations for these measures within each level of VG status.

Figure 12

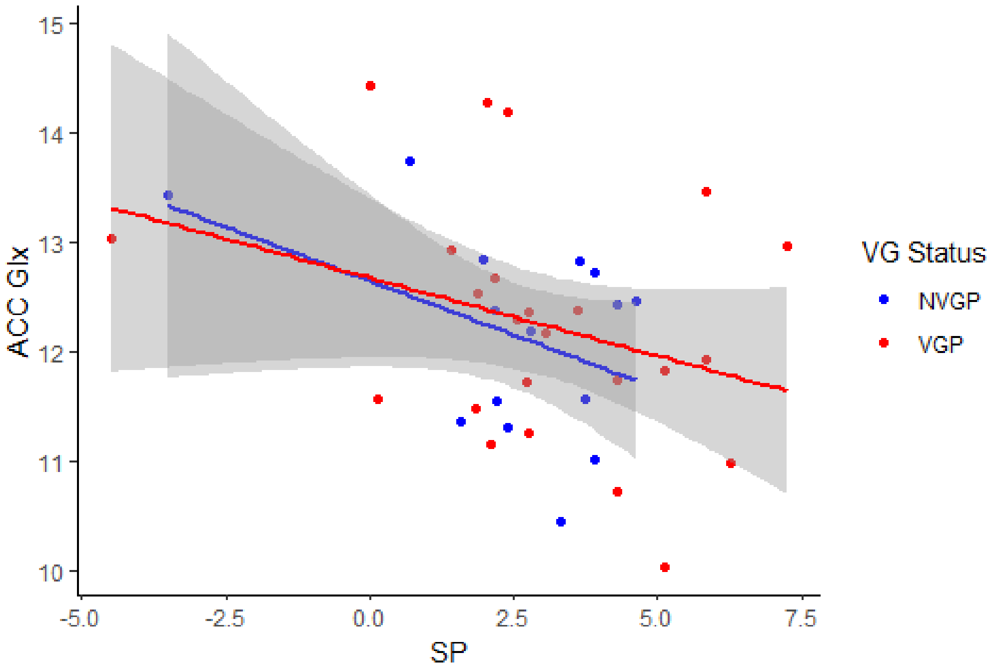
Scatterplot of Stopping Performance (SP) on Dorsolateral Prefrontal Cortex (DLPFC) GABA by Video Game (VG) Status



Note: Error bars represent 95% confidence interval

Figure 13

Scatterplot of Stopping Performance (SP) on Anterior Cingulate Cortex (ACC) Glx by Video Game (VG) Status



Note: Error bars represent 95% confidence interval.

Table 11 shows Pearson correlations for the NVGP group. There was a significant moderate correlation between SP and DLPFC GABA (r (13) = -.561, p = .029), suggesting that in NVGP, as GABA decreases in the DLPFC, the participants are able to stop successfully with a larger delay, indicating better performance.

Pearson correlations for the VGP group can be seen in Table 12. There was a significant moderate negative correlation between congruency cost and DLPFC GABA in VGP (r (22) = -.405, p = .05), suggesting that as DLPFC GABA decreases, the congruency effect is reduced. Additionally, there was a significant moderate negative correlation between congruent RT and SMA GABA (r (22) = -.463, p = .023), suggesting that reduced abundance of GABA in the SMA is associated with improved RT in congruent response time in VGP.

Additionally, Spearman's correlations were conducted for NVGP congruent and incongruent go accuracy and MRS data (Appendix J), and for VGP on the same measures (Appendix K), NVGP congruent, incongruent, and congruency RT cost and SP with ACC GABA (Appendix L), and the same for VGP in Appendix M. There were no significant

correlations between MRS data and behavioural measures (*p* > .05).

Table 11

Pearson Correlation Matrix NVGP HRIT Behavioural and MRS Data

		ACC Glx	DLPFC GABA	DLPFC Glx	SMA GABA	SMA Glx
Congruency Cost	*R*	-.036	.231	.175	.187	-.022
	p	.899	.407	.532	.561	.946
Congruent RT	*R*	-.256	-.219	-.045	-.539	-.124
	p	.357	.432	.875	.071	.701
Incongruent RT	*R*	-.302	-.113	.048	-.495	-.150
	p	.275	.689	.864	.102	.641
SP	*R*	-.427	$-.561^{*}$	-.007	-.399	.072
	p	.112	.029	.981	.199	.824

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 12

Pearson Correlation Matrix VGP HRIT Behavioural and MRS Data

		ACC Glx	DLPFC GABA	DLPFC Glx	SMA GABA	SMA Glx
Congruency Cost	*R*	-.187	.084	-.405*	.330	.113
	p	.382	.697	.050	.116	.599
Congruent RT	*R*	.089	-.114	.241	-.013	-.463*
	p	.678	.597	.256	.953	.023
Incongruent RT	*R*	-.055	-.043	-.075	.229	-.341
	p	.800	.843	.728	.282	.103
SP	*R*	-.313	-.376	-.236	.071	-.330
	p	.137	.071	.267	.741	.115

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

UPPSP

The UPPSP was scored to produce the individual factors of negative urgency (NURG), positive urgency (PURG), lack of premeditation (PREM), lack of perseverance (PERX), sensation seeking (SS), and a total impulsivity UPPSP score. Point biserial correlations were conducted on VG status and UPPSP subscales to investigate the hypothesis of the relationship between VG status and impulsivity. There was a significant negative correlation between VG status and positive urgency (pbr (37) = -.451, p =.004), with NVGP associated with higher positive urgency and VGP with less. Positive urgency is the tendency to act rashly as a result of positive affect.

Moreover, to investigate the effect of VG status and the relationship with UPPSP sub-scales, a set of Pearson correlations was conducted with the VGP group only, using years of experience and subjective rating of skill, as can be observed in Table 13. There was a significant moderate positive correlation between subjective ratings of skill and sensation seeking (*r* (22) = .449, *p* = .028), suggesting that as self-reported skill on video games increases, sensation seeking increases. No other correlations were significant.

Table 13

Pearson Correlation Matrix between UPPSP scores and VGP measures of VG experience

		Years Experience	Subjective Rating
NURG	Pearson Correlation	.076	-.101
	Sig. (2-tailed)	.726	.638
	N	24	24
PERS	Pearson Correlation	-.312	.301
	Sig. (2-tailed)	.137	.152
	N	24	24
PREM	Pearson Correlation	-.019	.006
	Sig. (2-tailed)	.929	.977
	N	24	24
PURG	Pearson Correlation	-.151	-.048
	Sig. (2-tailed)	.480	.825
	N	24	24
SS	Pearson Correlation	.052	.449*
	Sig. (2-tailed)	.811	.028
	N	24	24
UPPSP Total	Pearson Correlation	-.081	.212
	Sig. (2-tailed)	.707	.321
	N	24	24

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

UPPSP and HRIT

To investigate the relationship between the scores on the UPPSP and performance on the Hybrid Response Inhibition Task (HRIT), Pearson correlations were conducted between the five subscales of the UPPSP and total scores between the HRIT RT and SP data. Congruent and incongruent Go accuracy were not included in these analyses as those scores were at ceiling. Descriptive statistics for UPPSP by VG status and whole sample are presented in Table 14.

Table 14

Descriptive statistics for UPPSP data

		Mean	Std. Deviation
Negative Urgency	NVGP	2.38	.39
	VGP	2.25	.47
	Total	2.30	.44
Lack of Perseverance	NVGP	2.19	.42
	VGP	2.21	.43
	Total	2.20	.42
Lack of Premeditation	NVGP	1.88	.48
	VGP	1.97	.44
	Total	1.93	.45
Positive Urgency	NVGP	2.16	.51
	VGP	1.69	.44
	Total	1.87	.52
Sensation Seeking	NVGP	3.18	.41
	VGP	3.11	.66
	Total	3.14	.57
UPPSP Total	NVGP	2.37	.30
	VGP	2.23	.32
	Total	2.28	.31

Note: Video Game Player (VGP), Non-Video Game Player (NVGP)

The initial correlation matrixes included the whole sample for individual differences analysis. Table 15 presents the correlation matrix for UPPSP subscales and RT data. As can be seen, there were significant negative correlations between incongruent RT and lack of perseverance (*r* (37) = -.323, *p* = .045) and congruent RT and lack of perseverance (*r*(37) = -.320, *p* = .047), suggesting that lower lack of perseverance scores are related to improved response time regardless of congruency.

Table 16 presents SP and the UPPSP subscales and total scores. As can be observed, there are significant moderate negative correlations between SP and negative urgency (*r*(37) = -.431, *p* = .006), lack of perseverance (*r*(37) = -363, *p* = .023), positive urgency (*r*(37) = -.367, *p* = .021), and UPPSP total (*r*(37) = -.480, *p* = .002). The correlations of SP with sensation seeking and lack of premeditation were not significant (*p* >.05). This suggests that smaller scores of negative urgency are related to a larger stop timing, indicating better stopping performance. Likewise, a lower reported lack of perseverance is related to better-stopping performance, as it is negatively correlated with stop timing. Lower positive urgency is also related to larger SP scores, demonstrating better stopping ability. Lower impulsivity scores appear to be associated with successful stopping at larger delays. Exploratory analyses of MRS and UPPSP data are presented in Supplementary Analysis in Appendix G.

Table 15

Pearson correlation Matric UPPSP & HRIT Response Time

		NURG	PERS	PREM	PURG	SS	UPPSP Total
Incongruent RT	Pearson Correlation	-.286	-.323*	.030	-.188	.133	-.170
	Sig. (2-tailed)	.077	.045	.857	.251	.419	.300
Congruent RT	Pearson Correlation	-.220	-.320*	.004	-.111	.175	-.112
	Sig. (2-tailed)	.178	.047	.983	.501	.287	.496
Congruency Cost	Pearson Correlation	-.106	-.020	.038	-.117	-.052	-.089
	Sig. (2-tailed)	.521	.902	.819	.479	.752	.589

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed).

Note: Negative Urgency (NURG), Lack of Perseverance (PERS), Lack of Premeditation (PREM), Positive Urgency (PURG), Sensation Seeking (SS)

Table 16

Pearson Correlation Matrix UPPSP subscales and Stopping Performance (SP)

		SP
NURG	Pearson Correlation	-.432**
	Sig. (2-tailed)	.006
PERS	Pearson Correlation	-.363*
	Sig. (2-tailed)	.023
PREM	Pearson Correlation	-.169
	Sig. (2-tailed)	.303
PURG	Pearson Correlation	-.367*
	Sig. (2-tailed)	.021
SS	Pearson Correlation	-.236
	Sig. (2-tailed)	.147
UPPSP Total	Pearson Correlation	-.480**
	Sig. (2-tailed)	.002

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Note: Negative Urgency (NURG), Lack of Perseverance (PERS), Lack of Premeditation (PREM), Positive Urgency (PURG), Sensation Seeking (SS)

Combined Samples Behavioural Analysis

Upon the conclusion of data analysis for Chapter 3 behavioural data (Chapter 3: Results: Behavioural), an ad hoc decision was made to combine the current study sample with that of Chapter 2 (Chapter 2: Results: Behavioural**)**. This was undertaken to address the potential confounding effects of imbalances in group sizes and to investigate why previously observed behavioural effects in Chapter 2 were not observed in Chapter 3, Behavioural Analysis. The predictions for the results of data analysis are the same as those presented in Chapters 2 and 3; VGP will outperform NVGP on measures of interference resolution, action cancellation, and action withholding. These measures were recorded using the same Hybrid Response Inhibition Task (HRIT) task described in Chapters 2 and 3. The analyses conducted fall within the preexisting categories of accuracy, response time (RT), and stop delay.

The analysis of impulsivity has been dropped from the combined samples' behavioural analysis due to the different versions of the impulsivity measure employed in each study. The experiment reported in Chapter 3 utilised the (Negative) Urgency, Premeditation (lack of), Perseverance (lack of), Sensation seeking, Positive Urgency (UPPS-P) by Cyders et al. (2007), whereas Chapter 2 employed Short Urgency, Premeditation (lack of), Perseverance (lack of), Sensation seeking, and Positive Urgency (SUPPS-P; Cyders et al., 2014). This discrepancy arose because the procedure of Chapter 2 was conducted entirely online, and the duration was curtailed where possible. In Chapter 3, the full UPPS-P was employed as part of a larger study, which made the inclusion of the SUPPS-P redundant.

Statistical Analysis

The measures of interest were the accuracy rates and response times (RTs) for Go trials, the interference RT (incongruent Go minus congruent Go RTs), the proportion of false alarms for No-go trials and a characterisation of Stop performance. For Stop trials, the proportion of successful stopping was used. As previously described in this chapter, the summary statistic used the five stop signal delays; (SSDs), 35ms, 85ms, 135ms, 185ms, 225ms, to calculate the duration of stop signal delay at which successful stopping performance was at 75% for each participant's performance. This summary statistic is termed stopping performance (SP). A larger value of SP indicates better stopping performance, as the data reflects a less steep decline in accuracy at increasing SSDs. Hence, SP assesses the rate at which participants fall below 75% successful stopping depending on increasing SSDs.

Group outliers were determined by being more than three standard deviations away from the mean within each respective variable of interest. The present combined samples outlier detection was undertaken on the original datasets from Chapters 2 and 3 (before pre-treatment). As such, for the sake of clarity, outlier removal has not been repeated on already "*cleaned"* data. Listwise deletions were undertaken for this dataset; if a participant's performance was deemed an outlier on one variable, they were removed from the analysis. Five participants were removed from the combined samples, two of which met the requirements for the classification of VGP and the other three NVGP.

Each HRIT variable of interest was first assessed to ensure conformity with relevant parametric assumptions; the assumption of normality was conducted using the Shapiro-Wilk test and visual inspection of the histogram, QQ and detrended QQ plots. Homogeneity of variance was assessed using Lavene's test of equality of error variance, and the assumption of sphericity was assessed using Mauchly's test of sphericity. T-tests and mixed ANOVAs were conducted to assess group differences. Where required, non-parametric alternatives were performed, or in the case of mixed ANOVA, the Greenhouse-Geisser correction was applied. Mann-Whitney U tests were conducted for nonparametric analyses of group differences. Spearman rank correlations between HIRT performance and video game-relevant (subjective experience with video gaming, years of video gaming experience) variables were conducted as appropriate. Effect sizes are given in Cohen's d point estimate.

Sample Characteristics

Initially, the combined sample consisted of 111 participants; after outlier removal, this number decreased to 106. Out of 106 participants, VGPs were composed of 42 participants who played video games for more than 6 hours per week on average for a period of 6 months. NVGPs were identified as playing “once a month or less” on the VGEQ. See Table 17 for descriptive statistics per VPG (11.9% females) and NVGP (70.3% females) groups.

Behavioural Results

Accuracy

Accuracy for No-go ($M = 1$, $SD = 0$) and congruent Go trials ($M = .98$, $SD = .03$) was (near) perfect with a clear ceiling effect across the whole sample and hence was not analysed further.

During incongruent Go trials, sufficient variation was observed ($M = .88$, $SD = .15$). Comparing incongruent Go accuracy rates across VGP ($n = 42$, $m = 1.00$, $IQR = .08$) and NVGP ($n = 64$, $m = .88$, $IQR = .19$) using a Mann-Whitney U test showed a significant difference ($U = 1904$, $Z = 3.71$ $p < .001$), with VGP expressing higher accuracy than NVGP during incongruent Go trials. However, neither subjective experience with video gaming (r_s (42) = .12, $p = .496$) nor years of experience (r_s (43) =.03, $p = .868$) correlated significantly with the accuracy for incongruent Go trials as assessed by Spearman correlations in VGPs.

Interference RT (incongruent Go minus congruent Go) was analysed in a Mann-Whitney U test to assess the effect of video game use on interference cost. VGP expressed significantly reduced interference RT ($n = 42$, $m = 89.43$, $IQR = 71.17$) compared to NVGP ($n = 64$, $m = 112.55$, $IQR = 86.21$; $U = 829$, $Z = -3.27$, $p < .001$). However, in the VGP group, neither subjective experience (r_s (42) = -.12, $p = .481$) nor years of experience (r_s (42) = -.02, $p = .899$) correlated significantly with interference RTs as assessed by Spearman correlations.

To further investigate the effect of congruency, Go RTs were analysed using a mixed 2x2 ANOVA with congruency (Congruent *vs.* Incongruent) and VGP status (VGP *vs.* NVGP) as factors. Descriptive statistics for each group for congruent and incongruent Go RT are presented in Table 17. The results showed a significant main effect of congruency (*F* (1,104) = 497.87, $p < .001$, η_p^2= .83) with longer RTs for incongruent (*M* = 623.71, *SD* = 75.58) than congruent trials (*M* = 508.43, *SD* = 66.98) across groups. While the main effect of VGP status was not significant (*F* (1,104) = .92, *p* = .340, η_p^2=.01), VGP status interacted significantly with congruency (*F* (1,104) = 11.54, $p < .001$, η_p^2= .10). Follow up Bonferroni corrected independent samples *t*-test showed significantly faster Go RTs for incongruent trials (*t* (104) = 2.07, *p* = .041, two-tailed, *d* = .41) in VGP (*M* = 606.00, *SD* = 70.25) compared to NVGP (*M* = 635.33, *SD* = 72.25), with a mean difference of 29.33 (95% CI, 1018 to 57.47) ms.

In contrast, no significant difference (*t* (104) = .35, *p* = .726, two-tailed, *d* = .07) was observed for congruent Go RTs between NVGP (*M* = 506.58, *SD* = 61.76) and VGP (*M* = 511.27, *SD* = 74.93), with a mean difference of 4.69 (95% CI, -31.19 to 21.80) ms. This suggests the nature of the significant difference in interference RT observed is driven by VGP exhibiting significantly shorter incongruent RT than NVGPs, also explaining the observed cross-over interaction.

Table 17

Descriptive statistics for video game players (VGP) and non-video game players (NVGP) groups

		NVGP (*N* = 64)	VGP (*N* = 42)
Age (years)	Range	18-32	18-59
	M (*SD*)	20.97 (2.55)	23.48 (7.90)
Sex	*Female*	45	5
	Male	19	37
VGEQ *M* (*SD*)	Years of Video Game Experience	-	13.88 (7.15)
	Subjective Rating of Skill	-	5.64 (1.17)
HRIT RT *M* (*SD*)	Interference RT	128.75 (53.04)	94.73 (46.14)
	Congruent Go	506.58 (61.76)	511.27 (74.93)
	Incongruent Go	635.33 (72.25)	606.00 (70.25)
HRIT Accuracy *M* (*SD*)	Congruent Go	.98 (.04)	.99 (.01)
	Incongruent Go	.85 (.17)	.94 (.10)
	No-go	1 (0)	1 (0)
	SP	1.55 (2.60)	3.08 (2.31)

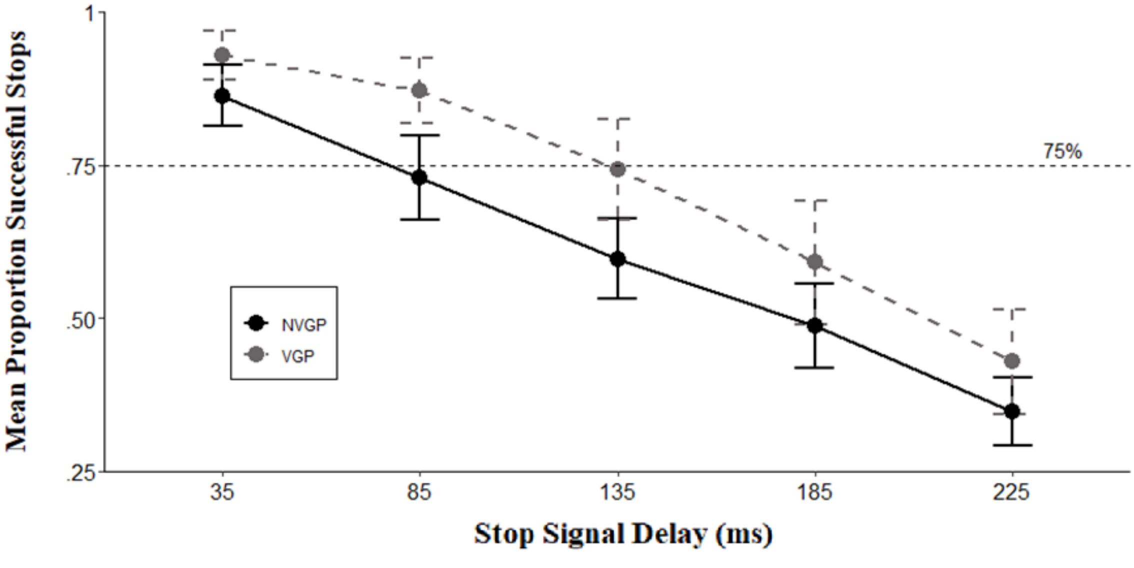
Note. Video Game Players (VGP), Non-Video Game Players (NVGP), Mean (M), Standard Deviation (SD), Interference response times (RT) = Congruent Go - Incongruent Go. Covert Video Game Experience Questionnaire (VGEQ), Hybrid Response Inhibition Task (HRIT), Stopping Performance (SP).

Stop Trials

Figure 14 displays the proportion of successful stopping across five SSDs in VGP and NVGP. The figure includes a horizontal line at 75% successful stopping, visualising the value of SP in VGP and NVGP. To assess group differences in SP, a Mann-Whitney U was conducted between VGP (*n* = 42, *m* = 2.65, *IQR* = 2.74) and NVGP (*n* = 64, *m* = 2.06, *IQR* = 2.29). For VGP, we found significantly better SP than for NVGP (*U* = 1791, *Z* = 2.89 *p* =.004), indicating a slower rate of stopping performance decline at increasing SSDs. Spearman correlations between SP and years of experience were not significant (r_s (42) = .01, *p* = .935). However, there was a significant, albeit weak, negative correlation between SP and subjective rating of skill (r_s (42) = -.34, *p* = .029). As the subjective rating of skill increased, the value of SP decreased, suggesting that higher levels of subjective skill correlate with worse performance on the Stop signal task and vice versa.

Figure 14

Proportion Successful Stops Across Stop Signal Delays in VGP and NVGP Groups on the HRIT



Note: Error bars 95% confidence interval. Video Game Player (VGP). Non-Video Game Player (NVGP). Hybrid Response Inhibition Task (HRIT). The horizontal line depicts 75% successful stopping, termed Stopping Performance (SP).

Discussion

The aim of the current study was to investigate the relationship between the abundance of GABA and Glx in the DLPFC, ACC, and SMA and performance on a hybrid response inhibition task (HRIT) designed to assess three components of response inhibition, action cancellation, action withholding, and interference resolution. Additionally, to investigate how GABA and Glx in the regions of interest correlated with video game experience measures and video game play. As the HRIT used in this experiment is the same as in Chapter 2, the same hypotheses were of interest with the aim of replicating the results observed in Chapter 2. Namely, it would be observed that the task produced the desired effects of action cancellation, action withholding, and interference resolution and could assess how performance on these measures differed depending on group allocation and correlated with impulsivity data.

While it was observed that there was a statistically significant effect within subjects on measures of action cancellation (via the summary statistics of stop timing) and interference resolution in response time, it was again observed that No-go conditions were at the ceiling across the entire sample. Additionally, there was no significant within-subjects effect of congruency on response time. This pattern of results partially replicates those found in Chapter 2. It suggests that the HRIT is capable of inducing action cancellation through stop-signal conditions. Moreover, the culminating evidence suggests that the HRIT produces stimulus-response compatibility effects in congruent and incongruent conditions of Go to measure interference effects. However, this was observed more consistently in response time than compared to accuracy. The HRIT cannot reliably produce action withholding through prepotent responses in No-go conditions (Gerhardt et al., 2021; Sebastian et al., 2013). As such, action withholding and No-go condition data were not analysed for this study. The suggestions of increasing difficulty of the No-go condition from Chapter 2 are restated here, namely increasing difficulty by increasing prepotency of response (increasing Go trials relative to No-go and stop), reducing the response time deadline, or increasing the event rate (Benikos et al., 2013; Lindqvist & Thorell, 2008; Raymaekers et al., 2004; Wessel, 2018), would allow a difference to be observed and meet the purpose the task was designed for.

Regarding relationships between neurometabolites in the regions of interest and performance on measures of the HRIT, it was observed that there was a significant negative correlation between Congruent condition correct response time and SMA Glx, as the concentration of Glx in the SMA increased, response time for correct responses was significantly decreased. This relationship is quite logical in that the SMA is noted as being responsible for control of action, motor preparation and execution (Picard & Strick, 2001; Wardak, 2011), as well as forming part of the motor subsystem of the prefrontal-striatal network (Orth et al., 2022). Moreover, Liddle et al. (2001) observed increased activation of the SMA and pre-SMA in Go trials compared to No-go trials; however. there was no congruency manipulation in Liddle et al.'s (2001) paradigm to further complement the current findings. Nevertheless, the increased activation of the SMA in Go conditions supports the notion of the SMA's role in making and monitoring responses (Rubia et al., 2003; Sebastian et al., 2013), which would appear to be the nature of the correlation currently observed in Go trials. This relationship was observed in the group as a whole as well as independently in each of the NVGP and VGP groups, making it the only correlation between MRS data and performance on the HRIT to do so. Simmonds et al. (2008) demonstrated in their meta-analysis of experimental paradigms employing Go No-go and functional magnetic resonance imaging (fMRI) that the SMA was involved in the selection of appropriate behaviour, either selecting or inhibiting a response in both simple and complex Go No-go paradigms. It, therefore, could be assumed that participants with higher levels of Glx in the SMA benefitted from congruent facilitation as stimulus-response compatibility resulted in less need to select or inhibit a response, and the increased concentration of excitatory neurotransmitters allowed this facilitation to be more readily acted upon.

Additionally, regarding the relationships between GABA and Glx in the regions of interest (DLPFC, ACC, SMA) and performance on measures of the HRIT, it was found that ACC Glx negatively correlated with Stopping Performance (SP). In SP, larger scores are better as they illustrate the length of stop signal delay needed to reduce participant performance below 75% successful stopping. In line with this, the negative relationship demonstrates that a lower concentration of ACC Glx is significantly correlated with better stopping performance. This effect was observed across the entire sample but not when controlling for video game play group allocation. Put simply, the role of Glx, glutamate in particular, is to trigger neurons to release neurotransmitters and is a major excitatory transmitter in the brain (Zhou & Danbolt, 2014).

Weidacker et al. (2022) found no correlation between the ACC GABA or Glx in the ability to stop on a stop-signal task. However, they found that ACC Glx positively correlated with errors in Go conditions in a stop-signal task. Additionally, results from fMRI research have implicated the role of the ACC as a region responsible for performance monitoring in inhibitory control tasks such as the Switching Stroop task, where the task demands switch between naming the colour of the word or the word itself (MacDonald et al., 2000). The results of the current study, ACC Glx negatively correlated with SP, may have observed that lower concentration of neuronal excitability and glutamatergic transmission results in more effective performance monitoring of action cancellation and less impulsive responding. Appendix G includes supplementary analysis of MRS and UPPSP data and found that there was a significant positive correlation between ACC Glx and negative urgency, the tendency to act rashly in response to negative affect, suggesting that participants with lower levels of ACC Glx may have been less impacted by incorrect responses and able to maintain performance. Taken together, these findings seem counterintuitive, given the proposed role of glutamine in neuronal excitation.

If the theorised expected value of control (EVC) function of the ACC is assumed here (Shenhav et al., 2013), it could be surmised that the lower concentration of Glx in the ACC in more successful stopping performance could be a signifier of a more efficiently functioning control network. The concentration of ACC Glx is lower, suggesting that fewer control signals are being triggered to release to the relevant regions (Zhou & Danbolt, 2014) and achieving better response inhibition performance, in this case, more effective stopping at longer stop delays. Meaning that participants who are able to complete the task effectively require less input from control networks as they are responding less impulsively in general. Support for this theory can be lent from the finding from the current study of a significant negative correlation between SP and DLPFC GABA, where the lower concentration of GABA in the DLPFC is related to more successful stopping performance, suggesting an overactive response selection and control network that is impulsively responding. This is in line with the findings of Weidacker et al. (2022) who found that increased ACC Glx was associated with increased error rates in a stop-signal paradigm, albeit in Go conditions. Decreased ACC Glutamine has previously been associated with increased striatal activation related to increased cognitive control in Stroop task congruency cost and errors (Naaijen et al., 2018), and ACC Glx has been correlated with increased self-reported impulsivity and errors in action withholding (Cohen-Gilbert et al., 2015).

Additionally, Silveri et al. (2013) found that higher levels of GABA in the ACC were correlated with worse response inhibition performance and reduced accuracy in a Go No-go task. This could suggest that the GABAergic transmission in the ACC is related to neuronally inhibiting EVC-control signals exiting the ACC and cascading alteration to downstream nodes in control networks and initiating control processes in regions such as the DLPFC

(Brockett et al., 2020). Further support for this account of the roles of the ACC in assessing the value control-related processes (or performance monitoring more generally) and the DLPFC for implementing the control comes from MacDonald et al. (2000), who observed DLPFC activation when participants were tasked with naming the colour but not reading the word, suggesting DLPFC's role in top-down controlled processing and interference resolution to enable goal-directed behaviour and optimum performance. MacDonald et al. (2000) found that the ACC was more active on congruent trials rather than incongruent trials and was found to monitor conflict, as participants with the largest Stroop effects tended to have more ACC activation.

While MacDonald et al. (2000) observed the hypothesised relationship between the ACC and DLPFC as monitoring and initiating controlled processes, respectively; the Stroop task was used to measure this relationship via interference resolution and stimulus-response compatibility. In the current HRIT paradigm where interference resolution and stimulus-response compatibility are assessed by Simon effects (according to Sebastian et al. (2013), although the interference resolution condition more closely resembles the spatial Stroop task due to the notable exception of a colour stimulus and the inclusion of a symbolic arrow cue (Lu & Proctor, 1995)) there was no such relationship found between the concentration of GABA in the DLPFC or Glx in the ACC and measures of interference resolution, only with measures of action cancellation. Moreover, there was no significant correlation between DLPFC GABA and ACC Glx[1].

Yet, when taken together with the observed lack of action withholding effects (near-perfect No-go responding across the entire sample), it could be hypothesised that the EVC

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[1] A Pearson correlation was conducted between ACC Glx and DLPFC GABA and revealed no significant relationship between the variables (r (37) = -.07, p = .690).

calculations and controlled processing were directed toward the more “difficult” or costly action cancellation/ stop condition response inhibition. Additionally, this effect was only observed in the sample as a whole; when correlations were run between behavioural data and measures of MRS between groups, there was no significant correlation between ACC Glx and SP regardless of group allocation, as previously noted. DLPFC GABA significantly correlated with SP in NVGP but not in VGP participants (although in VGP, the correlation did approach significance).

Yet, behaviourally, there was no significant difference between groups in their stopping performance, suggesting that the stop signal delay at which both groups fell below 75% successful stopping performance was not significantly different. Taken together, it could be assumed that VGP were able to undertake the demands posed by the stop-signal condition without the need for additional performance monitoring, EVC input, or controlled processing input. It would be easy to suggest that this pattern of results could also imply that the neuronal inhibitory excitatory balance is being disrupted (Krause et al., 2013) in VGP, yet there is no significant difference between VGP and NVGP across all behavioural measures (action cancellation and interference resolution) in the accuracy of responding, response time, or stopping performance in the Chapter 3 sample.

A higher baseline concentration of ACC Glx is related to worse stopping performance; this suggests that baseline Glx in the ACC is indicative of a more active EVC system to regulate control systems such as the frontostriatal network (Chambers et al., 2009; Orth et al., 2022), and the DLPFC GABA (Brockett et al., 2020; MacDonald et al., 2000), to counteract impulsive responding. In VGP, it could be hypothesised that the abundance of Glx in the ACC has been modified through neuroplastic changes through habitual video game use (Chapman et al., 2022) as less input is needed from EVC as there are more executive function resources available that can be used more readily. Hence it would be less efficient to review the value of implementing control processes. Rather, it is more effective to implement them once the task is sufficiently demanding (Diamond, 2013; Dye et al., 2009a, 2009b).

Alternatively, the notion that action cancellation appears to recruit a different neural system to action withholding (Raud et al., 2020) and the observed abundance of ACC Glx correlating with stopping performance may indicate that a more active EVC (as evidenced by increased ACC Glx) limits the ability to readily change between response selection (action withholding) and response inhibition (action cancellation) and that VGP are observed as having a more flexible EVC system to allow for these changes. However, there was no association between VG status and levels of GABA or Glx in the DLPFC, ACC, or SMA. To investigate this finding more effectively, tasks that can manipulate cognitive load while effectively assessing executive function are needed to identify the improved performance of VGP over NVGP (Brown, 2006; Diamond, 2013) particularly in pure individual component analyses using the Go No-go task and the Stop signal task, as well as in a modification of the HRIT that allows for manipulation of task difficulty. This behavioural methodology combined with functional MRS (fMRS) and functional magnetic resonance imaging (fMRI) would inform the nature of the involvement of the ACC during task completion and elucidate findings in this area. If the EVC ACC hypothesis is to be confirmed, it would be hypothesised that it would be observed that in NVGP, there would be more ACC activation and Glx during the action cancellation compared to action withholding, and this would linearly correlate with executive function load. Additionally, ACC activation would correlate with DLPFC and striatal activation in errors compared to correct responses. Overall, it is expected that VGP will observe a similar trend but significantly less activation and ACC Glx than their NVGP counterparts. Yet, comparatively, VGP activation of ACC with increasing load would be demonstrably larger in magnitude than the NVPG as the additional executive function resources become recruited to manage task demands and perform effectively.

Another direction for further research into this topic is to investigate the involvement of the striatum, as this area has been implicated in implementing control processes in response inhibition tasks and correlated with the levels of Glx in the ACC (Naaijen et al., 2018). Moreover, how video game play may affect the recruitment of the striatum through functional magnetic resonance imaging (fMRI). Additionally, the use of magnetic resonance spectroscopy to investigate the abundance of GABA and glutamate/ glutamine (Glx) in the striatum to identify what relationship there is between GABAergic and Glutamatergic systems and performance on the HRIT, specifically in action cancellation or SP. Previous research by Sebastian et al. (2013), Zandbelt and Vink (2010) and Gerhardt et al. (2021) have identified the striatum in response inhibition paradigms. Zandbelt and Vink (2010) identified activation of the striatum in conjunction with successful stopping in a stop signal paradigm in what is hypothesised to be suppressing of the primary motor cortex. Further, the volume of the striatum has been shown to predict video game skill acquisition (Erickson et al., 2010). There is a convergence of evidence to suggest this region is of interest and may give more insight into the GABA and Glx systems involved in response inhibition and how this, in turn, correlates with video game experience and skill.

Self-reported impulsivity scores demonstrated that VGP categorisation was associated with lower positive urgency, and NVGP was associated with higher positive urgency. As there was no behavioural difference between groups on any measure, it is difficult to determine how this difference in positive urgency, the tendency to act rashly as the result of positive affect, is borne out in the data. In future replications with larger sample sizes with the aim of being able to observe behavioural differences in VGP and NVPG, particularly with the increased cognitive demand to observe differences in executive function (Diamond, 2013). It may be observed that VGP makes fewer errors after consecutive correct responses than VGP, particularly when feedback is given.

Upon the conclusion of the behavioural analysis of the sample obtained in the experiment reported here (Chapter 3), the ad hoc decision was made to include the data from the HRIT in Chapter 2 to investigate heterogeneity between the results of analysis in the two experiments. As previously stated, the measures of impulsivity were dropped due to a lack of conformity in measures used between studies, and MRS data was only available for the sample obtained in Chapter 3.

Results of the behavioural analysis found that VGP outperformed NVGP on all measures that were analysed, namely, accuracy on incongruent Go, interference effects driven by a faster response to incongruent Go but no difference on congruent Go and stopping performance. Ceiling effects were observed in No-go, as found in Chapters 2 and 3, and congruent Go. Therefore, it can be concluded that frequent video game play in the previous 6 months is associated with improved response inhibition performance in interference resolution and action cancellation. The potential for ceiling effects to mask a potential difference between groups has been discussed previously in this thesis. However, effect sizes were small and were not consistently observed across analyses.

Of note, in the combined sample, there are issues with imbalance in not only the number of participants in each group but also in the sex of participants in each group. The NVGP group (*n* = 64) was substantially larger than the VGP group (*n* = 42), predominately as a result of the disparity in the sample from Chapter 2. Likewise, the VGP group was approximately 88% male, while the NVGP group was 70%. The majority of participants in Chapter 2 were females, while in Chapter 3, due to potential MRS confounds, only males were sampled. Despite the account for how this disparity arose in the current combined sample, females constituting a higher proportion of NVGP groups and males a higher proportion of VGP groups is not uncommon in literature (Anderson & Bushman, 2001; Boot et al., 2008; Castel et al., 2005; Green & Bavelier, 2003, 2006a, 2006b, 2007; Phan et al., 2012; Winn & Heeter, 2009). While disproportionately male VGP groups and disproportionately female NVGP groups were more prevalent in the past, the imbalance, while narrowing, exists in recent research (Buono et al., 2020; Gillian Dale et al., 2020; Dale & Shawn Green, 2017; Leonhardt & Overå, 2021; Lopez-Fernandez et al., 2019). Dale et al. (2020) observed differences between VGP and NVGP in useful field-of-view (a measure of spatial attention) tasks after controlling for age and gender. Yet, the authors found that gender had significant confounding effects on multiple object tracking.

Indeed, the effect of sex in interference resolution paradigms such as the Simon task has been observed (Evans & Hampson, 2015; Mosso et al., 2020; Stoet, 2017). Longer female reaction time is a consistently reported finding (Evans & Hampson, 2015; Mosso et al., 2020; Stoet, 2017). Stoet (2017) observed that females exhibited larger interference effects, and response times increased following an error. Likewise, Evans and Hampson (2020) observed smaller interference effects in males compared to females, and importantly, this was driven by faster responses in incongruent trials. Significantly reduced interference effects in males compared to females mirror the findings of the current combined samples in that VGP exhibited smaller interference effects than NVGP. Moreover, this, too, was driven by faster responses to incongruent stimuli, suggesting improved inhibition of proponent responses and reduced stimulus-compatibility effects.

To assess action cancellation, Evan and Hampson (2020) also incorporated a Stop Signal Task (SST) into their design and observed no effect of sex, with males and females exhibiting no significant differences in Stop Signal Reaction Time (SSRT), stop signal delays, and the proportion of successful Stops and Go's. Likewise, Li et al. (2006), while investigating different patterns of neuronal activation between men and women during an fMRI SST, observed no differences in any metric of task performance between men and women. The same research group later replicated these behavioural findings using a larger sample size (Li et al., 2009). However, Gaillard et al. (2020) observed a significant difference in SSRT between males and females, with a moderate effect size but no differences in other measures (such as proportion correct Stop and Go). Yet, Li et al. (2009) and Li et al. (2006) recruited equal numbers of males and females, whereas Gaillard et al. (2020) were weighted towards more females (23 females compared to 15 males).

While gender imbalance is an important limitation, the combined samples did overcome the criticism of sample size across the two chapters. Moreover, the effect observed in SP appears to be driven by recent frequent video game play. Measures of video game play, such as video game play subjective experience or years of video game use, did not correlate with performance. The lack of a significant correlation provides further support for the notion that recent frequent use is the behaviour resulting in improvements in response inhibition cognitions, at least regarding action cancellation.

An important question remains: How far do the effects of recent video game play transfer across cognitions related to executive functions? Chapters Two and Three utilised measurements of response inhibition due to its critical role in inhibition processes (Mostofsky & Simmonds, 2008). Inhibition was selected as it is identified as a domain-general executive function (Friedman & Miyake, 2004; Friedman et al., 2008; Miyake & Friedman, 2012) that interacts with other core (Barkley, 1997, 2001; Dempster & Corkill, 1999) and higher-order executive functions (Diamond, 2013; Diamond et al., 2007). Therefore, these response inhibition subprocesses were prime candidates for assessing the potential for video game use to alter executive functions. To extend these findings, a domain-specific executive function must be measured to observe the extent of implicit training of video game use, such as working memory updating (Baddeley, 2012; Baddeley, 2020; Baddeley & Hitch, 1974; Friedman & Miyake, 2004; Miyake & Friedman, 2012; Miyake et al., 2000). Moreover, including multiple methods for increasing demands of the task and cognitive load will allow for more direct testing of one of the central predictions of this thesis, that sufficient load is required to observe the difference in executive function performance (Diamond, 2013; Diamond et al., 2007) and differences between VGP and NVGP (Dye et al., 2009a; Gobet et al., 2014; Green & Bavelier, 2007, 2012; Green & Bavelier, 2015). Lastly, measuring the task demands experienced by participants within this paradigm will allow for confirmation that task demands are being manipulated in the task. Chapter Four aims to extend the findings presented in the combined analysis to those of working memory updating and to use manipulations of task load to understand the inconsistencies in behavioural outcomes between Chapters Two and Three.

To conclude, it was observed that behaviourally, there is no significant difference between NVGP and VGP in terms of measures of action cancellation and interference resolution. While it was not possible to assess the difference between groups due to ceiling effects in the action withholding condition, the HRIT did reliably induce effects of response inhibition in the action cancellation and interference resolution condition, as seen in Chapter 2. It was observed that there was no significant association between groups and the concentration of GABA and Glx in the DLPFC, ACC, and SMA. It was observed that lower values of ACC Glx were associated with more successful stopping performance. Likewise, lower DLPFC GABA and more successful stopping performance were hypothesised to be a reflection of error processing and efficient expected value of control systems (EVC). It was also observed that lower SMA Glx results in longer response times on congruent conditions, suggesting the facilitatory effect of stimulus-response compatibility is compounded by higher levels of SMA Glx. Lastly, there was an association between self-reported positive urgency and video game play status, suggesting the VGP tend to act less rashly in response to positive affect than their NVPG counterparts. However, this trend was not observed in any measure of the HRIT.

Chapter 4: Effect of Video Game Use on Updating and Sustained Attention

Chapter 3 observed a small and inconsistent behavioural effect of video game use on response inhibition. Therefore, the present chapter will investigate the potential of these effects to be more pronounced with sufficient load (Diamond, 2013; Diamond et al., 2007; Dye et al., 2009b; Gobet et al., 2014; Hubert-Wallander, Green, & Bavelier, 2011), and assess transfer from the domain-general component of executive function, response inhibition as a component of inhibition, to a domain-specific executive function such as working memory updating (Baddeley, 2012; Baddeley, 2020; Baddeley & Hitch, 1974; Friedman & Miyake, 2004; Miyake & Friedman, 2012; Miyake et al., 2000). Two potential methods for increasing cognitive load are identified, diminishing the available executive function resources via time on task (Thomson et al., 2015), and by increasing the working memory updating load and the demands of the task response requirements (Kane et al., 2007; Owen et al., 2005).

Sustained attention is the ability to consciously self-sustain the processing of repetitive and non-arousing stimuli, qualities that would otherwise lead to habituation and distraction towards other stimuli (Robertson et al., 1997). Sustained attention represents an essential attentional function and determines the efficacy of higher-order aspects of attention, such as selective and divided attention (Sarter et al., 2001). Vigilance is the capacity to sustain attention to any environmental source of information over prolonged periods of watch (Szalma et al., 2014) and is a top-down process (Carrasco, 2011; Pinto et al., 2013).

Vigilance has been the focus of numerous investigations for over 70 years (Mackworth, 1948) and understanding this capacity is crucial, as it is an important component of performance in several applied domains such as security, aviation, and driving, with elements of vigilance occurring in a variety of aspects of human existence (Salzma et al., 2014). Vigilance is comprised of two main indices; “Vigilance level” and “Vigilance decrement” (Starter et al., 2001). Vigilance level is one’s ability to detect stimuli. In contrast, vigilance decrement refers to a negative relationship between time on task and performance, where there is a decline in vigilance level as time on task increases. This decrease in performance can relate to an increase in target detection reaction times or a decrease in perceptual sensitivity to target stimuli, leading to a decrease in correct detections (Helton & Russell, 2011).

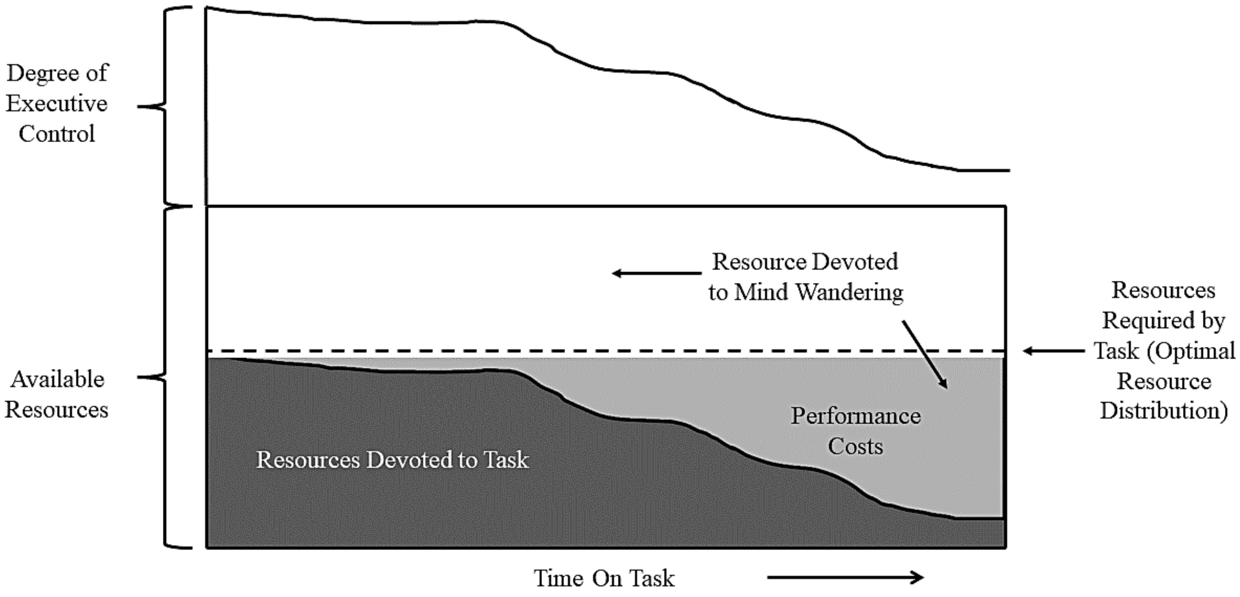
Two main theoretical accounts for vigilance decrement are commonplace in vigilance research: underload theories (Braboszcz & Delorme, 2011), overload theories (Helton & Russell, 2011, 2015), and a combination of elements of the two theories, coined resource control theory (Thomson et al., 2015, 2016). The underload account is split into two hypotheses: mindlessness and mind wandering. The mindlessness hypothesis theorises that vigilance tasks by design are under-stimulating and monotonous. As a result, attention is withdrawn from the task, leading to a mindless approach to target detection with reduced sensitivity for critical trials (Robertson et al., 1997). The mind-wandering account builds upon the same foundation as the mindlessness hypothesis. However, it posits that when the stimuli the observer perceives do not sufficiently hold attention, the observer instead attends to self-generated task-unrelated-thought (TUT) or mind-wandering (Braboszcz & Delorme, 2011).

To continue, the overload hypothesis, also known as the resource depletion hypothesis, operates off the assumption that humans are limited in their information processing abilities at any particular moment in time (Warm et al., 2008). Therefore, vigilance decrement is a result of the duration and demands of the task, and when the available resources become limited, there is a reduced ability to detect targets as a result of insufficient attention toward task demand (Thomson et al., 2016).

Lastly, the combination hypothesis or resource control account, depicted in Figure 15, posits that there is a finite supply of executive function resources (Thomson et al., 2015, 2016). Once this supply has been depleted, no executive function resources will be available to direct attention to task-related thought, and as such, attention will be directed towards TUT. Figure 15 depicts a visualisation of the resource control account of sustained attention. Therefore, sustained attention measures the allocation of executive function resources over time. There is a debate over which account holds the most relevance to observed data. However, the resource control theory described here uses aspects of the mind-wandering and resource/overload hypothesis to produce a theory to best account for the observed data in vigilance studies, something neither of the other hypotheses is able to do alone (Thomson et al., 2015).

Figure 15

A Visualisation of the Resource Control Account of Sustained Attention (Thomson et al., 2015)



Note: Figure 15 and its description are adapted from Thomson et al. (2015). The amount of available resources to the observer remains constant (as depicted by the Y-axis), as do the task's demands (as depicted by the dashed horizontal line). Executive control over the allocation of resources declines over time (downward trending line at the top of the figure). The waning executive control results in a disproportionate amount of resources directed toward mind wandering (a combination of white and grey areas) and away from resources devoted to the task (decreasing a dark grey area), resulting in costs to performance (a light grey area below the line).

Therefore, it is possible to assess performance on vigilance tasks using a task designed to measure working memory performance as a measure of working memory updating to allow for an understanding of sustained attention as a function of executive function as defined by Miyake et al. (2000). Working memory capacity tasks measure a construct that is important to higher-order cognition and is related to executive function (Engle, 2016). Moreover, evidence from Baddeley et al. (1999) suggests that the temporary representation of visual stimuli taxes performance and places demand on executive processes. The performance decline was detectable over a 30-minute period, but participants did demonstrate a recovery effect in the final 10-minute period. This was taken to reflect a vigilance decrement, and when taken together with Engle (2016) and the unity and diversity account of executive function (Friedman & Miyake, 2004; Miyake & Friedman, 2012; Miyake et al., 2000), demonstrates the ability of a working memory updating task to measure both executive function capabilities and sustained attention performance.

Supporting the notion of a sustained attention working memory updating paradigm in Helton and Russell (2011) participants undertook an adapted letter detection vigilance task that manipulated either spatial or verbal working memory load (or no memory control). The authors observed vigilance decrement in measures of response time and perceptual sensitivity in SDT and noted that working memory load exacerbated this effect, indicating utilisation of executive function resources. Likewise, Caggiano and Parasuraman (2004) observed vigilance decrement in participants undertaking a continuous performance task dependent on working memory updating.

Additionally, Caggiano and Parasuraman (2004) provided support for this interpretation, showing that participants undertaking a continuous target discrimination task dependent on working memory with the successive presentation of stimuli having poor perceptual quality demonstrate vigilance decrement effects. These effects are the result of increased activation of storage and cognitive control processes related to the working memory system. As the task is continuously performed, this diminishes vigilance systems. Likewise, Helton and Russell (2011) found similar effects in their working memory vigilance task. Participants undertook an adapted letter detection vigilance task that manipulated either spatial or verbal working memory load (or no memory control). The authors observed vigilance decrement in measures of response time and perceptual sensitivity in SDT and noted that working memory load exacerbated this effect, indicating utilisation of executive function resources. The evidence that working memory demand increases vigilance effects (Parasuraman, 1979) is relevant here as in the General Introduction, the review of literature such as Green and Bavelier (2007), Dye et al. (2009a) and Gobet et al. (2014) demonstrated the need for increased cognitive load to invoke video game players' increased attentional capacity.

As such, utilising a paradigm with the capability to manipulate cognitive load in a continuous performance task will allow for measuring vigilance levels in an executive function task with the ability to observe the effects of video game play in line with the findings of Green and Bavelier (2007), Dye et al. (2009a) and others (Bavelier, Achtman, et al., 2012; Bavelier et al., 2018; Bavelier & Green, 2019; Gobet et al., 2014; Hubert-Wallander, Green, Sugarman, et al., 2011). One such paradigm could utilise the verbal *n*-back task (Kirchner, 1958; Mackworth, 1959), which is commonly accepted to measure executive function, attention, and working memory capacity (Gajewski et al., 2018; Owen et al., 2005). The *n*-back task (Kirchner, 1958) typically, participants monitor a series of stimuli to identify if a stimulus currently presented matches that of a previous stimulus presented *n* trials previously. Modulations of task difficulty arise when changing the value attributed to the pre-determined value *n,* typically 0,1,2 or 3. The task requires constant updating and manipulation of the stimuli in working memory in the order they were presented (Owen et al., 2005). Manipulations of 0-back are used as control conditions, requiring participants to respond to a prespecified target stimulus upon presentation. This does not require manipulating information held in working memory.

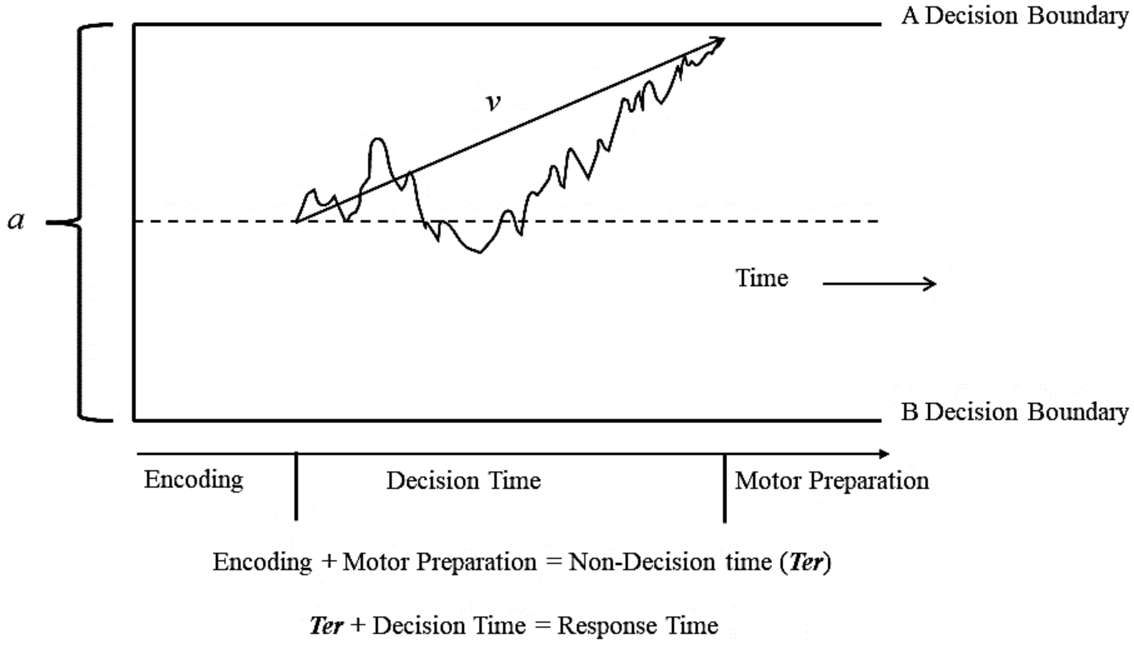
However, there is a caveat here that verbal vigilance tasks utilising alphanumeric stimuli can often be unable to show vigilance decrement effects (See et al., 1995). This is due to the familiarity participants often exhibit for this type of stimuli, yet sufficient load, a low rate of target stimuli, and a high rate of stimulus presentation should overcome this issue (See et al., 1995). A high rate of stimulus presentation is typically considered to be 24 events/min and has been shown to reduce sensitivity to targets significantly (Loeb & Binford, 1968); in successive tasks, this has been shown to be an appropriate event rate to produce vigilance decrement effects (See et al., 1995). However, recent evidence has identified the need for cognitive vigilance tasks to use a higher event rate (40 events/min) to produce a more pronounced vigilance decrement compared to the aforementioned "high" event rate, with fewer hits, more false alarms, and reduced sensitivity as measured by signal detection theory in higher event rate conditions compared to low (Claypoole et al., 2019).

Importantly, the 24 events/min condition did result in vigilance decrement effects except in the proportion of false alarms (reduced proportion hits, higher reaction times, decreased sensitivity, and increased response bias). This supports the use of 24 events/min as a means to produce vigilance decrements but highlights that this may not be the most effective event rate in a 20-minute vigil with a target rate of 5 per 6-minute vigil. Fast event rates require the discrimination of signals from noise more frequently and, as such, deplete information processing resources to a greater extent (Sawyer et al., 2014). Moreover, signal probability affects the quality of sustained attention, with higher signal probability (or signal-to-noise ratio) resulting in reduced vigilance decrement (Sawyer et al., 2014).

Signal detection theory (SDT, Green and Swets (1966)) is a common approach to analysing data in vigilance or sustained attention research (Lerman et al., 2010; Sarter et al., 2001; Swets, 1977; Thomson et al., 2016). SDT examines an observer's behaviour in the presence of ambiguous stimuli and their ability to detect signals amongst background noise. However, drift diffusion modelling has been applied to working memory tasks, such as the *n*-back , with great effect (Lynch et al., 2019; Shine et al., 2016), suggesting utility in a working memory-based sustained attention paradigm. Drift diffusion modelling accounts for cognitive processes and provides a decomposition of behavioural performances into cognitively relevant latent variables representing the speed and accuracy of information processing (Ratcliff & McKoon, 2008). Drift diffusion modelling assumes that decision-making is a noisy process where information is accumulated over time; Figure 16 depicts this process adapted from Ratcliff and McKoon (2008). While drift diffusion modelling may appear qualitatively similar to SDT, the inclusion of reaction time data allows for analysis of information processing speed, non-decision time encoding and motor executive processes, and speed accuracy trade-offs (Sarter et al., 2001). As such, the use of both modelling techniques will allow for comparison with existing literature on sustained attention (SDT) while allowing for examination of speed/accuracy trade-offs in VGP compared to NVGP.

Figure 16

Drift Diffusion Decision Model (Ratcliff & McKoon, 2008)



*Note: Depicted is the Drift Diffusion Decision Model adapted from Ratcliff and McKoon (2008). Boundary separation (**a**), drift rate (**v**) and Non-Decision time (**Ter**) are displayed during a fictitious two-choice trial.*

Figure 16 represents the rate of information accumulation, termed "drift rate" (*v*). Additionally, the speed of motor and perceptual processes not directly related to decision processes, such as stimulus encoding and response execution, are included in this model, and termed "non-decision time" (*T*er). Lastly, a measure of the speed-accuracy trade-off is supplied using the variable boundary separation (*a*), illustrating response caution. In regards to *n*-back data higher drift rates index improved *n*-back performance, whereas lower drift rates demonstrate fewer correct responses and more variable reaction times (Lynch et al., 2019; Shine et al., 2016).

Previous research has observed that alterations to the executive function capabilities as a result of Attention Deficit Hyperactivity Disorder result in slower drift rates and faster non-decision times, resulting in a slower information processing system but no speed-accuracy trade-off, compared to controls, as measured by drift-diffusion modelling on a stop signal task (Karalunas & Huang-Pollock, 2013). Therefore, it is predicted that video game players will be observed to exhibit faster non-decision times as a result of increased speed of psychomotor skills (Chalhoub et al., 2016) and faster drift rate, exemplifying enhanced executive control over the information accumulation processes (Colzato et al., 2013; Nuyens et al., 2019).

Video Game Use and Sustained Attention

Video game-based interventions, where patients are trained on video games or engage in casual video game play, have been proposed in regard to an ever-expanding list of disorders and impairments, such as a form of visual impairment known as amblyopia (Gambacorta et al., 2018) and age-related cognitive decline (Basak et al., 2008; Stern et al., 2011). A systematic review by Pallavicini et al. (2018) demonstrates the efficacy of video game-based interventions in improving the well-being of adults. This is not only for non-commercial video games developed with the express purpose of video game training to ameliorate conditions or improve performance, coined “serious games” (Susi et al., 2007; Zyda, 2005), but also commercial video games.

However, despite the interest in using video game play as an intervention, at the time of writing, very little research has been conducted on the effects of video game use on sustained attention (Schmidt et al., 2013; Trisolini et al., 2018). The primary focus of research on the effect of video game use on attention is primarily on visual selective attention due to the nature of stimuli presented in video games (Green & Bavelier, 2003, 2006a), high rate of stimuli presentation, high field of view, and multiple object tracking.

This selective visual attention research has demonstrated that action video game play is related to behavioural improvements, with improvements in performance observed in behaviours related to the three main attentional networks (Petersen & Posner, 2012; Posner & Petersen, 1990); Alerting (Colzato et al., 2013; Dye et al., 2009a, 2009b; West et al., 2008), orienting (Dye et al., 2009a), and executive control (West et al., 2008; Hummer at al., 2010; Li et al., 2010; Green & Bavelier, 2010; Chisholm et al., 2010; Chisholm & Kingston, 2011; Little et al., 2012; Wang et al., 2017; Deleuze et al., 2017). A crucial caveat to these findings is that improved performance by video game play on attentional tasks appears to only be exhibited when the task is sufficiently demanding. That is when there is an increase in cognitive load, action video game players (VGP) will outperform the non-video game player (NVGP) counterparts (Green & Bavelier, 2007).

Additionally, a causal link has been established between video game play and improved performance on a range of selective attention tasks, evidenced by training studies with varying methodologies (Ballesteros et al., 2017; Baniqued et al., 2014; Bediou et al., 2018; Boot et al., 2017; Glass et al., 2013; Green & Bavelier, 2006a, 2007; Hutchinson et al., 2016; Kuhn et al., 2017; Li et al., 2010; Olfers & Band, 2018; Stern et al., 2011; Szalma et al., 2018; Teo et al., 2012; Wang et al., 2014; Wang et al., 2016; Wu & Spence, 2013). The primary results here demonstrate the ability of video game training to improve performance on selective attention tasks compared to NVGP controls or baseline. However, there is evidence that this causal link may not be consistently supported by observed data (see Sala et al. (2018) for a meta-analysis). One such example is that there is an improvement in performance on a flanker task as a result of video game training, but only in younger adults; no improvement was observed in participants aged 58 and over (Wang et al., 2014). Yet, Basak et al. (2008) demonstrated improved performance on a range of tasks assessing aspects of executive control in 18 participants with an average age of 68.89 (*SD* = 5.03) with the use of real-time strategy video game training, when compared to age matched controls (*N* = *16,M* = 69.88, *SD* = 5.92). Thus, demonstrating the ability for video game use to improve a wide array of cognition, dependent on the genre utilised in interventions. A meta-analysis on action video game training in healthy adults by Wang et al. (2016) found moderate benefit from training in overall cognitive ability and a moderate to small benefit in specific cognitive domains. In both overall cognitive ability and domain specific improvements, young adults benefited more than their older adult counterparts.

The improved performance observed in selective attention research (albeit with the observed heterogeneity of results) can be taken in conjunction with current sustained attention models to inform predictions for the effect of video game use on sustained attention. Of particular relevance to this thesis is the improved performance observed in tasks designed to assess executive functions.

To continue, predictions on the effects of video game play on sustained attention can be informed by the limited previous research in this area, although to date, only one cross-sectional design and one training design have been conducted (Schmidt et al., 2013; Trisolini et al., 2018). Schmidt et al. (2013) utilised a game-based vigilance task and found that VGP outperformed NVGP in the proportion of correct responses across the vigil. However, it was noted that the observed difference between groups was more pronounced in training on the game-based task than during the transfer test phase. During the training phase, there was a target rate of 2.05; during the test phase, there was a target rate of 1.96, with a duration of 18 minutes and 24 minutes, respectively. However, it is more probable that VGP experience benefits were offset by short-term gains following training by the NVGP condition and not task difficulty or target/event rate. Moreover, in this kind of gamified vigilance task it is not clear what would be considered an "event" as stimuli are not presented in discrete trials. While this holds value to real-world experiments, particularly of the target population of bomb disposal experts, it limits the ability of the research to be interpreted in regard to the wider research area.

Trisolini et al. (2018) conducted a sustained attention task, in the form of a jumping square task, to assess the effect of action video game play on performance in this task in adolescents (age: *M*=15, *SD*=0.83). While it is noted that adolescents sustained attention capabilities are relatively fully developed at this age, their results did not demonstrate a difference in the sustained attention metric. Attentional capacity, as measured by the visual enumeration task, did support the notion of increased attentional function in action video game players, but the results in the sustained attention task demonstrated increased sustained attention performance in the initial phase of the task along a more severe vigilance decrement as time on task increased. It is not possible to ascertain the event rate in the description provided, but a target rate of 18 per 10-minute vigil was reported. Importantly, there was no manipulation of executive load in this paradigm which may have limited the ability of the task to identify the enhanced sustained attentional function in action VGPs adequately. In regard to the resource control theory of sustained attention (Thomson et al., 2015) it is possible that as the task was not sufficiently demanding the additional executive resources were diverted to task-unrelated thought, and once time on task effects began to diminish performance, it was not possible to redirect the executive function resources back to task-related thought in VGPs.

Therefore, the aim of the present study is to investigate the effects of video game use on sustained attention through the use of a continuous performance task that measures working memory capability to enable for the manipulation of cognitive load on an executive function task whilst sustaining attention. This should allow for the inclusion of Green and Bavelier (2007) findings that the hypothesised improved performance of VGP is a result of improved executive function in sufficiently demanding tasks. Moreover, keeping a consistent target rate with Trisolini et al. (2018) of 18 targets per 10 minute vigil but across a 30 minute period of watch with an event rate of no less than 24 event/min should allow for direct interpretation of the findings. It is hypothesised that in conditions of low or no attentional load there will be no significant difference in the reaction times and accuracy data between the two groups. In the high load condition, we expect to observe VGPs performance to be significantly better than NVGPs. This will be identified by faster reaction times and high percentage of accuracy. It is expected that there will be a similar trend of decrement between the two groups in no and low load, but with the two groups significantly differing at high load, with VGPs showing less vigilance decrement. This will be assessed by dividing the 30-minute vigil into three time points of ten minutes, for both reaction time and accuracy. Diffusion modelling and signal detection theory (Green & Swets, 1966; Stanislaw & Todorov, 1999) will also be applied to the data and similar results are expected from these variables.

Methods

Participants

A total of 40 Swansea University students (25 males, with an age range of 19 – 35, M = 22.45, SD = 3.85), all right-handed with normal or corrected-to-normal vision, participated in the current study. No participants reported neurological conditions or to be on any medication known to modulate attentional functions. Participants completed a questionnaire to determine their video game play status (described below), and were subsequently selected and divided into two groups; video game players (VGP) (12 males, 8 females; age *M* = 20.80 *SD* = 1.77), and non-video game players (NVGP) (3 males, 17 females; age *M*=24.10 *SD*=4.64). The criterion for inclusion in the VGP condition was 6 hours of video game play per week for the last 6 months. For inclusion in the NVGP condition, the requirement was less than 1 hour per week of video game play over the last 6 months. These criteria were established upon review of previous research to ensure a valid comparison (Trisolini et al., 2018; Chisholm & Kingstone, 2011; Green & Bavelier, 2010; 2007; 2006; 2003).

Participants were reimbursed with course credits for their participation, with a travel cost renumeration of £5 upon the completion of the final session of this study. All participants provided informed consent in accordance with the guidelines set by the ethics committee at Swansea University. All participants provided signed, informed consent to participate in the study, which was approved by the School of Psychology Ethics Committee, Swansea University.

Materials

As per the requirements of Swansea University ethics, all participants were supplied with an information sheet with rational and experimental details. Furthermore, a consent form and a debrief form were supplied to all participants who took part. A series of self-report questionnaires were used throughout this experiment. In chronological order of their administration to participants, they were: video game habits self-report, a demographics questionnaire, pre-screening form, the SUPPS-P impulsive behaviour scale (Cyders et al., 2014; Cyders et al., 2007), Stanford sleepiness scale (Hoddes et al., 1973), and the National Aeronautics and Space Administration task load index (NASA TLX(Hart, 2016; Hart & Staveland, 1988)). The SUPPS-P was described in Chapter 2 Methods Materials, the same version was used in this study.

Video Game Habits Self-Report, Demographics, and Pre-screening forms

The video game habits self-report asked participants to report how many hours per week they played action video games over the last six months and which titles and genres they recall playing. The demographics questionnaire was used to obtain information regarding the participant's age, gender, and level of education. The pre-screening form was administered to obtain information regarding handedness, visual acuity (normal or corrected to normal), medication (that may affect attentional capabilities), and neurological conditions (relating to attentional function).

The Stanford Sleepiness Scale (SSS; Hoddes et al., 1973)

The Stanford sleepiness scale is a seven-point scale that determines the degree of sleepiness the participant is currently experiencing (Hoddes et al., 1973). The participant is asked to use the seven-point scale below to pick what best represents how they are feeling at the current moment in time. The options range from 1 – "*Feeling active, vital, alert, or wide awake*" to 7 – " *No longer fighting sleep, sleep onset soon; having dream-like thoughts*", with a range of options in between. This was used to determine if participants would be able to participate in a vigilance task without producing a confound of sleep deprivation. Therefore, participants responding with a value of 4 or greater were rescheduled for a later date and reassessed before commencing the experimental session.

National Aeronautics and Space Agency Task Load Index (NASA TLX; Hart, 2006)

Lastly, the NASA TLX, is a multi-dimensional scale that estimates the workload experienced by the participant immediately after (or during) performing a task (Hart, 2016; Hart & Staveland, 1988). There are 6 subscales that represent relatively independent groups of variables: mental demand, physical demand, temporal demand, effort, performance, and frustration level. The NASA TLX is a two-part evaluation procedure that consists of weights and ratings.

The NASA TLX procedure begins upon completion of the experimental task (here, the n-back). Initially, participants are informed of the scale/factor definitions; for instance, performance is defined as how well they feel they undertook the task. Then the participants evaluate each factor's contribution to a specific task's workload (the weight). This is undertaken using 15 possible pair-wise comparisons of the 6 subscales. Each pair is presented on a card; participants circle or name which of the pair contributed more to the perceived workload of the task, for instance, physical demand or mental demand. The number of times each subscale is selected is then tallied by the researcher, which are then ranked to produce a weighting for each of the subscales. Then, participants rate each of the six subscales independently using the definitions provided earlier. Each scale includes descriptions of “Low” and “High” or “Good” and “Poor” on either end of the scale. The scales represent a numerical range of 0 – 100 that is divided into 20 equal intervals, each representing increments of five. After this, the researcher is then able to produce an adjusted rating by multiplying the weight by the raw rating for each subscale and the weighted rating using the adjusted rating divided by 15. The weighted rating is then the final score and represents the perceived workload experienced by the participant.

Task presentation

The computerised task used in this study was presented on a “DELL P2214H” monitor with a resolution of 1920 x 1080. The python-based software package OpenSesame was used to both design and run the n-back, in particular OpenSesame version 3.2.6 (Mathot, Schreji, & Theeuwas, 2012) using the “Psycho” backend with “psychopy” 1.85.3 (Peirce et al., 2019Openseame ran on a “DELL Optiplex 9020 SFF” running “MAC OS”.A standard qwerty keyboard was used to obtain responses from participants.

N-back task

In addition to the materials detailed above, a continuous performance computerised task was administered as part of this experiment, a verbal *n*-back. Although, as previously stated in the introduction, the *n*-back is typically considered a task assessing the function of working memory monitoring, it has direct comparisons to functions of attention particularly executive function (Scharinger et al., 2015). The *n*-back increases the attentional load with each level. Three experimental conditions (levels of the *n*-back) were used in this experiment; 0-back, 1-back, 2-back.

At 0-back, or no load, the participant is required to respond to a target letter “x” by pressing the space bar on the on the keyboard. For all other sequentially presented letters the participant must not respond, identifying the stimuli as a non-target. For the 1-back condition, or low load, the participants were required to respond by pressing the space bar when the letter currently presented on the screen matches that presented one trial ago (immediately before). Again, all non-targets required no response. At the 2-back, or high load condition, the participant was required to respond with the space bar if the stimuli currently displayed matched that presented two letters ago, also termed two back. Behavioural measures of accuracy and reaction times (milliseconds) were recorded by PsychoPy and saved in an output file. Further data were obtained from the participants through the completion of each condition.

The verbal stimuli presented sequentially in the n-back were obtained from a set list of possible letters: 'a','b','c','d','e','f','g','h','j','k','m','n','o','p','r','s','t','u','w','y','z’. All letters had a height of 100 pixels and were presented in Arial font at position (0, 0) in pixels. The letters and background were both grey; 128, 128, 128 in rgb. All trials containing stimuli were presented for a duration of 1000ms or until the participant responded. In each experimental condition there were 720 trials and 721 inter stimulus intervals, for a total duration of 30 minutes. The inter-stimulus intervals were jittered between five possible times in milliseconds: 1100, 1300, 1500, 1700, and 1900, resulting in an event rate of 24 events/min.

There were 51 trials conforming to the demands of the task (targets) and as such requiring a response of pressing the space bar, per condition. This was established in order to be comparable with Trisolini and colleagues’ (2018) research on VGP and sustained attention, in which there were 18 targets per 10 minutes of time on task. The present experiment presents 17 targets per 10 minutes of time on task.

All stimuli were presented on a Gabor grating with rgb colour 1, 1, 1. The Gabor grating was opaque, orientation of 45 degrees, position of (0, 0), and a size of (0.9, 0.9) The texture used in presenting the Gabor grating is sin, with a gauss mask. There was a linear interpolation, with no phase cycles, a spatial frequency of 20.0, and a texture resolution of 256. The inter stimulus interval consisted of the Gabor grating presented on the grey background, with a fixation cross. The fixation cross was opaque and had a width and height of 40 pixels, presented on the centre of the screen. The cross was again grey, 128, 128, 128 in rgb.

Prior to the commencement of any level of the n-back, self-paced instructions were presented to the participant in black font on a grey background, with a font of Arial and a size of 100 pixels. The instructions informed the participants of the responses required for targets and non-targets and how targets are determined for the given level of the *n*-back (i.e. 2-back the stimuli presented two ago). Training for each load followed the same format as the experimental trials. The training consisted of 100 trials with at least 7 targets to ensure they were familiar with task requirements and response criteria.

Design

A mixed model design was used for this experiment; the between-group variable was video game play status, and the within-subject manipulation was attentional load (no, low, and high load), determined by the level of the *n*-back. A second within-subjects condition was the time point on each level of the *n*-back, which was split into 3 intervals of 10 minutes. This experiment had three experimental sessions and a pre-screening session, an experimental session for each load on the *n*-back.

Procedure

Potential participants were invited to a pre-screening session to determine their eligibility to participate in the current study. Potential participants provided informed consent and completed the video game habits self-report the demographics questionnaire, and the exclusion criteria questionnaire. Upon completion of these documents, the researcher assessed responses to determine eligibility. If participants were deemed ineligible to participate, they were withdrawn from the study and reimbursed with 15 minutes' worth of internal participant recruitment credits. If eligible, they completed the SUPPS-P and the Stanford sleepiness scale (SSS). This concluded the pre-screening session for participants who responded with values of three and below of the SSS, they immediately proceeded to the first experimental session. If the time SSS values were four or greater, the participant was given a date to participate in the first experimental session.

Participants completed the SSS again (the same criteria for rescheduling were applied) and were given a training session with instructions displayed prior to undertaking the training. The training consisted of 100 trials with at least 7 targets to ensure they were familiar with task requirements. After the participant was trained, the participant completed the given level of the *n*-back condition for that session for a duration of 30 minutes. The order in which the participants undertook the three levels of the *n*-back was randomised, but all completed each level once. Participants then completed the NASA TLX and were given the details for when the next experimental session would be conducted. The next session was held no sooner than 7 days after the one preceding it, to avoid carry-over effects. Each session followed the same format, with the only exception being the load administered with the *n*-back, with the remaining levels used. Upon the culmination of the third and final experimental session participants were thanked for their participation, given a £5 travel renumeration and course credits, and fully debriefed.

Results

The hypotheses made for this study were as follows. Firstly, participants identified as VGP would outperform NVGP controls in high cognitive load (2-back) conditions. It was then hypothesised that performance would be different between the two groups at low load (1-back) and no load (0-back). This would be demonstrated in both reaction and proportions of hits and false alarms, where faster reaction times and higher proportions of hits would be indicators of better performance. Regarding diffusion modelling, it was hypothesised that data from the VGP condition would show a reduced decision time and drift rate across all time points in high and low loads, compared to NVGP. Regarding signal detection theory, it was hypothesised that VGP would demonstrate a higher level of perceptual sensitivity and a more conservative response bias.

Prior to analysis, this data was pre-treated to remove outliers. For reaction time, an average reaction time was produced for each participant, in each load, at each time point. Individual reaction times that were more than had an absolute Z score of 2.5 or greater from their relative average reaction time (that is, in the same participant, load, and time point) were removed. This criterion was established based on approaches observed in sustained attention paradigms and working memory task analysis (Blotenberg & Schmidt-Atzert, 2019; Yeung & Han, 2023; Yeung et al., 2021). This led to the removal of 57 data points across all conditions and time points.

Diffusion modelling on this data was completed using the "EZ diffusion model for response time and accuracy" (Wagenmakers, van der Maas, & Grasman, 2007). Measures of drift rate (v), boundary separation (a), and non-decision time (T_{er}) were obtained.

The proportion of correct responses and false alarms were checked for outliers; each load and timepoint were averaged for each group and Z scores were produced for every participant's proportion for that block. Proportions of correct responses and false alarms with Z scores with an absolute value greater than 2.5 were replaced with the mean for that block (the average proportion of correct/ false alarms for participants in that group under that load at that timepoint). The criterion of an absolute Z score of 2.5 was used to identify accuracy outliers to keep consistency with reaction time processing. The mean replacement was only undertaken for the data analysis of Diffusion modelling, as this method required complete data sets and could not handle discrepancy of observations across sub-plot factors (Wagenmakers et al., 2007), thus eliminating the possibility of removing outliers from data completely. However, in subsequent analyses, missing data and data removed due to being an outlier were not replaced with any value.

Diffusion Modelling

Drift diffusion modelling was fitted to each participant's behavioural performance for each level of the *n*-back using the EZ-diffusion model (Wagenmakers et al., 2007). Diffusion modelling accounts for cognitive processes and provides a decomposition of behavioural performances into cognitively relevant latent variables representing the speed and accuracy of information processing (Ratcliff & McKoon, 2008). This represents the rate of information accumulation, termed "drift rate" (*v*). Additionally, the speed of motor and perceptual processes not directly related to decision processes, such as response execution and stimulus encoding, are included in this model, and termed "non-decision time" (*T*er). Lastly, a measure of the speed-accuracy trade-off is supplied using the variable boundary separation (*a*), illustrating response caution.

Through the theorised increased executive function of VGP players (Dye et al., 2009a; Green & Bavelier, 2015; Wang et al., 2017), it was predicted that both a faster drift rate and a lower non-decision time would be recorded, which would suggest a faster progression throughout all stages of information processing from perception to action execution (Shine et al., 2016). Additionally, NVGP would demonstrate a higher response boundary, exhibiting a more severe speed-accuracy trade-off typically in higher cognitive loads, as a result of fewer executive function resources compared to VGP, resulting in the need to produce faster but more error-prone responses and thus a reduced response caution.

Traditionally, diffusion modelling is only applied to data with reaction times (RT) that are less than 1500 msec and are from decisions that are captured from a single-stage decision process (Ratcliff & McKoon, 2008). Here, Ratcliff and McKoon (2008), state that multiple-stage processes such as reasoning tasks are not appropriate for modelling, and in it would appear that the *n*-back (in 1-back and 2-back variations) which requires the maintenance and updating of a dynamic rehearsal while responding to every trial would be in violation of this. However, diffusion modelling has been applied to reaction time data in cognitive psychology since its inception (Ratcliff, 1978); and there are examples of this in various paradigms not originally intended by Ratcliff and McKoon (2008) (Voss et al., 2013).

As mentioned in the introduction of this chapter, this method of diffusion modelling has been applied to *n*-back data with great effect (Lynch et al., 2019; Shine et al., 2016). Higher drift rates index improved *n*-back performance, whereas lower drift rates demonstrate fewer correct responses and more variable reaction times. Additionally, as stated in Lerche and Voss (2016), a central assumption for diffusion modelling is that information is continuously accumulated and that once one of two response thresholds is met, this accumulation process ends. Here, the *n*-back being utilised as a continuous performance task to initiate a vigilance decrement would suit this supposition.

The descriptive statistics for drift rate are shown in Table 18. As can be observed in Table 18, VGP demonstrate a higher drift rate compared to NVGP across all levels of the *n*-back and each 10-minute time interval, although this difference is small. Prior to analysis assumptions of parametric analysis were observed by this data. To assess this interaction, a 2x3x3 repeated measures ANOVA was conducted on the data, VGP status (VGP and NVGP), attentional load (0-back, 1-back, 2-back) and time point (1,2,3).

There was a statistically significant effect of attentional load, $F(2,66)=62.76$, $p<.001$, but no significant interaction of attentional load and VGP status $F(2,66)=0.24$, $p=.79$.

Likewise, there was a significant effect of time point on drift rate, *F*(2,66)=8.43, *p*=.001, but no significant interaction between time points and VGP status, *F*(2,66)=0.74, *p*=.742.

Lastly, a significant interaction was observed between load and time point, *F*(4,132)=3.72, *p*=.007, but no interaction between load, time point and VGP status, *F*=(4,132)=0.75, *p*=.56. Additionally, no between-subjects' effects were observed *F*(1,33)=0.20, *p*=.66. The above demonstrates that as the task increased in attentional load and as time on task increased, the rate of information accumulation was significantly affected, suggesting that vigilance decrement effects equally hindered the ability of both groups to successfully process information to discern signals from noise.

Table 18

Drift rate Means and Standard Deviation (SD), across load (level of n-back), time point, and VGP status (3dp).

Load	Time Point	VGP status	Mean	*SD*
0-back	1	NVGP	0.033	0.005
		VGP	0.035	0.005
	2	NVGP	0.032	0.006
		VGP	0.034	0.006
	3	NVGP	0.032	0.006
		VGP	0.036	0.004
1-back	1	NVGP	0.028	0.006
		VGP	0.026	0.011
	2	NVGP	0.023	0.009
		VGP	0.024	0.015
	3	NVGP	0.021	0.009
		VGP	0.023	0.014
2-back	1	NVGP	0.016	0.008
		VGP	0.018	0.009
	2	NVGP	0.018	0.011
		VGP	0.019	0.008
	3	NVGP	0.014	0.014
		VGP	0.014	0.010

Note: Timepoint: 1=0-10 minutes, 2=10-20 minutes, 3=20-30 minutes. VGP=Video game player, NVGP= non-VGP

The descriptive statistics for variable boundary separation are displayed in Table 19, during low loads, VGPs demonstrate a similar overall mean boundary separation to controls, but remain stable with increasing time whereas NVGPs boundary separation reduce as time on task increases. This is the case for both no load (0back) and low load (1back). In high load, VGP show a similar reduction in boundary separation as time on task increases but their boundary separation is consistently higher in each time point than their NVGP counterparts.

This suggests that NVGP are more prone to adopting a more liberal speed accuracy trade off as the effects of time and cognitive load increase compared to VGP. To assess this interaction, a 2x3x3 ANOVA was conducted on the data, VGP status (VGP and NVGP), load (0back, 1back, 2back) and time point (1, 2,3). A statistically significant effect of load was observed, *F*(2,66)=28.92, *p*>.001, but the interaction between load and VGP status did not meet significance, *F*(2,66)=2.64,*p*=.08. Further, no significant effect of time point was observed, *F*(2,66)=.28,*p*=.76, and no interaction between time point and VGP status, *F*(2,66)=.45,*p*=.63, load and time point, *F*(4,132)=1.59, *p*=.18, and load, time point and VGP status, *F*(4,132)=2.20,*p*=.07. Likewise, there was no between subject effects, *F*(1,33)=1.32, *p*=.26.

Table 19

Boundary Separation Means and Standard Deviation (SD), across load (level of n-back), time point, and VGP status (3dp).

Load	Time Point	VGP Status	Mean	SD
0-back	1	NVGP	0.926	0.077
		VGP	0.950	0.074
	2	NVGP	0.973	0.093
		VGP	0.926	0.100
	3	NVGP	0.970	0.065
		VGP	0.952	0.078
1-back	1	NVGP	0.933	0.132
		VGP	0.932	0.126
	2	NVGP	0.858	0.093
		VGP	0.930	0.131
	3	NVGP	0.864	0.123
		VPG	0.913	0.095
2-back	1	NVGP	0.801	0.055
		VGP	0.884	0.119
	2	NVGP	0.826	0.127
		VGP	0.873	0.127
	3	NVGP	0.836	0.119
		VGP	0.840	0.108

Note: Timepoint: 1=0-10 minutes, 2=10-20 minutes, 3=20-30 minutes. VGP=Video game player, NVGP= non-VGP

Thus, suggesting that time on task did not affect the response conservativeness in all participants, and that only when the cognitive load increased did participants become more liberal in their response criterion. It appears this effect is independent of the vigilance decrement and only affected by cognitive load. This also suggests that the effects of increased impulsivity in VGP participants did not affect their response criterion, perhaps as a result of increased executive function allowing more impulsive responses that do not result in more errors discerning the target from non-targets and resulting in comparable performance to the NVGP control. This will be investigated further when taking into account non-decision time.

Table 20 shows the descriptive statistics for non-decision time; as can be observed in all loads, NVGP non-decision time is higher than that of VGP in each time point; however, as time on task increases, the size of this difference is reduced. A 2x3x3 ANOVA was conducted on non-decision time data, VGP status (VGP and NVGP), load (0back, 1back, 2back) and time point (1,2,3). Prior to inferential analysis, the data was checked to ensure there were no violations of parametric assumptions; a violation of sphericity was observed in time point data, hence the Greenhouse-Geisser correction was applied.

There was a significant effect of load, $F(2,66)=32.21, p<.001$, but no evidence of an interaction between load and VGP status, $F(2,66)=.55, p=.58$. Likewise, there was a significant effect of time point, $F(1.64, 54.21)=8.04, p=.003$, but no evidence of an interaction between timepoint and VGP status, $F(1.64, 54.21)=1.88, p=.17$. There was a significant interaction between load and time point, $F(3.39,117.72)=4.50, p=.002$, but no interaction of load, timepoint, and VGP status, $F(3.39,117.72)=.77, p=.53$. Lastly, there was no between-subjects effect of VGP status, $F(1,33)=.60, p=.45$.

This suggests that both increased load and time on task prolonged non-decision time, which may be a result of increased workload, particularly if physical fatigue is affecting participants at later time points. Additionally, VGP participants demonstrated no reduction in non-decision time compared to NVGP. This suggests that the hypothesised increase in executive function in VGP does not lead to less lag time between perceptual processing and motor response, further casting doubt on the perceived increased performance on visuospatial working memory tasks as a result of training motor response. The effect of cognitive load on non-decision time is noteworthy, perhaps demonstrating a cognitive “slow down” resulting in slower motor responses.

Table 20

Nondecision time Means and Standard Deviation (SD), across load (level of n-back), time point, and VGP status (2dp).

Load	Time Point	VGP Status	Mean	SD
0-back	1	NVGP	578.56	59.78
		VPG	559.80	79.52
	2	NVGP	582.56	66.86
		VGP	568.09	79.30
	3	NVGP	564.75	84.60
		VPG	569.49	71.34
1-back	1	NVGP	611.81	82.24
		VGP	604.78	91.08
	2	NVGP	662.77	94.75
		VGP	635.34	92.39
	3	NVGP	651.46	95.06
		VGP	653.69	118.17
2-back	1	NVGP	664.64	63.16
		VGP	646.05	81.71
	2	NVGP	686.08	87.12
		VGP	641.43	88.07
	3	NVGP	686.78	75.90
		VGP	655.06	70.62

Note: Timepoint: 1=0-10 minutes, 2=10-20 minutes, 3=20-30 minutes. VGP = Video game player, NVGP = Non-VGP.

Signal Detection Theory

To evaluate the effects of VGP status in varying amounts of cognitive load during a vigilance experiment on sensitivity of decision making, signal detection theory (SDT(Green & Swets, 1966)) was performed on this data. SDT examines an observer's behaviour in the presence of ambiguous stimuli and their ability to detect signals amongst background noise. This ambiguity in the *n*-back paradigm is the decision if the stimulus currently presented matches the stimuli stored in the phonological loop and meets the task requirements (target) or if the currently presented stimulus does not match stimuli stored in the phonological loop and or meet the demands of the task for the given cognitive load (noise). Unlike boundary separation in diffusion modelling, due to the lack of the inclusion of the reaction time, SDT offers additional information, modelling perceptual processing to characterise signal detection performance based on independent measures of perceptual sensitivity and response bias (See et al., 1997). Utilising the information from correctly identified targets and noise is termed hit rate (*H*, based on hits and correct rejection); as well as mistakenly identifying targets as noise and vice versa, termed false alarm rate (*F,* produced using misses, and false alarms).

The first dimension is the ability of the observer to discriminate the targets from noise termed perceptual sensitivity. Here, two frequently used measures include the nonparametric index *A'* and the parametric equivalent *d'* (See et al., 1997; Stanislaw & Todorov, 1999). However, the use of *A'* has been disputed by Zhang and Mueller (2005) with the recommendation made that *A* is a more suitable alternative for nonparametric index of perceptual sensitivity. As the data that SDT is being applied to does not meet the assumptions for parametric analysis, *A* was calculated using the method detailed in Zhang and Mueller (2005) to avoid making distributional assumptions. While the index *A'* is suitable when *H* or *F* is close to or equal to 1 or 0, which from Tables 23 and 24 is an issue of particular relevance to the current data set, the theoretical implications of using this measure when there is a dispute over whether it is truly devoid of assumptions of distributions warrants additional caution (Pastore et al., 2003), and as such the use of the index *A* was employed for this data set.

Similarly, response bias has the parametric index β as well as a range of non-parametric indices including *B''* and B'_H (see Stanislaw and Todorov (1999) for a full discussion of these indices). Given that *A* is being utilised to nonparametrically index perceptual sensitivity, the associated response (or here decision) bias will be indexed using *b* that was constructed alongside the latest proof of *A* (Zhang & Mueller, 2005). Additionally, as stated by Pastore et al. (2003), *A'* and *B''* are not independent measures and under certain conditions *A'* is not an accurate estimate of the area under the receiver operating characteristic curve.

Consistent with traditional parametric indices of perceptual sensitivity, larger *A* values demonstrate an increased ability to discriminate between targets and noise, while more positive values for *b* indicate a conservative decision bias, while negative values suggest a liberal bias. Prior to analysis of this data, assumption checks for parametric analysis were applied. Significant violations of normal distribution were observed in both groups and across conditions. The nonparametric data was analysed using an R software package for the Nonparametric analysis of longitudinal data in factorial experiments (nparLD) (Noguchi et al., 2012). The package is a nonparametric equivalent of a factorial ANOVA, and as such, there were no violations of assumptions within the current data set. Here, nparLD works in the case of missing data, eliminating the need to impute missing data or exclude participants from analysis; such rank-based methods are robust to outliers. This procedure makes no assumption based on distribution, and the shape of distribution may change between conditions (Brunner & Puri, 2001; Durand et al., 2020; Noguchi et al., 2012). The analysis package nparLD has been described in detail in Chapter 2 Results. Using the procedure established in Durand et al. (2020), relative treatment effect (RTE) statistics are used to estimate effect sizes which are proportional to Cohen's *d* when the data are normally distributed (Brunner et al., 2018; Brunner & Puri, 2001). Outliers were detected using the criterion of a Z score larger than 2.5 for the relevant timepoint, load, and group. This led to the removal of 12 data points in the *A* index calculations and 5 in *b*.

Perceptual Sensitivity

As can be observed in the descriptive statistics presented in Table 21, perceptual sensitivity is affected by increasing cognitive load and time on task. Yet, there appears to be little difference between the VGP and NVGP in terms of measures of central tendency or dispersion. This follows the trends previously observed in analyses on proportions of hits and false alarms and diffusion modelling analysis.

Table 21

Median (Mdn), Interquartile range (IQR) of Perceptual Sensitivity (A) for VGP and NVPG conditions on a n-back task across 30 minute a vigil

		VGP				NVGP			
N-Back	Time point	Mdn	IQR	Q1	Q3	Mdn	IQR	Q1	Q3
0	1	0.99	0.00	0.99	0.99	0.99	0.01	0.98	0.99
	2	0.99	0.00	0.99	0.99	0.99	0.01	0.98	0.99
	3	0.99	0.00	0.99	0.99	0.99	0.01	0.98	0.99
1	1	0.98	0.03	0.96	0.99	0.98	0.02	0.97	0.99
	2	0.98	0.06	0.93	0.99	0.97	0.03	0.95	0.98
	3	0.98	0.02	0.96	0.98	0.96	0.06	0.92	0.98
2	1	0.94	0.05	0.92	0.97	0.95	0.04	0.92	0.96
	2	0.93	0.08	0.90	0.98	0.95	0.07	0.91	0.98
	3	0.92	0.08	0.88	0.95	0.95	0.10	0.87	0.97

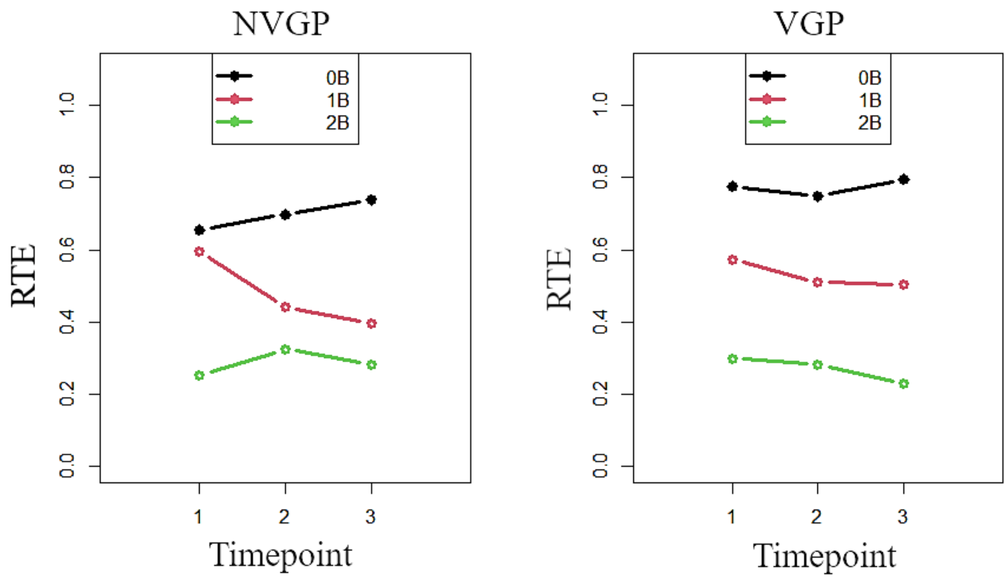
Note: *n*-back: 0=0back/ no load, 1= 1back/ low load, 2=2back/ high load. First Quartile (Q1), Third Quartile (Q3). Timepoint: 1=0-10 minutes, 2=10-20 minutes, 3=20-30 minutes.

To analyse perceptual sensitivity further, nparLD F1-LD-F2 analysis was conducted on cognitive load (manipulated by the level of the *n*-back) and time (30-minute vigil with performance averaged per 10 minutes) in the VGP and NVGP groups. RTE is used here as the measure of effect size, as the area under the Receiver Operating Characteristic (ROC) curve is equal to RTE, highlighting its utility as an effect size in this instance (Brunner et al., 2018). The main effect of within-subjects factor cognitive load was significant: $F(1, 38.58) = 113.15, p < .001$. Alternatively, the main effect of within-subjects factor time was not significant $F(1.91, 38.58)=1.6$, $p = .20$. The interaction of cognitive load and time was significant: $F(2.87,38.58) = 4.28$, $p < .01$. However, the between subjects factor of VGP status was not significant: $F(1, 38.58) = 0.62$, $p = .43$. Likewise, the interaction of: VGP status and cognitive load ($F(1.95, 38.58) = 1.23$, $p = .29$), VGP status and time ($F(1.90, 38.57) = 0.15$, $p = 0.85$), and VGP status, cognitive load, and time ($F(2.70,38.58) = 1.65$, $p = .18$) were not significant. This suggests that participants, irrelevant of recent video game play history, are less able to differentiate between targets and non-targets as the cognitive load increases, and that here again is an interaction with time on task. However, the hypothesised vigilance decrement is not provoked by increasing time on task alone and requires further manipulations of executive function capabilities to produce an effect on perceptual sensitivity. This would suggest that in contrast to the underload hypothesis (Braboszcz & Delorme, 2011; Humphrey et al., 2018; Pattyn et al., 2008), high cognitive load is needed to deplete executive function resources and affect perceptual sensitivity sufficiently.

Figure 17 displays relative treatment effects (RTE). A similar trend is observed here as in Table 21; however, there is a clearer treatment effect for VGP, with delineations between each load increasing throughout the time course. As with NVGP, there were larger effects at lower loads, which demonstrated a negative linear trend as load increased.

Figure 17

Relative Treatment Effect (RTE) of Perceptual Sensitivity (A) for NVGP and VGP at 0-, 1-, and 2-back across all Timepoints



Note: Relative treatment effect (RTE) statistics are estimate effect sizes which are proportional to Cohen's *d* (Brunner et al., 2018; Brunner & Puri, 2001).

Decision Bias

Table 22 provides the descriptive statistics for decision bias *b*. As cognitive load increased, both groups exhibited a more conservative response bias; however, this was more pronounced in the VGP condition compared to NVGP. Additionally, it can be observed that no and low cognitive load time on task has little effect on the decision bias of participants in each condition. Yet, in high cognitive load (2-back), the effect of time on task is more pronounced and varied between groups. VGP exhibits fluctuations across time, while NVGP bias demonstrates a negative linear trend, becoming more biased toward rejecting the stimuli presented. This may suggest a waning of executive function, with participants utilising a more stringent decision bias to maintain the appropriate vigilance level, mitigate the effects of vigilance decrement, and avoid producing more false alarms. Interestingly, this is not needed in low and no load, so this would suggest an effect of high cognitive load. However, there is a stark contrast between VGP and NVGP and time on task in these high and low cognitive load conditions.

Table 22

Median (Mdn), Interquartile range (IQR) of Decision Bias (b) for VGP and NVPG conditions on a n-back task across 30 minute a vigil

		VGP				NVGP			
N-Back	Time point	Mdn	IQR	Q1	Q3	Mdn	IQR	Q1	Q3
0	1	0.10	0.01	0.09	0.10	0.10	0.10	0.09	0.19
	2	0.10	0.09	0.10	0.19	0.10	0.03	0.09	0.13
	3	0.10	0.01	0.09	0.10	0.10	0.08	0.10	0.18
1	1	0.19	0.40	0.10	0.50	0.20	0.27	0.10	0.38
	2	0.19	0.61	0.10	0.71	0.37	0.38	0.20	0.58
	3	0.20	0.25	0.19	0.45	0.35	0.49	0.20	0.69
2	1	0.54	0.39	0.35	0.75	0.53	0.26	0.48	0.74
	2	0.48	0.54	0.20	0.74	0.50	0.67	0.19	0.86
	3	0.67	0.40	0.50	0.90	0.46	0.57	0.32	0.89

Note: *n*-back: 0=0back/ no load, 1= 1back/ low load, 2=2back/ high load. First Quartile (Q1), Third Quartile (Q3). Timepoint: 1=0-10 minutes, 2=10-20 minutes, 3=20-30 minutes.

To analyse decision bias further, nparLD F1-LD-F2 analysis was conducted on cognitive load (manipulated by the level of the *n*-back) and time (30-minute vigil with performance averaged per 10 minutes) in the VGP and NVGP groups. The main effect of within-subjects factor cognitive load was significant: $F(1.97, 37.33) = 103.00, p < .001$. Additionally, the main effect of within-subjects factor time was significant $F(1.94, 37.33)=3.23, p = .04$. Yet, the interaction of cognitive load and time was not significant: $F(3.77, 37.33) = 1.95, p = .10$. The between subjects factor of VGP status was not significant: $F(1, 37.33) = 0.48, p = .49$. Likewise, the interaction of: VGP status and cognitive load

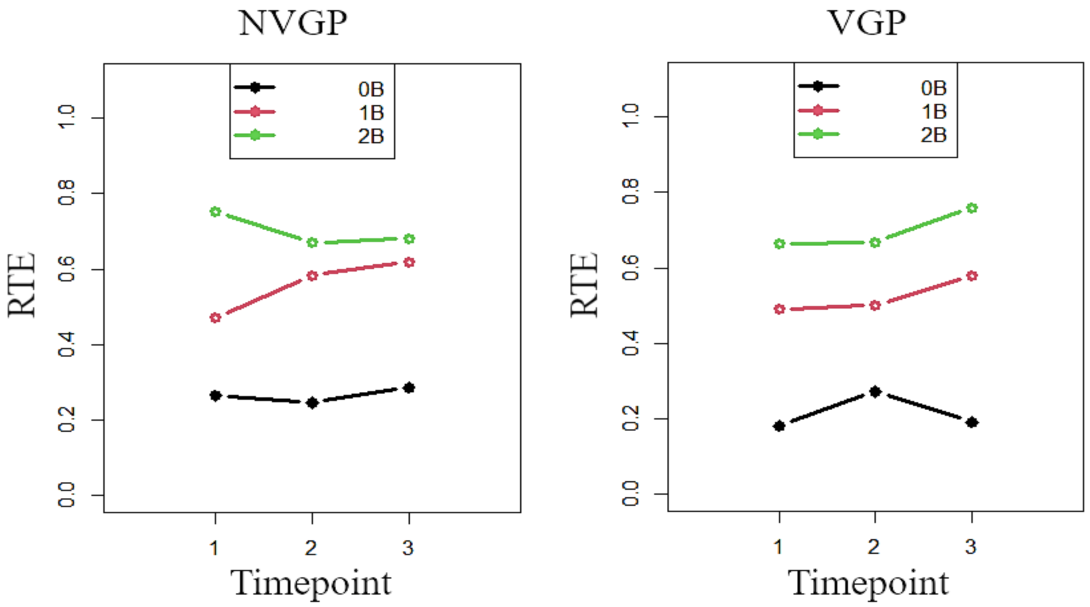
(*F*(1.97, 37.33) = 0.26, *p* = .77), VGP status and time (*F*(1.94, 37.33) = 0.47, *p* = 0.60), and VGP status, cognitive load, and time (*F*(3.78, 37.33) = 2.31, *p* = .06) were not significant.

These findings, along with Figure 18, demonstrate that the control 0-back condition has little to no effect on the participant's decision bias regardless of group allocation compared to the 1-back and 2-back conditions. There is, however, an effect of cognitive load and time on task here with an interaction of the two within-subjects factors that do not meet significance. To investigate this further, 0-back was removed from the analysis, and an F1-LD-F2 analysis was conducted. The same parameters were used as established above only with the removal of 0-back conditions. Conceptually, this is not without merit, as the demands of the 0-back condition differ greatly from those of the 1-back and 2-back conditions. There is little to no activation of the phonological loop in 0-back, with the target detection based on stimuli attributes and not if this stimulus was presented previously within a certain presentation series. It could, therefore, be argued that this demonstrates a different perceptual process.

When 0-back is excluded from analysis, similar effects are observed. The main effect of the within-subjects factor cognitive load was significant: *F*(1, 35.66) = 24.91, *p* < .001. Additionally, the main effect of within-subjects factor time was significant *F*(1.98, 35.66)=3.46, *p* = .03. Interestingly, the interaction of cognitive load and time did not reach significance: *F*(1.97, 35.66) = 2.87, *p* = .06. The between-subjects factor of VGP status was not significant: *F*(1, 35.66) = 0.01, *p* = .97. Likewise, the interaction of: VGP status and cognitive load (*F*(1, 35.66) = 0.14, *p* = .71), VGP status and time (*F*(1.98, 35.66) = 0.59, *p* = .55), and VGP status, cognitive load, and time (*F*(1.97, 35.66) = 2.40, *p* = .09) were not significant.

Figure 18

Relative Treatment Effect (RTE) of Decision Bias (b) for NVGP and VGP at 0-, 1-, and 2-back across all Timepoints



Note: Relative treatment effect (RTE) statistics are estimate effect sizes which are proportional to Cohen's *d* (Brunner et al., 2018; Brunner & Puri, 2001).

These results suggest that while the *n*-back is a valid tool to manipulate participants' decision bias regardless of video game experience and that vigilance decrement affects both groups equally, there is no interaction with cognitive load and time on task. This may suggest that the effects of both *n*-back and time on task do not provide sufficient demand on the participants to alter their decision bias further. The inclusion of a 3-back condition may produce this effect as participants become more liberal as the demands outweigh their available executive function resources, but this will be discussed further in the discussion.

Behavioural Data

Accuracy – Proportion Correct and False Alarms

Prior to the analysis of this data, assumption checks for parametric analysis were applied. Violations of normal distribution were observed in both groups and across conditions via analysis with the Wilks Shapiro test (p>.05). Therefore, nonparametric analysis of longitudinal data was utilised for these analyses (except were stated otherwise in instances where the data conformed to parametric analysis). Proportions correct (correct identification of targets and noise) and false alarms (responding to noise as if it were a target) were obtained from the data for each participant, in each load, and at each time point.

The descriptive statistics for proportion correct responses are shown in Table 23. As can be observed here, there is a clear vigilance decrement in the VGP group in 2-back where, whereas NVGP performance remained relatively stable across time points regardless of the level of the *n*-back. We can also observe that performance, as measured by the proportion of hits, reduced as the cognitive load was increased, as expected. The Plots are made for the 1-back and 2-back levels of the *n*-back in Figures 19 and 20. The results from 0-back have been excluded here as, as can be observed in Table 23, there were ceiling effects with both groups achieving perfect performance. While this has implications for the methodology employed here, these will be discussed in greater detail.

Table 23

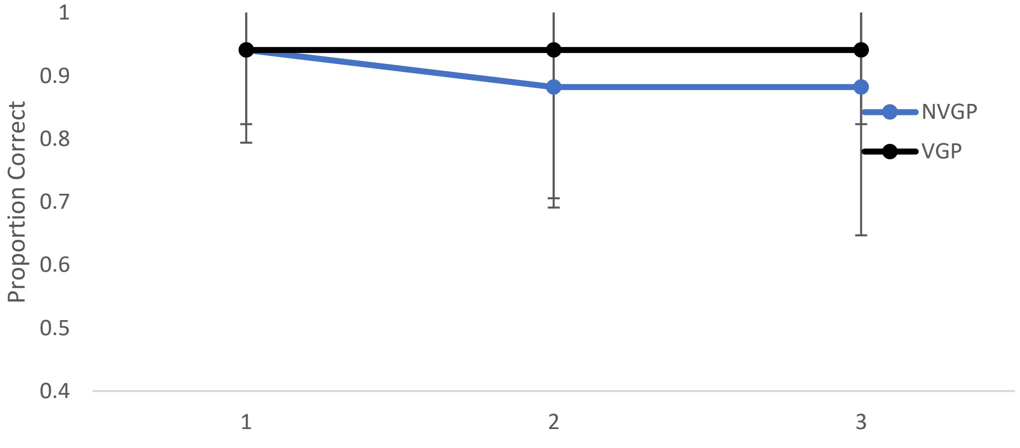
Median (Mdn) and Interquartile range (IQR) of proportion hits for VGP and NVPG conditions on a n-back task across 30 minute a vigil

		VGP				NVGP			
n-back	Time point	Mdn	IQR	Q1	Q3	Mdn	IQR	Q1	Q3
0	1	1.00	0	1.00	1.00	1.00	0.06	0.94	1.00
	2	1.00	0.03	0.97	1.00	1.00	0.06	0.94	1.00
	3	1.00	0	1.00	1.00	1.00	0.06	0.94	1.00
1	1	0.94	0.15	0.85	1.00	0.94	0.12	0.88	1.00
	2	0.94	0.25	0.75	1.00	0.88	0.18	0.76	0.94
	3	0.94	0.12	0.82	0.94	0.88	0.24	0.71	0.94
2	1	0.76	0.18	0.71	0.88	0.82	0.13	0.71	0.84
	2	0.82	0.24	0.71	0.94	0.82	0.29	0.65	0.94
	3	0.71	0.24	0.59	0.82	0.82	0.29	0.59	0.88

Note: *n*-back: 0=0back/ no load, 1= 1back/ low load, 2=2back/ high load. First Quartile (Q1), Third Quartile (Q3). Timepoint: 1=0-10 minutes, 2=10-20 minutes, 3=20-30 minutes.

Figure 19

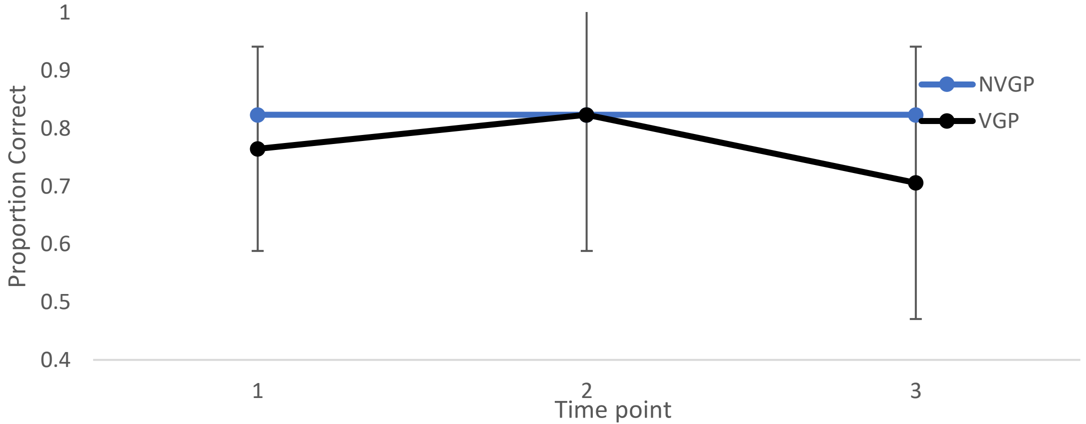
Median of proportion correct responses in 1-back for VGP and NVGP during a 30 minute vigil



Note: Proportion correct shown for each level of the Video Game Play Condition, Video Game Players (VGP) and Non-Video Game Players (NVGP). Error bars displayed using Interquartile range

Figure 20

Median of proportion correct responses in 2-back for VGP and NVGP during a 30 minute vigil



Note: Proportion correct shown for each level of the Video Game Play Condition, Video Game Players (VGP) and Non-Video Game Players (NVGP). Error bars displayed using Interquartile range

In Figure 19, it can be inferred that NVGP did exhibit a decline in performance over time consistent with a vigilance decrement, providing provisional evidence for the ability of the *n*-back to produce vigilance effects and the related drop in cognitive efficiency. However, as seen in Figure 20 in the NVGP group in 2-Back, VGP in 1-back conditions did not demonstrate an expected reduction in the proportion of correct responses.

The descriptive statistics for false alarms are shown in Table 24. As can be observed, the proportion of false alarms is effectively without fault, demonstrating a greater ceiling effect for this measure. The interquartile range and third quartile data have been presented in three decimal places to exemplify this trend further. No plots have been made for this data due to the trend not benefitting from being displayed graphically; however, Table 24 does illustrate the variability in performance as cognitive load increases, but this remains relatively stable across time, regardless of group. Therefore, nonparametric analysis of longitudinal data was utilised for these analyses (Noguchi et al., 2012). The analysis package nparLD has been described in detail in Chapter 2 Results. Using the procedure established in Durand et al. (2020), relative treatment effect (RTE) statistics are used to estimate effect sizes which are proportional to Cohen's *d* when the data are normally distributed (Brunner et al., 2018; Brunner & Puri, 2001).

Table 24

Median (Mdn), Interquartile range (IQR) of proportion False Alarms for VGP and NVPG conditions on a n-back task across 30 minute a vigil

		VGP				NVGP			
n-back	Time point	Mdn	IQR	Q1	Q3	Mdn	IQR	Q1	Q3
0	1	0.00	0.001	0.00	0.001	0.00	0.004	0.00	0.004
	2	0.00	0.000	0.00	0.000	0.00	0.001	0.00	0.001
	3	0.00	0.002	0.00	0.002	0.00	0.000	0.00	0.000
1	1	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000
	2	0.00	0.004	0.00	0.004	0.00	0.004	0.00	0.004
	3	0.00	0.004	0.00	0.004	0.00	0.000	0.00	0.000
2	1	0.00	0.004	0.00	0.004	0.00	0.004	0.00	0.004
	2	0.00	0.004	0.00	0.004	0.00	0.004	0.00	0.004
	3	0.00	0.004	0.00	0.004	0.00	0.004	0.00	0.004

Note: *n*-back: 0=0back/ no load, 1= 1back/ low load, 2=2back/ high load. First Quartile (Q1), Third Quartile (Q3). Timepoint: 1=0-10 minutes, 2=10-20 minutes, 3=20-30 minutes

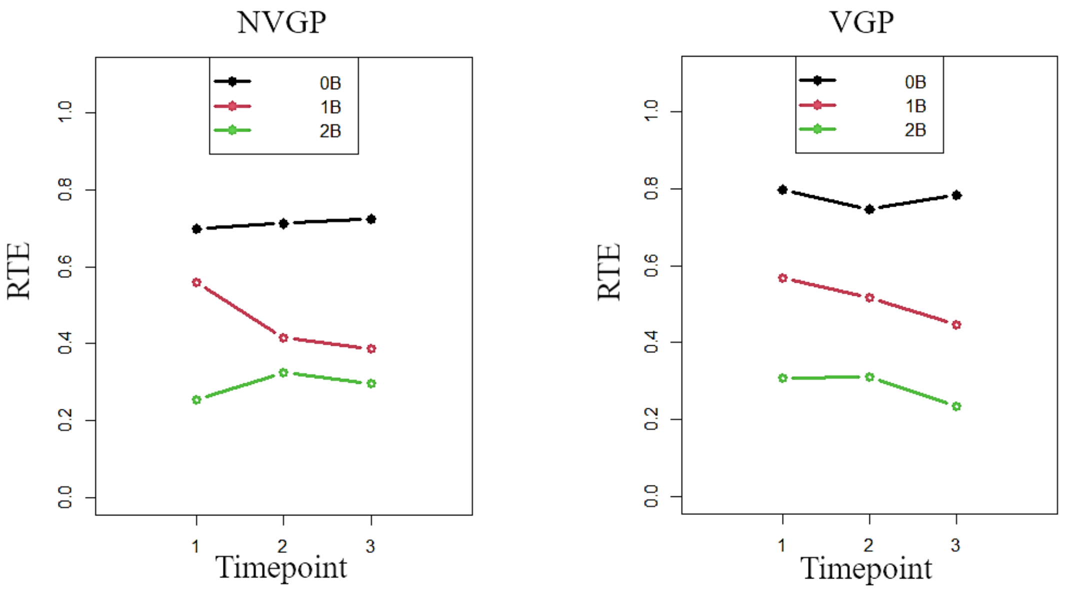
For proportion correct nparLD analysis, a F1-LD-F2 analysis was conducted to examine the effect of cognitive load (manipulated by the level of the *n*-back) and time (30-minute vigil with performance averaged per 10 minutes) on participants proportion of hits in the VGP and NVGP groups. The main effect of within-subjects factor cognitive load was significant, $F(1.92, 38.49) = 119.45, p < .001$. Additionally, the main effect of within-subjects factor time was significant, $F(1.99, 38.49)=3.8, p = .02$. Likewise, the interaction of cognitive load and time was significant, $F(3.26,38.49) = 3.55, p = .01$.

However, the between subjects factor of VGP status was not significant: $F(1, 38.49) = 0.71, p = .40$. Furthermore, the interaction of: VGP status and cognitive load ($F(1.92,38.49) = 0.89, p = .41$), VGP status and time ($F(2,38.49) = 0.44, p = 0.65$), and VGP status, cognitive load, and time ($F(3.26,38.49) = 1.09, p = .35$) were not significant.

The above demonstrates that the *n*-back produced the effects of increasing cognitive load as expected, and that a vigilance decrement was also produced, both within and between levels of the *n*-back (regarding proportions of correct responses). Figure 21 shows the relative treatment effects for NVGP and VGP at all loads and timepoints. As be seen here, only at no cognitive load do Random Treatment Effect (RTE) values exceed 0.6, with the highest values in the VGP group at 0-Back.

Figure 21

Relative Treatment Effects (RTE) of Proportion Correct Responses for NVGP and VGP at 0-,1-,2-back across all Timepoints



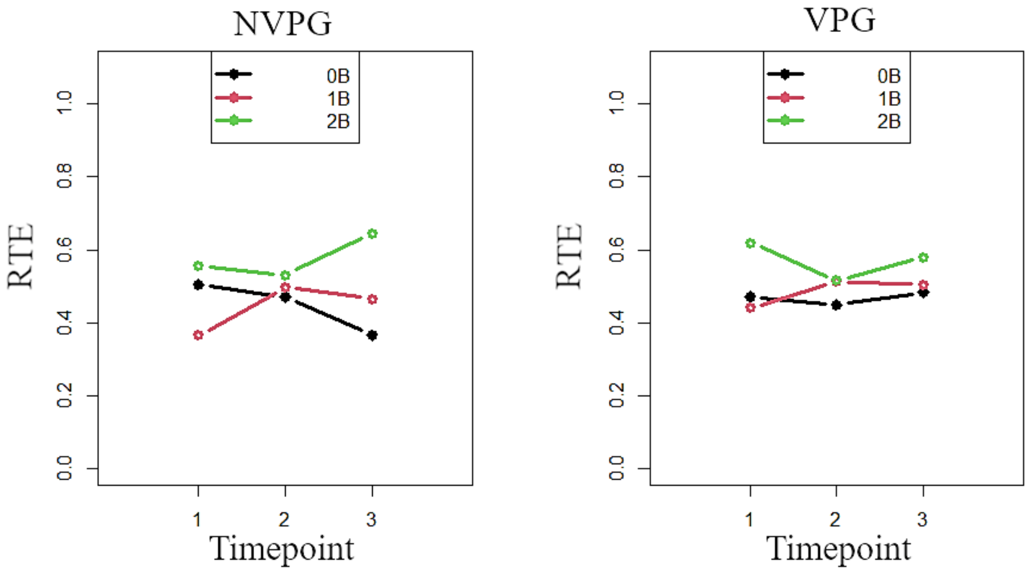
Note: Relative treatment effect (RTE) statistics are estimate effect sizes which are proportional to Cohen's *d* (Brunner et al., 2018; Brunner & Puri, 2001).

For proportion of false alarms nparLD analysis, a F1-LD-F2 analysis was conducted to examine the effect of cognitive load (manipulated by the level of the *n*-back) and time (30-minute vigil with performance averaged per 10 minutes) on participants proportion of false alarms in the VGP and NVGP groups. The main effect of within-subjects factor cognitive load was significant: $F(1.72, 35.64) = 9.92$, $p < .001$. However, there was no significant effect of the within-subjects factor time: *F*(1.86, 35.64) = 0.19, *p* = .81. The interaction between cognitive load and time was also not significant: *F*(3.31, 35.64) = 2.37, *p* = .06.

The between-subjects factor of group allocation, or VGP status, did not reach significance here: *F*(1, 35.64) = 0.39, *p* = .54. Likewise, the interactions of VGP status with cognitive load (*F*(1.73, 35.64) = 0.33, *p* = .68), time (*F*(1.08, 35.64) = 0.46, *p* = .61), and cognitive load & time (*F*(3.3, 35.64) = 1.08, *p* = .35) were all non-significant. Figure 22 shows the false alarm RTE for VGP and NVGP across all cognitive loads and timepoints. As opposed to the trends displayed in Figure 22, we can see that regardless of cognitive load or timepoint during a 30-minute vigil there is very little change in the RTE and that this does not exceed 0.7 in any permutation.

Figure 22

Relative Treatment Effects (RTE) of Proportion False Alarms for NVGP and VGP at 0-,1-,2-back across all Timepoints



Note: Relative treatment effect (RTE) statistics are estimate effect sizes which are proportional to Cohen’s *d* (Brunner et al., 2018; Brunner & Puri, 2001).

The above further demonstrates the ability of the *n*-back to significantly increase cognitive load with each level of the *n*-back, leading to more false alarms. Yet, unlike the proportion of correct responses, we do not observe the same reduction in performance here as time on task increases. Taken together, it could be inferred that the n-back paradigm was successful in producing a vigilance decrement, but that this was limited to omission errors rather than commission errors, and that video game play over the past 6 months did not modulate this effect.

Table 25

Mean (M), Standard Deviation (SD) and Standard Error of the Mean (SEM) of MRT for VGP and NVPG conditions on a n-back task across 30 minute a vigil

		VGP			NVGP		
n-back	Time point	M	SD	SEM	M	SD	SEM
0	1	570.50	79.55	18.75	589.60	57.67	13.23
	2	576.95	78.47	18.50	598.05	74.20	17.02
	3	583.44	69.54	16.39	575.57	89.68	20.57
1	1	624.97	101.72	23.34	628.32	89.74	20.59
	2	651.13	94.89	21.77	678.49	92.95	21.32
	3	670.83	114.72	26.32	671.17	98.16	22.52
2	1	667.37	91.87	20.54	679.59	61.72	14.16
	2	661.81	88.68	19.83	694.70	86.49	19.84
	3	685.99	83.23	18.61	697.11	76.51	17.55

Note: *n*-back: 0=0back/ no load, 1= 1back/ low load, 2=2back/ high load. First Quartile (Q1), Third Quartile (Q3). Timepoint: 1=0-10 minutes, 2=10-20 minutes, 3=20-30 minutes.

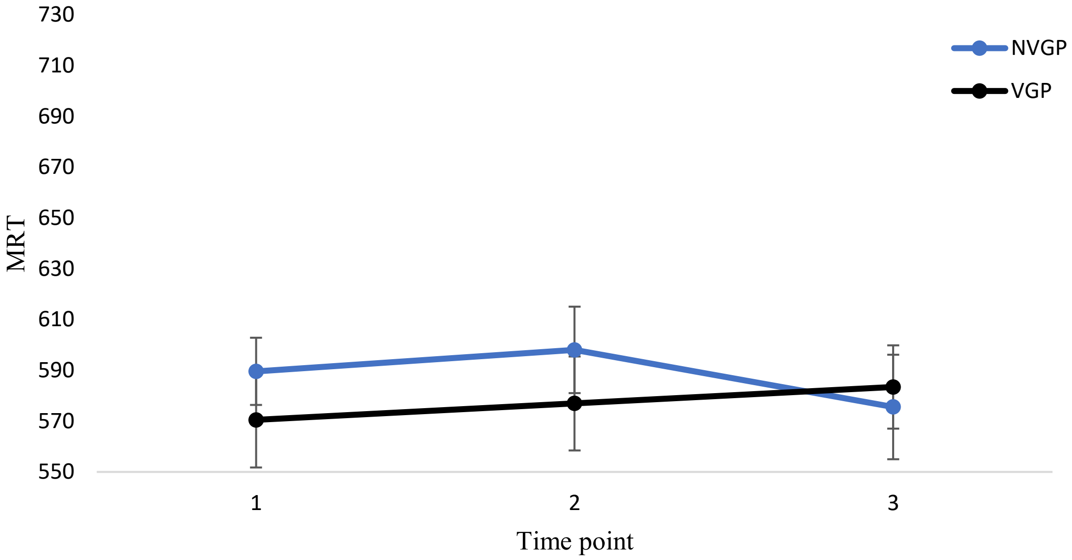
Reaction Time

Reaction time data was collected for each correct response made by participants throughout the task during each level of the *n*-back. To reiterate there were 51 targets in total and 17 targets per 10-minute vigil. The reaction times for each 10-minute vigil under each load was averaged to produce a mean reaction time (MRT) for each time point under each load. As previously mentioned, the individual reaction times under each timepoint and load were assessed against the MRT for the relevant dependent variables and reaction times with an absolute Z score of more than 2.5 were removed from analysis, leading to the removal of 57 data points. Descriptive statistics of Mean Response Time (MRT) can be observed in Table 25. Figures 23, 24 & 25 are the MRT for each group depicted in a line graph under 0-back, 1-back, and 2-back respectively.

As can be observed from the figures, there was a linear upward trend in reaction times both within and between loads. This not only demonstrates an effect of vigilance decrement, with the typically observed decrease in performance as time on task increases; but also signifies that the increase of attentional load between levels of the *n*-back did result in a decrease in performance measured by reaction time. Between groups, we can infer that there was little heterogeneity in the reaction times which will need to be investigated further, however it does appear to be in line with the hypothesised results with VGP outperforming NVGP across all loads and between most time points.

Figure 23

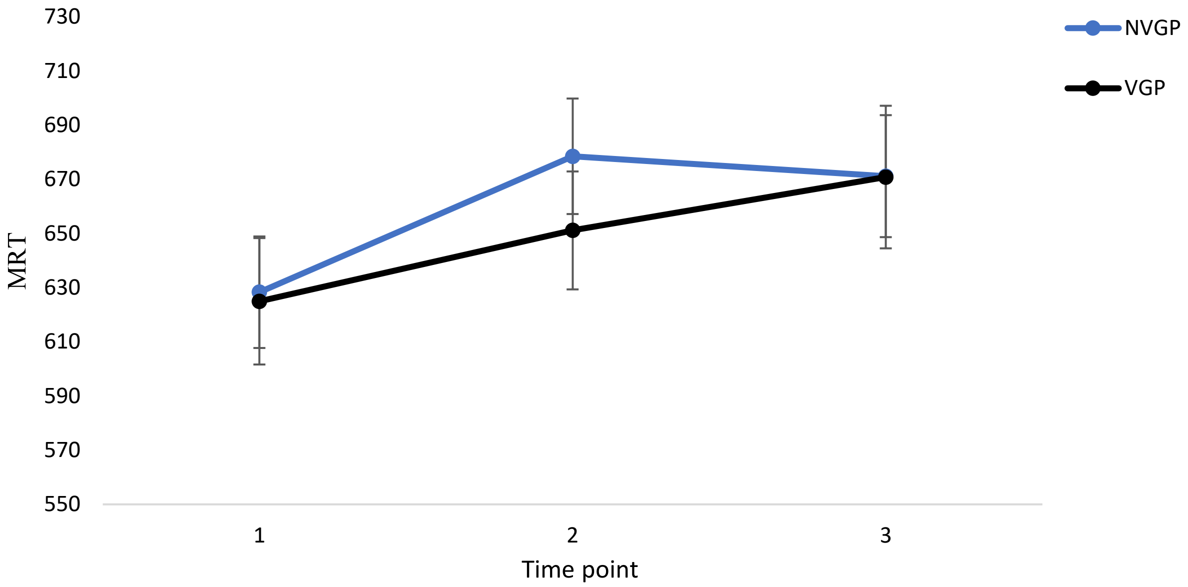
MRT in 0-back for VGP and NVGP during a 30-minute vigil



*Note:*Mean reaction time (MRT) shown for each level of the Video Game Play Condition, Video Game Players (VGP) and Non-Video Game Players (NVGP). Error bars displayed using Standard Error.

Figure 24

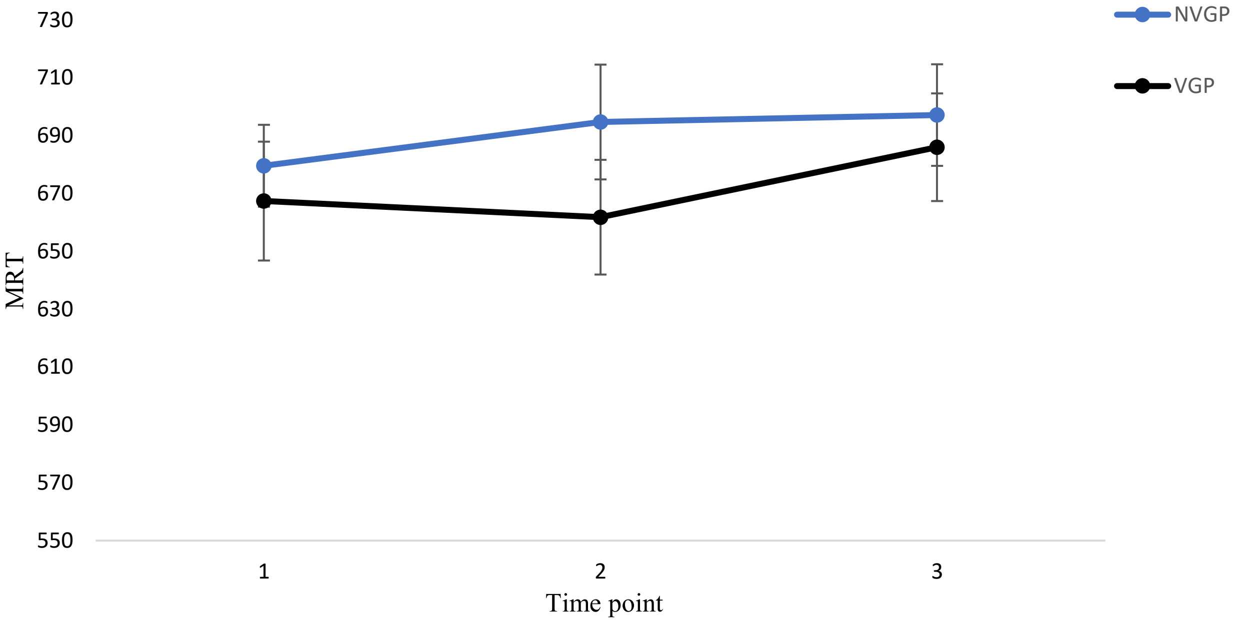
MRT in 1-back for VGP and NVGP during a 30-minute vigil



Note: Mean reaction time (MRT) shown for each level of the Video Game Play Condition, Video Game Players (VGP) and Non-Video Game Players (NVGP). Error bars displayed using Standard Error.

Figure 25

MRT in 2-back for VGP and NVGP during a 30 minute vigil



Note: Mean reaction time (MRT) shown for each level of the Video Game Play Condition, Video Game Players (VGP) and Nn-Video Game Players (NVGP). Error bars displayed using Standard Error.

To investigate these trends further, a 2x3x3 repeated measures analysis of variance (ANOVA) was employed assessing the interaction between VGP status (VGP, NVGP), Load (0-back, 1-back, 2-back), and time point (1,2,3). Prior to conducting these analyses, the data was assessed to ensure that it met the assumptions for parametric analysis. All assumptions were met by this data, except Mauchly's test indicated that the assumption of sphericity had been violated, $\chi2(2) = 7.15$, p =. 028 for the within subject effect of time. Degrees of freedom for interactions involving this variable were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .50$).

There was a significant effect of attentional load on MRT, $F(2,68)=33.89$, $p<.001$, $\eta^2=.50$; but no significant interaction of attentional load and VGP status $F(2,68)=.813$, $p=.45$,

η^2=.02. This suggests that while increasing load did significantly affect participants performance, the groups responded similarly to this effect.

For timepoint, there was a significant effect on MRT $F(1.67, 59.62)=9.20$, $p=.001$, η^2=.21; but there was no interaction between timepoint and VGP status on MRT $F(1.67, 59.62)=2.34$, $p=.11$, η^2=.06. Results suggest that while time on task did significantly affect vigilance performance on the *n*-back, performance was altered to the same extent for both VGP and NVGP.

There was a significant interaction between load and timepoint in the *n*-back on MRT $F(3.45, 117.17)=6.13$, $p<.001$, η^2=.15, but there was no significant interaction between load, timepoint, and VGP status $F(3.45, 117.17)=.65$, $p=.61$, η^2=.02. This suggests that while performance was affected by increases in attentional load and time on task, there was no difference between two groups.

Lastly, the between subjects effects observed no significant effect of VPG status on MRT $F(1,34)=.499$, $p=.49$, η^2=.01. Taken together, while these results provide further validation of the *n*-back to manipulate cognitive load and produce vigilance effects in the role of a continuous performance task; there is little evidence to support the theorised improved executive function in VGP leading to improved performance despite vigilance decrement effects when compared to controls.

NASA TLX

Table 26

Median (Mdn), Interquartile range (IQR) of NASA TLX workloads for VGP and NVPG conditions on the n-back

		VGP				NVGP			
n-Back	Workload	Mdn	IQR	Q1	Q3	Mdn	IQR	Q1	Q3
0	MD	180.00	261.25	58.75	320.00	140.00	325.00	25.00	350.00
	PD	5.00	120.00	0.00	120.00	25.00	60.00	0.00	60.00
	TD	120.00	77.50	87.50	165.00	105.00	130.00	20.00	150.00
	P	65.00	100.00	20.00	120.00	105.00	130.00	20.00	150.00
	E	165.00	218.75	71.25	290.00	210.00	150.00	75.00	225.00
	F	45.00	213.75	0.00	213.75	65.00	195.00	0.00	195.00
	AT	46.83	17.00	42.08	59.08	54.67	19.00	44.67	63.67
1	MD	240.00	280.00	120.00	400.00	255.00	240.00	160.00	400.00
	PD	0.00	50.00	0.00	50.00	0.00	110.00	0.00	110.00
	TD	80.00	160.00	40.00	200.00	130.00	220.00	40.00	260.00
	P	100.00	75.00	30.00	105.00	120.00	90.00	60.00	150.00
	E	200.00	235.00	65.00	300.00	210.00	200.00	100.00	300.00
	F	120.00	130.00	35.00	165.00	90.00	210.00	0.00	210.00
	AT	56.00	22.67	46.00	68.67	63.67	21.00	52.67	73.67
2	MD	400.00	122.50	327.50	450.00	375.00	155.00	320.00	475.00
	PD	0.00	28.75	0.00	28.75	0.00	0.00	0.00	0.00
	TD	135.00	118.75	61.25	180.00	150.00	90.00	120.00	210.00
	P	65.00	103.75	46.25	150.00	90.00	105.00	60.00	165.00
	E	270.00	195.00	165.00	360.00	300.00	220.00	180.00	400.00
	F	110.00	171.25	46.25	217.50	45.00	245.00	10.00	255.00
	AT	65.67	13.25	60.17	73.42	72.33	9.00	68.00	77.00

Note: Mental Demand (MD), Physical Demand (PD), Temporal Demand (TD), Performance (P), Effort (E), Frustration (F), Adjust Total (AT).

Prior to analysis of NASA TLX data, the score for each subscale provided by participants at the end of an experimental were weighted based on the procedure described by Hart (2016); Hart and Staveland (1988). This provided weighted values for: effort, frustration, mental demand, physical demand, performance, and temporal demand. These scores were then summed and dived by 15 to provide an overall task load score. Prior to analysis of task load index data for no, low, and high cognitive load the data were pre-treated to remove outliers. One VGP performance data point in the 1-back condition and one VGP & NVGP physical demand data point in the 2-back condition were removed for Z-score values greater than 3.0. Violations of normality were observed across all sub-scales and *n*-backs for both NVGP and VGP.

Presented in Table 26 are the descriptive statistics for the NASA TLX, total task load scores show a positive linear trend increasing as task load increases. Here one can see that VGP participants have reported a lower perceived total perceived task load compared to their NVGP counterparts. This is despite there being no difference in performance between the two groups as evidenced by the previous analyses. Another interesting note here is the performance and frustration score; VGP consistently rated their performance lower than NVGP participants in combination with reporting higher ratings of frustration in 1-back and 2-back. Effort and mental demand also express a positive linear trend with increasing cognitive load in both groups. However, VGP reports higher mental demand but less effort than NVGP except for 1-back, where this trend is reversed. To investigate these trends further, nparLD F1-LD-F1 where video game play status (VGP/NVGP) was the whole plot factor and level of the *n*-back associated with the given NASA TLX sub-scale were the sub plot factor.

For adjusted total task load scores, the main effect of between subjects factor VGP status was not significant, $F(1, 38.95) = 3.62, p = .06$; the main effect of the within-subjects factor cognitive load was however significant, $F(1.84, 37.33) = 22.14, p<.001$. The interaction of cognitive load and VGP status did not reach significance, $F(1.84, 37.33) = 0.33, p = .70$. From this it can be inferred that while increasing cognitive load did increase perceived workload, this did not differ between groups. Mental demand scores produced similar results with a significant main effect of the within-subjects factor cognitive load (*F*(2, 35.35) = 32.08, *p* <.001) but no significant effect of VGP status (*F*(1, 35.34) = 0.26, *p* = .61) or significant interaction (*F*(2, 35.34) = 0.23, *p* = .80). The same results were yielded from analysis of physical demand; significant main effect of cognitive load (*F*(1.97, 36.52) = 4.95, *p* <.01), but no significant effect of VGP status (*F*(1, 36.52) = 0.00, *p* = .99) and no significant interaction (*F*(1.97, 36.52) = 066, *p* =.52). However, there is a caveat to the physical demand results as the median reported values for 1-back and 2-back was zero for both groups. Lastly the same trend was obtained from analysis of effort subscale data, with a significant main effect of cognitive load (*F*(1.89, 38.86) = 7.11, *p* =.001), with no significant effect of the between-subjects factor (*F*(1, 38.86) = 0.18, *p* = .68) or interaction (*F*(1.89, 38.86) = 0.37, *p* =.67).

In contrast, analyses of subscales temporal demand, frustration, and performance produced no significant main effects or interactions. Regarding temporal demand, the between-subjects factor VGP status (*F*(1, 37.92) = 0.42, *p* = .52), within-subjects factor *n*-back (*F*(1.93, 37.92) = 2.22, *p* = .11), and interaction (*F*(1.93, 37.92) = 1.66, *p* = .19) were not significant. Frustration subscale analysis produced no significant effect of VGP status (*F*(1, 37.67) = 0.14, *p* = .70), cognitive load (*F*(1.99, 37.67) = 0.64, *p* = .53), or interaction (*F*(1.99, 37.67) = 0.60, *p* = .55). Lastly, perceived performance analysis did not produce any significant main effect of VGP status (*F*(1, 38.73) = 2.67, *p* = .11), cognitive load (*F*(1.94, 38.73) = 0.61, *p* = .54), or interaction of the within and between factors (*F*(1.94, 38.73) = 0.22, *p* = .79). Thus, there is a suggestion that the manipulation of the *n*-back on video game play did not affect the perceived performance, level of frustration felt, or temporal demand experienced while undertaking the vigilance task. Similarly, manipulations of the *n*-back did not produce any significant effects on these sub-scales of perceived workload which is unusual given one would assume a task increasing in difficulty would produce a reduced estimate of performance and higher levels of frustration.

SUPPS-P

Prior to the analysis of the impulsivity data obtained from the SUPPS-P, the scores were coded following the protocol stated in Cyders et al. (2014). This produced scores for each participant in the five sub-scales measured: negative urgency, lack of perseverance, lack of premeditation, sensation seeking, and positive urgency. The SUPPS-P also provides a total impulsivity score based on the summation of these subscales. The data was assessed for outliers, and assumptions checks for parametric analysis were undertaken. Violations of normality were observed in the sub-scale lack of perseverance, and as such, the data will be analysed non-parametrically.

Table 27

Mean(M), Standard Deviation (SD) and Standard Error of the Mean (SEM) of SUPPS-P scores for VGP and NVPG conditions

	VGP			NVGP		
SUPPS-P	*M*	*SD*	SEM	*M*	*SD*	SEM
Negative Urgency	9.45	2.58	0.58	8.43	2.25	0.49
Lack of Perseverance	6.75	1.86	0.42	6.81	1.66	0.36
Lack of Premeditation	7.30	2.43	0.54	6.76	1.79	0.39
Sensation Seeking	11.45	2.91	0.65	10.43	2.23	0.49
Positive Urgency	8.30	2.89	0.65	6.43	1.80	0.39
Total	43.25	6.51	1.46	38.86	5.87	1.28

Noticeable in Table 27, which presents the measures of central tendency and dispersion for VGP and NVGP conditions, the two groups scored similarly in all sub-scales, with VGP displaying more variance. However, there is evidence to suggest based on the total impulsivity score, that VGP self-reported higher levels of impulsivity. An independent samples one-tailed t-test was conducted to compare total impulsivity scores, lack of premeditation, sensation seeking, positive urgency and negative urgency in VGP and NVGP conditions.

There was a significant difference in impulsivity scores for VGP and NVGP conditions: $t(38.01) = 2.27$, $p= .01$, suggesting that VGP are generally more impulsive than NVGP participants. There was also a significant difference in positive urgency scores for VGP and NVGP conditions: $t(31.62) = 2.48$, $p<.01$, reflecting more positive urgency in VGP than their counterparts. However, the difference in values obtained from VGP and NVGP for lack of premeditation ($t(34.82)=0.80$, $p= .21$), sensation seeking ($t(35.58)=1.26$, $p= .11$), and negative urgency ($t(37.67)=1.35$, $p=.09$) did not approach significance. Similarly, a Mann-Whitney U test indicated that VGP scores for lack of perseverance were not significantly higher than NVGP scores, U=208 $p=.97$.

Discussion

The aim of the present study was to investigate the effects of video game use on sustained attention. To this end, a continuous performance task that measures working memory capability was used to enable the manipulation of cognitive load on an executive function task while sustaining attention.

The above results demonstrate the ability of the *n*-back to function as a continuous performance task that produces a vigilance decrement. This was observed in reaction time and proportion of correct response measures, but not false alarms. Similarly, it was observed that cognitive load modulates this effect in these two measures. False alarm rates were only significantly affected by increasing cognitive load, not time on task, and these two factors did not interact. In all of these behavioural measures, we failed to observe any interaction with VGP status or a significant effect of group allocation.

The diffusion modelling showed that both groups were equally affected by the rate of information accumulation effects as a result of time on task and attentional load. Time on task and attention load demonstrate a significant positive relationship with information accumulation. Time on task did not affect the response conservativeness in all participants, and only when the cognitive load increased did participants become more liberal in their response criterion. The results show that this effect is independent of the vigilance decrement and was only affected by cognitive load. This also suggests that the effects of increased impulsivity in VGP participants did not affect their response criterion, perhaps as a result of increased executive function allowing more impulsive responses that do not result in more errors discerning the target from non-targets and resulting in comparable performance to the NVGP control. Non-decision time was observed to increase as cognitive load and time on task increased, but again, this was not affected by VGP status. This suggests that both increasing load and time on task increased non-decision time, which may be a result of increased workload, particularly if physical fatigue is affecting participants in later time points. Additionally, VGP participants demonstrated no decreased non-decision time compared to NVGP. This suggests that the hypothesised increased executive function in VGP does not lead to less lag time between perceptual processing and motor response, also casting doubt on the perceived increased performance on visuospatial working memory tasks as a result of training motor response. Decision bias was observed to be affected by time on task and cognitive load independently, with no significant interaction observed. These results suggest that the *n*-back is a valid tool to manipulate participants' decision bias regardless of video game experience and that vigilance decrement affects both groups equally.

Evidence from the NASA-TLX demonstrated that increasing the cognitive load did successfully produce higher levels of subjective workload, but that this did not differ between groups. This finding is logical in light of the equivalent performance between groups across cognitive loads. The results also supported a traditional finding of VGP being more impulsive than their NVGP counterparts (Irvine et al., 2013), with increased overall impulsivity scores on the SUPPS-P and positive urgency scores.

Regarding perceptual sensitivity, participants, regardless of recent video game play history, are less able to differentiate between targets and non-targets as the cognitive load increases, and there is an interaction with time on task. However, the hypothesised vigilance decrement is not provoked here by increasing time on task alone and requires further manipulations of executive function capabilities to produce an effect. This would suggest that in contrast to the underload hypothesis (Braboszcz & Delorme, 2011; Humphrey et al., 2018; Pattyn et al., 2008), high cognitive load is needed to sufficiently deplete executive function resources and affect perceptual sensitivity, as posited by the combination hypothesis (Thomson et al., 2015).

As described above, the present study failed to observe similar results to those found in Trisolini et al. (2018); however, there are a number of potential explanations for this discrepancy that may have implications for both the theoretical bases and methodological paradigms going forward. Principally, there are stark contrasts between the methodologies employed in Trisolini et al. (2018) and the present study. For example, the age group targeted and the cognitive tasks implemented. In regard to the cognitive tasks, Trisolini et al. (2018) state that action VGPs would exhibit a vigilance decrement when undertaking tasks that are "monotonous, long and tedious" (p.5) with the caveat that the continuous performance task used to measure vigilance level would be of consistent cognitive load. While the present study manipulates cognitive load, it should be stated that there is an argument that the *n*-back, as a serial visual presentation of infrequent targets, is consistent with the requisite characteristics of monotony and tediousness equivalent to the jumping square task (Trisolini et al., 2018). This is especially the case for no-load conditions, which emulate one of the earliest continuous performance tasks developed (Rosvold et al., 1956). Importantly, evidence suggests that more cognitively demanding tasks should produce the largest vigilance decrements (Helton & Russell, 2011; Thomson et al., 2015, 2016).

Regarding duration, the present study used a 30-minute paradigm with a target rate of 17 per 10-minute vigil, with Trisolini et al. (2018) duration at 20 minutes with a target rate of 18 per 10-minute vigil. Moreover, both the *n*-back and jumping square tasks require successive discrimination, particularly in the low and high load of the *n*-back (Parasuraman & Davies, 1977). However, there is uncertainty regarding the homogeneity of event rates, which avails the possibility for the decrement observed by Trisolini et al. (2018) to be the result of a reduction in perceptual sensitivity in the instance of sufficient memory load (Parasuraman, 1979). Further, as the present study utilised a 24 event/min rate, it is unlikely that the difference in results stems from the event rate unless a higher event rate was used, as 40 events/min has been demonstrated to produce a more pronounced vigilance decrement in cognitive vigilance tasks (Claypoole et al., 2019). In future studies of cognitive load manipulation, including a "high" and "low" event rate as well as differing cognitive loads may identify sufficient taxation of the executive function resources resulting in TUT in NVGP but the continued direction of executive function resources to goal-directed behaviour in VGP as a result of their hypothesised increased executive function.

Hypothetically, if the event rate used here was not rapid enough to sufficiently reduce perceptual sensitivity despite a high working memory load, the heterogeneity observed between results would suggest that NVGP and VGP do not differ in their response criteria overtime and are similarly reduced by vigilance effects, but they do differ in the reduction of perceptual sensitivity with VGP being more vulnerable to said effects when taking Trisolini et al. (2018) findings into consideration. However, the results of the present study do not purport a change of response criteria between NVGP and VGP in any cognitive load, and the event rate used here of 24 events/min reflects that of traditional continuous performance tasks (REFS) and according to Parasuraman (1979) is considered a high event rate.

This suggests that the tasks should not differ in their ability to exhaust perceptual sensitivity and are not erroneously reflecting a change in response criteria. Further investigations into event rate could yield more insight here; if it is the case that the jumping square task utilises a lower event rate than Trisolini et al. (2018), then their results could reflect a larger response criteria shift in action VGP, suggesting participants in this group either more readily adopted a more liberal response strategy or their subjective estimation of the probability of target occurrence becomes detrimental.

When adopting the inclusion of task type, sensory or cognitive task, into the Parasuraman and Davies (1977) vigilance taxonomy based on the evidence provided in the meta-analysis conducted by See et al. (1995), there is an additional potential explanation for the lack of support for Trisolini et al. (2018). See et al. (1995) found in their meta-analysis that successive sensory tasks increase vigilance decrement dramatically compared to high event rate cognitive tasks relative to their low event rate counterparts. The implication here is that sustained attention for cognitive tasks remains intact in VGPs, but when undertaking sensory sustained attention tasks, there is a distribution to their inhibitory control. One would expect to see the same trend across all task modalities in the successive continuous performance task paradigm if this data were to support the mindlessness hypothesis of vigilance decrement posited by Manly et al. (1999).

Whereas the data could be seen to support the resources depletion hypothesis or underload account (Helton & Russell, 2011, 2015; Humphrey et al., 2018) and the mind-wandering hypothesis (Braboszcz & Delorme, 2011). In that the sensory task is significantly more taxing and effortful than the cognitive *n*-back task, or that the external perceptual input from a sensory task is not sufficiently arousing to hold one's attention, in both cases, we would observe this specific reduction in vigilance level. In the future, reproducing this study utilising an adapted jumping squares task with modulations of task difficulty, such as an array of jumping squares with the same event rate, target rate, signal regularity, event asynchrony and signal amplitude, would enable a deeper understanding. Additionally, the inclusion of a measure of task difficulty, such as the NASA-TLX, would enable a direct comparison and provide more support for either the underload or mind-wondering hypothesis, with lower subjective scores of task difficulty supporting the former and higher supporting the latter as found in the current data set. This would further elucidate the effect of the sensory-cognitive distinction and improve the vigilance taxonomy provided by See et al. (1995).

When considering the resource-control theory of mind-wandering (Thomson et al., 2015) the present findings would suggest that the *n*-back requires the full complement of attentional resources, resulting in a vigilance decrement due to mind wandering, as observed in the jumping squares task, but that the available executive control resources are directed similarly across groups. It may be the case that VGPs exhibit a failure of executive control to inhibit these automatically generated and maintained task TUT in sensory tasks due to their familiarity with higher-rate perceptual stimuli. In contrast, video game training may not produce the same level of familiarity with cognitive task stimuli. This leads to the VGP to readily adopt a state where they learn to reduce the degree of executive control when confronted with less demanding sensory stimuli than those observed in video games. Concurrently, if the VGP become aware that the newly adopted state is resulting in a reduction of task performance, they may increase their control over executive resources, which results in a process akin to ego depletion (Baumeister & Vohs, 2007) as suggested by Thomson et al. (2015). There is also the possibility of speciality effects in the first vigil due to game-like effects that reduce as time on task increases, resulting in equivalent or reduced performance compared to NVGP.

The present data opens the possibility for an effect to be found in 3-back, as findings suggest that 2-back is not sufficient for video game players to exhibit a hypothesised improved performance under high cognitive load (Dye et al., 2009b; Green & Bavelier, 2007). It is also possible that the task difficulty is approaching unengaging in relation to the VGP condition, resulting in the proposed increased executive function being directed to ensuring that resources are devoted to the task and not self-generated thought. Whereas, in the NVGP condition, the task is sufficiently engaging through suitable difficulty so as not to require executive function to direct any resources toward task engagement. This would then produce the observed homogeneity in performance across a range of measures while informing a potential heterogeneity in regard to task engagement. It could be suggested that without this use of executive functions to direct attentional resources toward task engagement to overcome impulsive traits found in the VGP group, we would observe decreased performance in these lower cognitive loads compared to the non-video game playing control. The finding that the vigilance decrement effects are consistent across groups in this proposed interpretation of findings would suggest that while VGPs are exerting more executive control to remain on task, this larger "pool" of resources decreases at the same rate as NVGP.

That said, it is possible and based on the current findings, more probable that there is a limited effect of video game play on VGP sustained attention within the current paradigm. Primarily, the inclusion of participants into the VGP condition could be improved to ensure that there are effects of training through specific game genres. While the current literature focuses on action video game play with a wide array of criteria, the present study utilises the most frequently adapted criteria (Dye et al., 2009b; Green & Bavelier, 2003, 2006a, 2006b, 2007) there are still criticisms made of this that may have impacted the ability to find effects here. Using the age of onset of video game play alongside the current metric may enable a deeper understanding of the effects of video game play on development and later in life utilisation of executive functions (Hartanto et al., 2016).

Chapter 5: General Discussion

The present thesis attempted to understand the inconsistency in video game research assessing the performance of video game players (VGP) compared to non-VGP (NVGP) in a range of attentional and perceptual tasks by comparing VGP to NVGP on a range of tasks designed to assess executive function.

Regular video gameplay has previously been shown to improve performance on tasks assessing visual selective attention, interpreted as video game play increasing the available attentional resources (Green & Bavelier, 2006a), suggesting the potential for transfer as a result of video gameplay. This finding has been replicated several times with VGP outperforming NVGP counterparts in a range of visuo-spatial attention (Andrews & Murphy, 2006; Bavelier, Achtman, et al., 2012; Bavelier et al., 2018; Bediou et al., 2018; Castel et al., 2005; Chisholm et al., 2010; Chisholm & Kingstone, 2012, 2015; Donohue et al., 2010; Durlach et al., 2009; Dye et al., 2009a, 2009b; Green & Bavelier, 2006a; Hubert-Wallander, Green, & Bavelier, 2011; Li et al., 2010; Okagaki & Frensch, 1996; Pavan et al., 2019; Risenhuber, 2004). Training methodologies with active controls have found a similar pattern of results in tasks assessing visual spatial attention and enhanced cognitive function more generally (Glass et al., 2013; Hutchinson et al., 2016; Kuhn et al., 2017; Powers et al., 2013; Szalma et al., 2018).

Yet, the positive effects of recent frequent video game use are not consistently observed (Sala et al., 2018). Cross-sectional investigations have been unable to find a similar pattern of results (Gobet et al., 2014; Murphy & Spencer, 2009; Redick et al., 2017; Stockdale et al., 2017; Unsworth et al., 2015; van Ravenzwaaij et al., 2014). Training paradigms have also failed to observe differences in performance in tasks measuring attention and working memory (Ballesteros et al., 2017) or perceptual processing (van Ravenzwaaij et al., 2014), with significant effects at baseline observed to be non-significant at 3 months post-training (Ballesteros, Mayas, et al., 2015). Meta-analyses by Sala et al. (2018) failed to find an effect of video game use on visual attention, spatial ability, cognitive control, memory, or intelligence; Nuyens et al. (2019) in their meta-analysis excluded problematic levels of video game play and found VGP outperform measures of cognitive control. Bediou et al. (2018) conducted a meta-analysis and found a moderate effect of recent frequent video game use in cross-sectional designs and a smaller effect in training methodologies. Primary effects were observed on top-down attentional control and spatial cognition.

The improved cognitive ability of VGP is hypothesised to be the result of improved top-down attentional control (Chisholm et al., 2010) and cognitive control (Colzato et al., 2013) which suggests the potential for additional executive function resources compared to NVGP. The effects of video game play on inhibition have been less extensively studied in video game research, although findings suggest a relationship between video game use and inhibition (Deleuze et al., 2017; Zhang et al., 2022). Moreover, while Stockdale et al. (2017) did not observe a difference between NVGP and VGP on a response inhibition task, electroencephalography data demonstrated reduced neuronal recruitment in VGP compared to NVGP despite equivalent performance, suggesting fewer executive function resources were recruited to perform equally well.

It was predicted that enhanced executive functions drive the observed differences in VGP compared to NVGP in attention and perception (Andrews & Murphy, 2006; Bavelier, Achtman, et al., 2012; Bavelier et al., 2018; Bediou et al., 2018; Boot et al., 2008; Castel et al., 2005; Chisholm et al., 2010; Chisholm & Kingstone, 2012, 2015; Donohue et al., 2010; Durlach et al., 2009; Dye et al., 2009a, 2009b; Green & Bavelier, 2006a; Hubert-Wallander, Green, & Bavelier, 2011; Li et al., 2010; Okagaki & Frensch, 1996; Pavan et al., 2019; Risenhuber, 2004; Wang et al., 2014). Moreover, only when the tasks are sufficiently demanding does the additional executive function resources of VGP become measurable

(Bavelier, Achtman, et al., 2012; Bavelier et al., 2018; Bavelier & Green, 2019; Bavelier et al., 2011; Diamond, 2013; Diamond et al., 2007; Dye et al., 2009b; Gobet et al., 2014; Green & Bavelier, 2007, 2012), as such providing a potential account for the inconsistencies observed in the ability of VGP to outperform NVGP, be it through cross-sectional designs (Boot et al., 2008; Gobet et al., 2014; Redick et al., 2017; Unsworth et al., 2015; van Muijden et al., 2012; van Ravenzwaaij et al., 2014), or training methodologies (Ballesteros et al., 2017; Ballesteros, Mayas, et al., 2015; Sala et al., 2019; Sala & Gobet, 2019; Sala et al., 2018; van Ravenzwaaij et al., 2014). In turn, these investigations aimed to identify how video game use can enact far transfer, as the hypothesised domain-general improvement to cognition could be driven by domain-general resource control, executive function (Al-Thaqib et al., 2018; Baniqued et al., 2013; Duyck & Op de Beeck, 2019; Linares et al., 2019; Masurovsky, 2020; Poos et al., 2017; Sala et al., 2019; Souders et al., 2017).

Experimental Chapter 2 aimed to investigate the effects of video game use on response inhibition as part of a larger investigation of the effects of video game use on executive function. Response inhibition was selected as a candidate cognition to assess due to the role of inhibition in models of executive function (EF), conceptualising inhibition as a domain-general EF that interacts with other EFs (Barkley, 1997, 2001; Dempster, 1992; Dempster & Corkill, 1999; Friedman et al., 2008; Miyake & Friedman, 2012; Miyake et al., 2000). Response inhibitions also strongly correlate with higher-order EFs such as planning, decision-making and problem-solving (Diamond, 2013; Diamond et al., 2007). Lastly, response inhibition was identified as a vital function that enables goal-directed behaviours. (Mostofsky & Simmonds, 2008). As such, response inhibition was determined to be a prime candidate to observe any differences in EF in VGPs.

Response inhibition is defined as the ability to Response inhibition is the combination of three subcomponents: interference resolution, action withholding, and action cancellation

(Gerhardt et al., 2021; Sebastian et al., 2013; Zhang et al., 2017). These three subcomponents were selected to measure experimentally to capture the multifaceted nature of response inhibition processes appropriately, an approach taken in meta-analyses investigating response inhibition function (Argyriou et al., 2017; Mostofsky & Simmonds, 2008; Zhang et al., 2017). The tasks used to measure these three subcomponents were also identified; namely, interference resolution is measured by the Simon task (Simon, 1969) and Spatial Stroop (Wuhr, 2007). Action withholding is measured by the Go No-go (Donders, 1969) and action cancellation is measured by the Stop Signal Task (SST; Logan (1994)).

The effects of video game use have been less reliably observed on pure single-component tasks, such as the stimulus-response compatibility tasks (such as the Simon or spatial Stroop), the Go No-go, and SST. Latham et al. (2018) observed that experienced-VGP (a result of playing video games before the age of ten) were faster than NVGP in incongruent conditions. Specifically, experienced-VGP could resolve the stimulus-response conflict faster than NVGP. Hutchinson et al. (2016) trained NVGPs on either a first-person shooter video game or a control visual training game and compared their performance pre- and post-training on a Simon task. Post training participants trained on the first-person shooter game were observed to have reduced response time and reduced stimulus-response incompatibility cost. Unsworth et al. (2015) were unable to find evidence that video game play predicted the flanker effect or spatial Stroop task performance. Employing a similar design to Unsworth et al. (2015), Paap et al. (2020) investigated the effect of the frequency of video game use as a continuous variable. They observed that as the frequency of video game use increased, a composite measure of interference effects on the Simon task, the spatial Stroop, and the vertical Stroop reduced. However, once impulsivity, sex, IQ, and self-control were entered into the model the correlation became not significant.

In a Go No-go task, Azizi et al. (2018) observed faster but more impulsive responses in VGP compared to NVGP. VGP were reported as having a significantly faster response time and a higher false alarm rate. SDT identified more impulsive responses in terms of a high risk-taking bias in VGP than NVGP. However, speed was emphasised during task description, and across the entire sample, there was a negative correlation between response time and false alarm rate, suggesting a speed-accuracy trade-off across all participants.

Irvine et al. (2013), when comparing problematic VGP to healthy NVGP controls on the stop signal task, found no group differences in stop signal reaction time (SSRT). However, a linear regression implicated the genre of video game use to mask any potential differences between groups. It was noted that strategy genre VGP was associated with reduced action cancellation performance. Colzato et al. (2013) found that VGP action cancellation performance in a stop-signal task did not differ from NVGP. VGP were faster in responding to Go trials, and there was no difference between the two groups in overall accuracy. However, once SSRT had been computed on a 50% accuracy staircase procedure, the difference between the two groups on performance was not significant.

However, single-component tasks executive function tasks suffer from measurement impurity (Friedman & Miyake, 2004), and as previously stated, differences in executive function as a result of training are often only observed in the most demanding of task requirements (Diamond, 2013; Diamond et al., 2007) Therefore, as it was hypothesised that sufficient load is needed to observe enhanced executive function capabilities (Diamond, 2013), a hybrid task was employed that incorporates characteristics of the aforementioned tasks to measure the three subcomponents of response inhibition, the Hybrid Response Inhibition Task (HRIT; Sebastian et al. (2013)). It was hypothesised that overall, there would be a significant difference in reaction time and proportion correct between congruent and incongruent trials, based on traditional findings in interference resolution and stimulus-response compatibility effects manipulated by Simon tasks (Simon, 1969) and Spatial Stroop (Wuhr, 2007). It was hypothesised that performance would significantly differ between frequent Go trials and infrequent No-go trials. Lastly, it was also hypothesised based on the interactive race model (Verbruggen & Logan, 2008), and typical findings in experiments employing the SST (Logan, 1994) to measure the ability to cancel an initiated action that as stop signal delay (SSD) increased, the proportion of successful stops would decrease as a function of action cancellation. If the results of the analysis allowed for the acceptance of these hypotheses, it would demonstrate the ability of the HRIT to be used to measure the three separate components behaviourally and expand upon its current use in functional magnetic resonance imaging studies (fMRI) (Gerhardt et al., 2021; Sebastian et al., 2013)

Previous hybrid tasks have been utilised to assess the effect of video game use and genre on attention (Dye et al., 2009a) and response inhibition (Deleuze et al., 2017), respectively. Dye et al. (2009a) observed enhanced executive control of VGP. Deleuze et al. (2017) reported the differential effects of video game genre on response inhibition, with first-person shooter VGPs being faster and more impulsive than their counterparts. However, at the time of writing, no experiment has combined all three components within one task to measure the effects of recent frequent video game use. It was predicted that VGP would outperform NVGP across the three subcomponents of response inhibition. Additionally, due to findings that suggest that the level of experience of VGP is important in observing an effect of video game use (Hartanto et al., 2016; Latham et al., 2013), the years of experience with video games and the participant's subjective rating of their own skill were measured in this study. Years of experience and subjective rating of skill were recorded using the Covert Video Game Experience Questionnaire (CVGEQ; Sobczyk et al. (2015)); due to methodological constraints, the CVGEQ was adapted to remove covert components and was referred to as the VGEQ. Based on previous research, it was predicted that years of experience and subjective rating of skill would positively correlate with VGP performance on measures of response inhibition.

Finally, this chapter aimed to correlate trait impulsivity with video game use and response inhibition. Previous research has observed that video game play is correlated with higher self-reported trait impulsivity on the UPPS-P trait impulsivity scale (Billieux et al., 2011; Deleuze et al., 2017; Nuyens et al., 2016) and the Barrett Impulsivity Scale (Chen et al., 2020; Ding et al., 2014). Additionally, performance on a task measuring response inhibition and trait impulsivity has been shown to have a significant negative correlation (Aichert et al., 2012; Bari & Robbins, 2013). Therefore, it was predicted that VGP would be more impulsive than NVGP and that performance on the HRIT would negatively correlate with response inhibition performance.

The results from the analysis identified that the HRIT was capable of inducing stimulus-response compatibility effects with a significant difference in accuracy and response time between congruent trails and incongruent trails, producing effects akin to that of the Spatial Stroop (Wuhr, 2007) and Simon task (Simon, 1969). Moreover, there was a significant effect of stop signal delay (SSD), which was presented in Appendix B, in favour of a summary statistic, stopping performance (SP) that was presented in the Results section (description of the creation of this summary statistics is presented in Chapter 2 Results). The significant differences in the proportion of correct responses across levels of SSD indicate that the HRIT effectively measures changes in the ability to cancel an initiated action based on the temporal proximity of the stop signal. However, performance on No-go trials was found to be at the ceiling, with congruent Go proportion correct close to exhibiting ceiling effects. Therefore, while data obtained from the HRIT in Chapter 2 allowed for the analysis of interference resolution and action cancellation, action withholding could not be analysed further.

As such, the findings of Chapter 2 partially confirmed the hypotheses regarding the effects that would be observed by the HRIT, all except the action withholding. However, the pattern of results is not particularly surprising, Sebastian et al. (2013) and Gerhardt et al. (2021) were able to observe neuronal activation patterns consistent with the regions commonly associated with the three subcomponents of response inhibition but did observe small behavioural effects. As such, recommendations are made here that any future investigations employing the HRIT should alter the proportion of Go and No-go trials to make Go trials more frequent (currently 62.5% Go) and make responding more habitual. Additionally, reducing the duration of intertrial intervals and response windows in order to make responding quicker. Faster and more habitual responding should enable the task to measure the ability to withhold a proponent response and avoid ceiling effects (Benikos et al., 2013; Lindqvist & Thorell, 2008; Raymaekers et al., 2004; Wessel, 2018).

Regarding the main aims of Chapter 2, it was observed that VGP exhibited less congruency cost compared to NVGP. This effect was driven by VGP responding faster to incongruent stimuli than NVGP, whereas no significant difference was observed in response time to congruent stimuli. Moreover, there was a significant difference between VGP and NVGP in proportion correct on the HRIT, but this did not interact with congruency. These findings suggest that there was enhanced interference resolution in VGP compared to NVGP and that this was not the result of a speed-accuracy trade-off. In regard to action cancellation, it was found that VGP were able to maintain 75% accuracy at a longer SSD compared to NVGP, demonstrating enhanced action cancellation performance; effect sizes recorded on these analyses, however, were small. Therefore, VGPs were found to have improved interference resolution and action cancellation compared to NVGPs. However, experience playing video games and participants' subjective rating of skill did not correlate with performance on the HRIT in VGP participants, suggesting that recent frequent video game use was the driving factor behind the improved performance of VGP compared to NVGP. A larger sample size would have allowed for controlling the effects of experience, skill rating, and, importantly, impulsivity.

Regarding impulsivity, it was observed that measures of impulsivity correlated with HRIT on a number of measures. Positive urgency, the tendency to act rashly in response to positive affect, was positively correlated with congruency cost. Negative urgency, the tendency to act rashly in response to negative affect, and positive urgency were positively correlated with incongruent response time and incongruent accuracy. No significant correlations were observed between measures of urgency and congruent accuracy and response time. Total SUPPS-P score, a measure of overall impulsivity, was negatively correlated with incongruent accuracy. Lack of perseverance, lack of premeditation and sensation seeking did not correlate with any measure of the HRIT. Likewise, congruent accuracy, congruent response time, and SP did not significantly correlate with any measure of trait impulsivity from the SUPPS-P. It was found that urgency of any kind (positive or negative) was related to interference resolution. Specifically, the higher the self-reported trait urgency, the slower and less successful interference was resolved. Moreover, higher self-reported positive urgency was related to less successful interference resolution.

In relation to video game use, a point biserial found that VGPs are associated with reporting significantly lower levels of negative urgency than NVGP; the strength of this relationship was small to moderate effect. No other correlations were observed between video game player status, video game play experience measures in VGPs, and self-reported trait impulsivity. However, there is an important finding in the lack of significant correlations between these measures. These findings suggest that recent frequent video game play and history of video game use are not associated with higher levels of self-reported trait impulsivity. Moreover, the opposite is, in fact, true for negative urgency, where being identified as a VGP was related to lower levels of this measure. Therefore, it is possible to conclude that video game play has no negative effect on trait impulsivity.

This conclusion can also extend to response inhibition in this sample. While there are limitations that will be discussed, there was a series of small positive effects of video game use, such as faster and more accurate interference resolution and better stopping performance. Importantly, no speed-accuracy trade-off was observed, and there was a lack of any large negative effect.

Chapter Three aimed to replicate the effects of video game use on response inhibition as measured by the HRIT, utilising the same measures of video game use recorded by the VGEQ. Additionally, this aim extended to replicating the relationships observed between impulsivity and recent frequent video game use, as well as impulsivity and measures of response inhibition. However, the full form of the SUPPS-P, the UPPS-P impulsivity scale, was employed, deviating from Chapter Two. In addition to this, Chapter Three sought to extend the understanding of the nature of these effects by implicating changes to the concentrations of the neurotransmitters γ-Aminobutyric acid (GABA) and glutamate and glutamine coupled as Glx in a network associated with response inhibition, the fronto-parietal network (Chambers et al., 2009; Chen et al., 2020; Morein-Zamir & Robbins, 2015). Specifically, regions of interest were the Dorsolateral Prefrontal Cortex (DLPFC) (Chen et al., 2015; Chen et al., 2020), Supplementary Motor Area (SMA) and pre-SMA (Hermans et al., 2018; Sebastian et al., 2013), and the Anterior Cingulate Cortex (ACC) (Shenhav et al., 2013; Silveri et al., 2013). To assess the potential for video game use to enact neuroplastic change, as observed by differences in performance, it was predicted that there would be an accompanying difference between groups in the concentration of GABA and Glx in regions associated with those behaviours (Chapman et al., 2022). As such, *in-vivo* resting state magnetic resonance spectroscopy (MRS) was conducted on right-handed males free from contraindications that precluded entering a highly magnetic environment. Justification for these criteria was provided in Chapter Three, Methods, Participants.

Firstly, the analyses incorporating neurotransmitters will be summarised, followed by the measures replicating Chapter Two. The results of the analysis on the concentration of GABA and Glx showed no difference between VGP and NVGP in the ACC, DLPFC, and SMA. However, in the whole sample in measures of performance in the HRIT, it was observed that SMA Glx was negatively correlated with congruent Go response time, and ACC Glx and DLFPC GABA were negatively correlated with SP. The correlations were then split between VGP and NVGP. It was observed that for NVGP, there was a negative correlation between DLPFC GABA and SP. In VGP, congruency cost and DLPFC GABA were negatively correlated, as were congruent response time and ACC Glx. Therefore, results were unable to associate any potential improvement in response inhibition as a result of recent frequent video game use with alterations in the concentration of neurotransmitters in the fronto-pariental network.

A relationship between the DLPFC GABA and ACC Glx was hypothesised, attributed to the DLPFC's role in controlling executive functions (Barbey et al., 2013) and response inhibition (Aron et al., 2004; Oldrati et al., 2016) and the ACC hypothesised role in performing a cost/benefit analysis of enacting control processes to balance automatic and controlled behaviour, known as the expected value of control (EVC; Shenhav et al. (2013)). The results of the analysis did not confirm this hypothesis; there was no significant relationship between these regions and neurometabolites. Further research is needed to assess the function of the ACC in EVC and interactions with DLPFC GABA to influence control cognitions. In future, functional magnetic resonance spectroscopy (fMRS), a reliable measurement of neuronal activity (Stanley & Raz, 2018), could be used to assess the activation and functional connectivity between these two regions during a task that modulates the need for controlled and automatic behaviours, such as the Stroop task (MacLeod, 1991; Stroop, 1935). Studies utilising the Stroop task and fMRI have observed this pattern of activation and functional connectivity (Floden et al., 2011; Liu et al., 2008). During task completion, real-time measurements of GABA and Glx could offer additional insights into this theorised relationship between regions.

Similar deficits were observed in regard to measures of response inhibition and in assessing the ability of the HRIT to measure the three components of response inhibition: interference resolution, action withholding, and action cancellation. Namely, ceiling effects were observed in the No-Go condition, replicating an issue that arose in Chapter Two. However, while Chapter Two observed differences within subjects' effects on measures of action cancellation and interference resolution accuracy and response time, in Chapter Three, differences in interference resolution accuracy were not observed, only interference resolution response time and SP. This pattern of results is not uncommon; stimulus-response incompatibility effects and interference of the stimulus-irrelevant dimension on responding are noted as having robust effects on response time but limited effects on accuracy (Lu & Proctor, 1995; MacLeod, 1991).

Regarding self-reported impulsivity and replicating the effects observed in Chapter Two, VGP was associated with lower levels of self-reported positive urgency, and subjective skill rating in VGP participants positively correlated with sensation seeking. This suggests that recent frequent video game use is related to decreased impulsivity in response to positive affect, while perceiving oneself as more adept at playing video games is correlated with higher levels of sensation seeking. In the relationships between impulsivity and measures of response inhibition, there was a negative relationship between incongruent and congruent response time and lack of perseverance. Additionally, negative correlations were observed between SP and negative and positive urgency, lack of perseverance, and total impulsivity measured by UPPS-P total score.

In regard to the pattern of results observed in Chapter Two in measures of impulsivity and the HRIT, these findings replicate the association between lower levels of reported urgency and frequent recent video game use; however, previously negative urgency was negatively associated with recent frequent use, but here we observed this relationship with positive urgency. No other correlations were replicated between the two studies, suggesting that a larger scale experiment is needed to be able to confirm the relationship between video game play and impulsivity. Likewise, a larger sample, irrespective of video game use to assess the relationship between impulsivity and measures of response inhibition on the HRIT, may reflect a different pattern of results typically found in pure single-component measures of response inhibition subcomponents (Aichert et al., 2012; Bari & Robbins, 2013; Enticott et al., 2006; Horn et al., 2003; Leshem, 2016; Portugal et al., 2018; Wilbertz et al., 2014). It should be noted that Chapters Two and Three employed different versions of the UPPS-P, the short form and the full form, respectively. Therefore, while the short form is a reliable and valid adaptation of the full form (Cyders, 2013; Cyders et al., 2014), there is the potential for this to be the source of discrepancies between the two findings.

The final aim of Chapter Three was to replicate the behavioural differences between groups on measures of the HRIT. The analysis results showed that VGP and NVGP did not differ in any measures of response inhibition. In the VGP group, years of experience and the participant's subjective rating of skill on video games did not correlate with performance on any measure of the HRIT. Therefore, Chapter Three was unable to replicate any of the effects observed in Chapter Two.

The methodologies used in Chapters Two and Three, which both employed the same HRIT procedure and the VGEQ questionnaire, made it possible to conduct an ad hoc analysis by combining the data from the two samples. This was reported in Chapter 3, Results, Combined Samples Behavioural Analysis. The combined sample analysis was undertaken to address the potential confounding effects of imbalances in group sizes and to investigate the effects of video game use on response inhibition in a larger sample. As previously mentioned, No-go accuracy was at the ceiling and was not included in this analysis. Additionally, congruent Go accuracy was approaching the ceiling and was likewise not included in this analysis, response time for congruent Go was retained.

The combined sample analysis found that VGP were faster and more accurate in resolving interference than NVGP. This finding was observed in VGP, exhibiting a significantly greater proportion of correct on incongruent trials than in NVGP. VGP exhibited significantly reduced congruency cost compared to NVGP, and this difference was driven by VGP responding faster to incongruent trials than NVGP, but no difference between the two groups on congruent trials was observed. In stopping performance (SP), there was a significant difference between the two groups, with VGP able to maintain 75% accuracy at longer stop signal delays compared to NVGP, demonstrating better action cancellation capabilities. For measurements of years of video game experience and subjective ratings of skill in VGP participants, it was observed that subjective rating of skill negatively correlated with SP, but no other metrics correlated with measures of response inhibition performance. Therefore, the analysis of the combined sample can be interpreted as observing the same effects found in Chapter Two: the recent frequent video game use improves interference resolution speed (but not accuracy), and this effect is driven by faster responses to incongruent trials, overcoming stimulus-response incompatibility effects more readily than NVGP. Additionally, the VGP are able to cancel an initiated response more effectively than NVGP, but a novel finding that participants' perceived skill level is associated with worse action cancellation.

Lastly, Chapter Four sought to extend these findings by addressing two of the overall aims of the present thesis. Firstly, to utilise increasing task demands and cognitive load to enable measurement of the predicted enhanced executive function performance of VGP compared to NVGP (Eayrs & Lavie, 2021; Lavie, 1995; Lavie & Cox, 1997; Lavie et al., 2004). Secondly, to test the hypothesis of transfer effects of learning in relation to recent frequent video game play. That is, recent frequent video game play is able to enact changes in behaviour outside the environment and task that the implicit training has been completed in (Baniqued et al., 2015; Barnett & Ceci, 2002; Bavelier, Green, et al., 2012; Carroll, 1993; Duyck & Op de Beeck, 2019; Jaeggi et al., 2014; Lee et al., 2012; Lintern & Boot, 2021; Sala et al., 2019; Sala & Gobet, 2017; Sala et al., 2018; Zhao et al., 2018). In regards to the unity and diversity model of executive functions (Friedman & Miyake, 2004; Miyake & Friedman, 2012; Miyake et al., 2000) the domain-specific function of working memory updating was selected to measure the ability of the effects of video game use to transfer from the domain-general function of inhibition. Supporting this interpretation Engle (2016) found working memory capacity to be a construct that is vital for higher order cognition and executive function.

The *n*-back task (Kirchner, 1958) was selected as the measure of working memory updating as the task is designed to allow for manipulations of cognitive load. The verbal *n*-back (Mackworth, 1959) is a commonly accepted measure of executive function, attention, and working memory capacity (Gajewski et al., 2018; Owen et al., 2005). In regards to models of working memory (Baddeley, 2012; Baddeley, 2020; Baddeley & Hitch, 1974) increasing the level of *n* in the *n*-back taxes the central executive as active maintenance is required of the phonological loop (Baddeley et al., 1999). Modulations of task difficulty arise when changing the value attributed to the pre-determined value *n,* typically 0,1,2 or 3. The task requires constant updating and manipulation of the stimuli in working memory in the order they were presented (Owen et al., 2005).

Sustained attention was identified as another method to facilitate taxation of executive function resources. Sustained attention is the ability to consciously self-sustain the processing of repetitive and non-arousing stimuli, qualities that would otherwise lead to habituation and distraction towards other stimuli (Robertson et al., 1997). Sustained attention represents an essential attentional function and determines the efficacy of higher-order aspects of attention, such as selective and divided attention (Sarter et al., 2001). Vigilance is the capacity to sustain attention to any environmental source of information over prolonged periods of watch (Szalma et al., 2014) and is a top-down process (Carrasco, 2011; Pinto et al., 2013). Vigilance decrement is the measure of loss of performance as time on task increases. The resource control theory of sustained attention (Thomson et al., 2015) posits that the ability of an observer to direct resources towards a task depends on the level of executive control. As executive control wanes, resources are directed to task-unrelated thoughts, and performance suffers as a consequence. The demands of the task and the amount of resources are fixed within the observer, but individual differences exist. Therefore, the ability to sustain one's attention to a sufficient level relies on the amount of executive control that can be exerted and the availability of resources to direct towards the task and be occupied by task-unrelated thought. The larger the pool of executive function resources, the more resources can be occupied by task-unrelated thought before task performance suffers. Therefore, sustained attention was utilised in the paradigm of Chapter 4 to introduce another facet to observe differences in executive functioning in response to task demands, the demands of time on task as a result of waning executive control.

Supporting the notion of a sustained attention working memory updating paradigm in Helton and Russell (2011) participants undertook an adapted letter detection vigilance task that manipulated either spatial or verbal working memory load (or no memory control). The authors observed vigilance decrement in measures of response time and perceptual sensitivity in SDT and noted that working memory load exacerbated this effect, indicating utilisation of executive function resources. Likewise, Caggiano and Parasuraman (2004) observed vigilance decrement in participants undertaking a continuous performance task dependent on working memory updating.

As such, utilising a paradigm with the capability to manipulate cognitive load in a continuous performance task will allow for measuring vigilance levels in an executive function task with the ability to observe the effects of video game play in line with the findings of Green and Bavelier (2007), Dye et al. (2009a) and others (Bavelier, Achtman, et al., 2012; Bavelier et al., 2018; Bavelier & Green, 2019; Gobet et al., 2014; Hubert-Wallander, Green, Sugarman, et al., 2011). Previous research has found the VGP and NVGP do not significantly differ in their ability to sustain attention, however without manipulations of task difficulty (Trisolini et al., 2018).

In the analysis of Chapter Four, it was found that the n-back sustained attention paradigm succeeded in increasing load through manipulations of *n* and producing a vigilance decrement. For proportion correct and mean reaction time, there was a significant effect of time on task and cognitive load (and interaction between the two), but no interaction with or main effect of video game status. In false alarms, the effect of time on task was significant but not load, video game status, or any interactions. In diffusion modelling, a similar trend was observed, with an effect of time and load and significant interaction between the two, but no main effect or interaction involving video game status on drift rate and non-decision time. For boundary separation, only a significant load effect was observed. SDT measure perceptual sensitivity mirrored boundary separation; a main effect of the load was observed, but there was an interaction with time on task. However, time on task had no significant main effect, nor was there any main effect of or interactions with video game use. Lastly, decision bias followed similar trends, with the main effects of time and load but no interaction with or the main effect of video game use. The NASA-task load index analysis found that VGP and NVGP did not differ in their subjective self-reported workload but that the task was successful in increasing perceived workload. Increasing cognitive load significantly increased the perceived mental demand, physical demand, and effort, but there was no effect of cognitive load on temporal demand, frustration, or performance. VGP exhibited more positive urgency and total impulsivity, as reflected by the SUPPS-P measures.

Therefore, support has been provided for the ability of the *n*-back to be used within a sustained attention paradigm and observe vigilance decrement across common metrics of vigilance level and the ability of an observer to sustain attention, supporting findings of Helton and Russell (2011) and Caggiano and Parasuraman (2004). Moreover, that working memory updating load exacerbates the effect of time on task, potentially as a result of increased waning of executive control or an increase in relative resources required to maintain task performance (Thomson et al., 2015).

Taken together, the results of the three experimental chapters can be summarised as the effects of video game use on executive functions are minimal, weak, and unreliable. VGPs are faster at resolving interference and, at times, more accurate at doing so, but this is inconsistent. Additionally, VGPs are able to cancel initiated actions more successfully than NVGPs, but again, this effect is inconsistent. VGPs are associated with more impulsivity, particularly positive urgency, and lack of perseverance than their NVGP counterparts. These effects were found in both Chapter Two and the combined analysis of Chapter 3, and the impulsivity measures of Chapter Four. However, this weak positive effect of enhanced response inhibition appears to be domain-specific. Despite inhibition being theorised as a domain-general executive function (Friedman & Miyake, 2004; Miyake & Friedman, 2012;

Miyake et al., 2000), a function that interacts with other key executive functions in self-restraint frameworks (Barkley, 1997, 2001; Hofmann et al., 2012), and being associated with higher-order cognitive functions (Diamond, 2013), there appears to be no evidence that the effects of implicit training on this function transfer to domain-specific functions such as working memory updating (Baddeley, 2012; Baddeley, 2020).

The paradigm of Chapter Four, and the rationale behind utilising a hybrid task for response inhibition in Chapters Two and Three, was predicated on the hypothesis that in order to observe the effects of executive function training, sufficient task demands are required (Diamond, 2013). This pattern of results is true for visuo-spatial attention research and the observed improvement as a result of recent frequent video game play (Bavelier, Achtman, et al., 2012; G. Dale et al., 2020; Dye et al., 2009b; Gobet et al., 2014; Hubert-Wallander, Green, & Bavelier, 2011). However, performance under high levels of cognitive load did not differ between the two groups. Moreover, the performance difference between VGP and NVGP was inconsistent, with only mild positive effects.

Mostofsky and Simmonds (2008) noted that response selection and response inhibition are two measures of the same fundamental cognitive function linked to the pre-SMA. However, no differences were observed between groups in pre-SMA GABA or Glx, only on components of response inhibition, while response selection in the n-back yelled null effects. This pattern of results suggests that this locale of improvement across various cognitions in video game players (Bediou et al., 2018) is not a network-wide far-transfer enhancement of executive functions. Instead, there appears to be small-scale near transfer to single components of executive functions such as response inhibition, and these effects do not result in far transfer. Sala et al. (2019) came to a similar conclusion in their meta-analysis of the ability of video games to produce far transfer, that effects were limited to closely related cognitions and that skills did not generalise.

However, there is an interpretation that runs alongside the limited effect of video game use to produce benefits to executive function and cognition more generally. Across three experimental paradigms, there appears to be no large, consistent, negative impact of recent frequent video game use or history of video game use on behaviour or neuronally in the fronto-parietal network. Behaviourally, video game use did not negatively impact response inhibition, working memory updating, and sustained attention. Likewise, GABA and Glx in the DLPFC, ACC, or SMA were not altered in response to recent or history of video game use. A point must be made that video game use is more generally associated with increased urgency and impulsivity. However, this did not impact performance on measures of inhibition, sustained attention, or working memory.

Evidence from problematic video game play research suggests that excessive video game use, or video game use that meets the criteria to be deemed problematic, is associated with reduced performance on tasks measuring response inhibition (Argyriou et al., 2017; Azizi et al., 2018; Chen et al., 2015; Irvine et al., 2013), and working memory (Irak et al., 2021; Tolchinsky & Jefferson, 2011). Moreover, disruptions to the activation of the fronto-parietal network occur (Choi et al., 2021) associated with decrements in performance on measures assessing these cognitions. However, any large negative effect should have been readily apparent even in small sample sizes, suggesting that recent frequent video game use has a dissociable effect to that of problematic video game use. This interpretation is supported by the findings of the meta-analysis by Nuyens et al. (2019), who found that only a small positive effect of video game play remained once problematic video game play had been controlled for. In future, the experiments conducted in this thesis should be replicated to include an additional grouping variable of problematic video game use or treat video game use as a continuous variable.

The interpretation of the set of results presented within this thesis is a positive one. A weak, inconsistent, yet positive effect of video game play that does not appear to support the hypothesised ability of video game use to enact far transfer (Bavelier et al., 2018; Bavelier & Green, 2019; G. Dale et al., 2020; Sala & Gobet, 2017, 2019; Sala et al., 2018). Conversely, this does not represent a large, consistent negative effect of video game use on executive function. Given the opening paragraphs of this thesis, video game play is a prevalent pastime that a large proportion of the general population engages in regularly; the lack of a significant negative impact on executive function cannot be understated.

Limitations and Directions for Future Research

The three experimental chapters presented within this thesis are not without their limitations. In Chapter Two, there were issues of sample size, an imbalance of females (73.61% of the total sample) and an imbalance of NVGP (69.44%) compared to VGP, with a significant proportion of the females sampled fitting the requirements of NVGP (63.89% were female). In Chapter Three, only males were recruited due to methodological constraints of using MRS, with this sample weighted more towards VGP (61.54%). While this sample resulted in no significant effects observed, it allowed for an ad hoc analysis to address the gender and group imbalance and small sample size of the behavioural sample in Chapter Three. This combined sample of 106 participants was predominately NVGP (60.38%) but had a reduced imbalance compared to the previous samples. However, the gender imbalance remained, with females constituting the majority of NVGP (70.3%) and a minority of VPG (11.9%). As reviewed in the discussion of Chapter Three, the pattern of results of obtained in the combined sample, illustrating an improved interference resolution and action cancellation performance, mirrors that observed in the effects of sex on response inhibition (Evans & Hampson, 2015; Mosso et al., 2020; Stoet, 2017). While these findings are debated (Gaillard et al., 2020; Li et al., 2009), it is not possible to rule out the potential for a confound in the present sample. These sampling issues are not unique to the present set of experiment Chapters, and while disproportionately male VGP groups and disproportionately female NVGP groups were more prevalent in the past, the imbalance, while narrowing, exists in recent research (Buono et al., 2020; Gillian Dale et al., 2020; Dale & Shawn Green, 2017; Leonhardt & Overå, 2021; Lopez-Fernandez et al., 2019).

An additional effect of the small sample sizes in the samples obtained across the three experimental Chapters is that there was insufficient statistical power to control for measures of impulsivity on performance and, importantly, to assess the effects of video game genre on the measures of response inhibition, sustained attention, and impulsivity. As noted by G. Dale et al. (2020) modern video games exhibit many characteristics that were exclusive to *action* video games in the late 1900s and early 2000s. It is becoming increasingly common that video games, regardless of genre, exhibit a fast pace, high degree of perceptual, working memory, executive, and motor load, and the need to switch between focused and distributed attention. As such, the effect of video game use regardless of genre and the understanding of genre-specific effects is of critical importance to research methodologies going forward. A more granular assessment of genre and critically an agreed-upon framework for categorising video game genres relative to the executive function tapped while playing them is needed.

Recent research is identifying the effects of video game genre to be of greater importance in understanding the effects of video game use on cognition (Azizi et al., 2018; Bavelier & Green, 2019; Bawa et al., 2018; Bediou et al., 2018; Bernaldo-de-Quirós et al., 2021; Bonny & Castaneda, 2017; Choi et al., 2020; G. Dale et al., 2020; Deleuze et al., 2017; Dobrowolski et al., 2015; Gobet et al., 2014), and it is possible that the differential and inconsistent effects of video game use on cognition is not the result of far transfer of gaming on general cognitive ability, but instead near and limited transfer of implicit training on certain genres to the specific functions tapped by said genre. Revisiting the effects observed in this thesis with larger samples, balanced between gender and video game use, would allow for a more in-depth understanding of the specific roles of gender and genre on video game use and executive functions.

Another potential limitation is the limited age range sampled in the present methodologies. Neuroplasticity the ability of the nervous system to adapt in response to physiological change, injury, environmental demands or sensory experiences (Pascual-Leone et al., 2005), be it at the synaptic level or large-scale network change (Turrigiano & Nelson, 2004), is attributed to the ability of video games to improve a wide array of cognitions (Ballesteros, Kraft, et al., 2015; Ballesteros et al., 2018; Bavelier, Achtman, et al., 2012; Choudhury & McKinney, 2013; Focker et al., 2018; Focker et al., 2019; Isbell et al., 2017; Lohse et al., 2013; Monteiro-Junior et al., 2016; Nahum & Bavelier, 2020; Pappas & Drigas, 2019). Neurogenesis, the underlying function that allows for axonal growth, is debated to be limited in adult humans (Kumar et al., 2019), while early childhood and adolescence are seen as the critical stage for neuroplasticity (Hubener & Bonhoeffer, 2014). Therefore, longitudinal studies are needed to assess the impact of video game play at this age and to crystallise it into older age. Indeed, video game use has been suggested as a tool to invoke plasticity in aged populations (Anguera et al., 2013; Ballesteros, Kraft, et al., 2015; Bapka et al., 2017; Bavelier, Green, et al., 2012; Kuhn et al., 2017; Li et al., 2011; Mayas et al., 2014; Mishra et al., 2015; Monteiro-Junior et al., 2016; West et al., 2018; Wu et al., 2012), research has indicated that age of onset is a moderating effect of the ability of video game use to improve task-switching abilities (Hartanto et al., 2016), and lifelong amount of video game use has been implicated in structural changes in disparate cortical networks (Kuhn & Gallinat, 2014). Therefore, in combination with the genres played during critical stages, this relationship is of utmost importance to understand the multifaceted nature of the effects of video game use.

Another limitation of the present methodologies is that other hobbies were not taken into account and controlled for, such as other forms of interacting with digital media (films, internet usage), sports (general level of physical ability), or other modalities of video game play (exergames). Multitasking with media (Ophir et al., 2009), that is, watching the TV while on your phone, has been shown to have a negative effect on executive functioning (Cardoso-Leite et al., 2016; Courage et al., 2015; Minear et al., 2013). Moreover, research suggests that heavy media multitasking can mask the positive effects of video game use and that only in moderate multitaskers can the beneficial effects of video game use on executive control be observed (Cardoso-Leite et al., 2016). Engagement in open-skill sports, such as tennis, football, and surfing, as opposed to closed-skill sports, such as figure skating and shooting, has been to improve executive function (Formenti et al., 2021; Wang et al., 2013). Heilmann et al. (2022) conducted a meta-analysis of the effects of open and closed-skill sports on executive functions. They found that engagement in open-skill sports was associated with a weak to moderate effect of inhibitory control, working memory and cognitive flexibility.

Exergaming, or active gaming, is the combination of exercise and video games in systems such as the Nintendo Wii, Peloton bikes, Play Station Virtual Reality headsets, and others that require movement of the body to play (Al-Hrathi et al., 2012; Anderson-Hanley et al., 2011; Barcelos et al., 2015). Interest in the ability for exergaming to improve function has typically been focused on the physical and motor functionality of the user, be it after a stroke (Hung et al., 2017), cancer (Benzing et al., 2018; Tough et al., 2018), or for patients with Parkinson’s disease (Garcia-Agundez et al., 2019; Harris et al., 2018). However, there is a trend towards the potential cognitive benefits of exergaming (Al-Hrathi et al., 2012; Anderson-Hanley et al., 2011; Barcelos et al., 2015; Benzing & Schmidt, 2017; Best, 2012; Corregidor-Sánchez et al., 2021; Eggenberger et al., 2020; Halvorson, 2012; Hilton et al., 2014; Kooiman & Sheehan, 2015; Nagano et al., 2016; O'Leary et al., 2011; Ogawa et al., 2016; Ordnung et al., 2017; Perrot et al., 2021; Zhao et al., 2020). Controlling for the effects of sports participation, particularly open-skill sports, the use of exergaming, and media multitasking should allow for a greater understanding of the effect of traditional "couch play" video games on cognition generally and executive function more specifically. Failing to account for these potential confounding variables limits the conclusions that can be drawn of from the current sample.

As identified in the discussions of Chapters Two and Four, in particular, there remains the potential for increasing the task load further to observe the hypothesised implicit executive function training of video games that is masked in low loads (Diamond, 2013). Therefore, the use of the 3-back in the *n*-back (Kane et al., 2007; Palaus et al., 2020), traditional vigilance tasks with modulations of task difficulty (Al-Shargie et al., 2019), or manipulating task difficulty in pure measures of interference resolution, action cancellation, and action withholding has the potential to observe additional executive function resources as a result of video game play. Methods for increasing the task load of the Simon task, Spatial Stroop, Go No-go, and Stop signal tasks have been identified previously. In short, increasing the proportion of Go signals, reducing response deadlines, and reducing inter-stimulus-intervals should increase task difficulty by habituating responding (Congdon et al., 2012; Miyake et al., 2000; Tiego et al., 2018; Wessel, 2018).

Concluding Remarks

To conclude, this thesis investigated the effects of video game use on executive functions. In two experimental chapters, the effects of video game use on response inhibition were assessed behaviourally, and a small, inconsistent, positive effect was observed. That is, recent frequent video game play is associated with resolving interference faster and improving action cancellation. Investigations into the ability of video game play to affect concentrations of GABA and Glx in the DLPFC, ACC, and SMA found non-significant effects. Lastly, Chapter Four sought to increase cognitive load sufficiently to observe differences in executive function on a continuous performance *n*-back design to measure working memory updating and sustained attention. Here, too, no significant effects of video game use were observed. It was therefore concluded that there is a small, unreliable, yet positive effect of video game use on subcomponents of response inhibition, but that this effect does not transfer to over executive functions. Conversely, no large consistent decrement is attributed to the use of video games on inhibition, sustained attention, or working memory.

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Appendices

Appendix A

Calculation of 75% Accuracy on Stop Signal Trials

Participant Number	VG Status	35ms	85ms	135ms	185ms	225ms	Slope	Intercept	75% Accuracy
1	NVGP	0.8	0.8	0.6	0.6	0	-0.18	1.1	1.94
2	NVGP	0.8	0.4	0.6	0.4	0.2	-0.12	0.84	0.75
3	NVGP	1	0.8	0.6	0.8	0.4	-0.12	1.08	2.75
4	NVGP	0.8	0.6	0	0.6	0.2	-0.12	0.8	0.42
5	VGP	1	0.8	0.6	0.4	0.4	-0.16	1.12	2.31
6	NVGP	1	0.2	0.4	0.2	0	-0.2	0.96	1.05
7	VGP	1	0.8	0.4	0.6	0.2	-0.18	1.14	2.17
8	NVGP	1	0.8	0.4	0.2	0.4	-0.18	1.1	1.94
9	NVGP	1	0.8	0.8	0.8	0.6	-0.08	1.04	3.63
10	VGP	1	1	0.6	0.2	0	-0.28	1.4	2.32
11	NVGP	1	0.8	0.4	0.8	0.6	-0.08	0.96	2.63
12	NVGP	0.8	0.8	0.4	0.6	0.4	-0.1	0.9	1.50
13	NVGP	0.6	0.6	1	0	0.4	-0.1	0.82	0.70
14	VGP	1	1	0.8	0.8	0.4	-0.14	1.22	3.36
15	NVGP	1	1	1	0.4	0.4	-0.18	1.3	3.06
16	NVGP	0.4	0.4	0.4	0.6	0.4	0.02	0.38	18.50
17	NVGP	0.4	0.6	0.2	0.6	0.2	-0.04	0.52	-5.75
18	NVGP	1	1	0.4	1	0.2	-0.16	1.2	2.81
19	NVGP	0.6	0.4	0.4	0.2	0	-0.14	0.74	-0.07
20	NVGP	0.8	0.6	0.6	0.4	0.4	-0.1	0.86	1.10
21	NVGP	0	0.2	0.2	0	0	-0.02	0.14	-30.50
22	NVGP	1	1	0.2	0.4	0.4	-0.18	1.14	2.17
23	VGP	0.6	1	0.4	0	0	-0.22	1.06	1.41
24	VGP	1	0.4	0	0	0.2	-0.2	0.92	0.85
25	VGP	0.6	0.6	0.8	0	0.4	-0.1	0.78	0.30
26	NVGP	0.6	0.8	0.6	0.2	0.2	-0.14	0.9	1.07
27	VGP	1	1	1	1	0.8	-0.04	1.08	8.25
28	NVGP	0.8	0.8	0.4	0.8	0.2	-0.12	0.96	1.75
29	NVGP	0.4	0.2	0.4	0.2	0	-0.08	0.48	-3.38
30	NVGP	0.8	0.4	0.2	0.2	0	-0.18	0.86	0.61
31	NVGP	0.6	0.6	0.4	0.2	0.2	-0.12	0.76	0.08
32	VGP	0.6	0.6	0.4	0.2	0	-0.16	0.84	0.56
33	VGP	1	1	1	0.8	0.4	-0.14	1.26	3.64
34	NVGP	1	1	0.6	0.6	0.4	-0.16	1.2	2.81

Participant Number	VG Status	35ms	85ms	135ms	185ms	225ms	Slope	Intercept	75% Accuracy
36	NVGP	1	1	0.8	0.4	0.2	-0.22	1.34	2.68
37	VGP	1	1	1	0.6	0.6	-0.12	1.2	3.75
38	NVGP	1	1	0.8	0.4	0.2	-0.22	1.34	2.68
39	VGP	1	0.8	0.8	0.2	0.2	-0.22	1.26	2.32
40	VGP	1	1	1	1	0.6	-0.08	1.16	5.13
41	NVGP	1	1	0.4	0.6	0.8	-0.08	1	3.13
42	VGP	1	1	1	0.6	0.8	-0.08	1.12	4.63
43	NVGP	0.4	0.8	0.6	0	0.2	-0.12	0.76	0.08
44	NVGP	1	0.2	0.8	0.4	0.4	-0.1	0.86	1.10
45	NVGP	0.8	0.6	0.4	0.2	0.4	-0.12	0.84	0.75
46	NVGP	1	1	1	0.2	0.6	-0.16	1.24	3.06
47	NVGP	1	0.8	0.8	1	0.8	-0.02	0.94	9.50
48	VGP	1	0.8	0.6	0.6	0.4	-0.14	1.1	2.50
49	NVGP	0.8	0.4	0.4	0.6	0.2	-0.1	0.78	0.30
50	NVGP	1	1	1	1	0.4	-0.12	1.24	4.08
51	NVGP	1	0.6	1	0.4	0.4	-0.14	1.1	2.50
52	NVGP	0.6	0.6	0.8	0.4	0.6	-0.02	0.66	-4.50
53	VGP	0.8	0.6	0.4	0.8	0.8	0.02	0.62	6.50
54	NVGP	0.6	0.4	0.6	0.2	0.2	-0.1	0.7	-0.50
55	NVGP	1	0.6	0.8	0.4	0.2	-0.18	1.14	2.17
56	NVGP	1	1	0.6	0.4	0.6	-0.14	1.14	2.79
57	NVGP	1	0.8	0.8	1	0.6	-0.06	1.02	4.50
58	NVGP	1	1	0.6	1	0.4	-0.12	1.16	3.42
59	NVGP	1	1	0.8	0.4	0.6	-0.14	1.18	3.07
60	NVGP	1	0.2	0.6	0.6	0.6	-0.04	0.72	-0.75
61	NVGP	1	0.4	0.2	0.6	0.4	-0.1	0.82	0.70
62	VGP	1	0.8	0.8	0.4	0.2	-0.2	1.24	2.45
63	VGP	1	1	1	0.8	0.8	-0.06	1.1	5.83
64	NVGP	0.6	1	0.2	0.2	0.2	-0.16	0.92	1.06
65	NVGP	1	0.8	0.6	0.4	0.2	-0.2	1.2	2.25
66	VGP	1	1	1	0.4	0.4	-0.18	1.3	3.06
67	NVGP	0.4	0	0	0	0	-0.08	0.32	-5.38
68	NVGP	1	0.8	0.2	0.6	0.4	-0.14	1.02	1.93
69	NVGP	1	0.6	0.8	0.4	0.2	-0.18	1.14	2.17
70	NVGP	0.6	1	0.8	0.4	0.8	-0.02	0.78	1.50
71	VGP	0.2	0.8	0.2	0	0.4	-0.04	0.44	-7.75
72	NVGP	0.4	0.2	0.2	0.4	0	-0.06	0.42	-5.50

Appendix B *Supplementary Analysis of Stop-Timings Variables*

Table B1

Descriptive Statistics for Stop Timing by VG Status

		35ms		85ms		135ms		185ms		225ms	
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
VG Status	NVGP	.83	.22	.69	.28	.56	.26	.47	.27	.34	.22
	VGP	.89	.22	.85	.18	.69	.31	.47	.34	.40	.27
	Total	.85	.22	.73	.27	.60	.28	.47	.29	.36	.23

Table B1 presents the descriptive statistics for each of the five levels of stop timing. As can be observed, as the timing delay increases the proportion of successful stopping decreases, where NVGP appears to present a steeper decline in performance as timing delay increases, however, both groups equalise in their performance at 185ms. A 2x5 ANOVA was conducted to assess the effect of the between-subjects factor of VG status (VGP & NVGP) and the within-subjects factor of Timing delay (35ms, 85ms, 135ms, 185ms, 225ms) on the proportion of successful stopping. Prior to analysis assumption checks were undertaken with the data meeting the requirements for parametric analysis.

There was a significant within-subjects effect of Timing ($F(4,272) = 59.14, p<.001, \eta p2=.47$) and a significant linear trend ($F(1,68) = 248.62, p<.001, \eta p2=.79$), The between-subjects factor of VG status was not significant, ($F(1,68) = 2.92, p=.092, \eta p2=.04$), likewise the interaction effect of VG status and Timing was not significant ($F(4,68) = 1.44, p=.223, \eta p2=.02$). To follow up and assess the difference between levels of the withing-subjects variable of Timing, pairwise comparisons were conducted between each of the five levels, see Table B2 for the results of this analysis.

Table B2

Pairwise Comparisons Proportion Correct by Timings in Stop Task

					95% Confidence Interval for Difference [b]	
(I) Timings	(J) Timings	Mean Difference (I-J)	Std. Error	Sig. [b]	Lower Bound	Upper Bound
35ms	85ms	.09	.04	.126	-.01	.19
	135ms	.23*	.04	<.001	.13	.34
	185ms	.39*	.03	<.001	.29	.49
	225ms	.49*	.03	<.001	.39	.59
85ms	35ms	-.09	.04	.126	-.19	.01
	135ms	.14*	.04	.003	.03	.25
	185ms	.30*	.04	<.001	.18	.42
	225ms	.40*	.04	<.001	.30	.50
135ms	35ms	-.23*	.04	<.001	-.34	-.13
	85ms	-.14*	.04	.003	-.25	-.03
	185ms	.16*	.04	.009	.03	.29
	225ms	.26*	.04	<.001	.15	.36
185ms	35ms	-.39*	.03	<.001	-.49	-.29
	85ms	-.30*	.04	<.001	-.42	-.18
	135ms	-.16*	.04	.009	-.29	-.03
	225ms	.10	.03	.060	.00	.20
225ms	35ms	-.49*	.03	<.001	-.59	-.39
	85ms	-.40*	.04	<.001	-.50	-.30
	135ms	-.26*	.04	<.001	-.36	-.15
	185ms	-.10	.03	.060	-.20	.00

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Appendix C

Swansea University

MRI Procedure – Volunteer Safety Questionnaire

Surname: ……………………………………

Forenames: ……………………………………

Date of birth: ……………………...............…

Weight: ………………… Height.………....

Address: ………………………………………
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WARNING:
Due to the presence of the strong magnetic field certain implants, devices or objects may be hazardous to you and/or may interfere with the MR procedure. DO NOT ENTER the Magnet Room or the MR environment if you have any question or concern regarding an implant, device or object. Consult a member of MRI staff BEFORE entering the Magnet Room. The MR system magnet is ALWAYS on.

Please answer the following questions:		**Tick and Initial**	
		Yes	***No***
1.	***Do you understand that this is a research scan and is not useful for diagnosis?***	☐	☐
2.	***Do you understand the associated risk of voluntary participation?***	☐	☐
3.	***Do you allow us permission to contact your GP in regards to your scan?***	☐	☐

4.	Have you had an MRI procedure before?	☐	☐
	If **YES**, please provide details:		
5.	Do you have, or ever have had, a cardiac pacemaker, pacing wires, an artificial heart valve, cochlea implant, hearing aids, programmable hydrocephalus shunt or neuro stimulator?	☐	☐
	If **YES**, please provide details:		
6.	Have you ever had any heart or head surgery?	☐	☐
	If **YES**, please provide details:		
7.	Have you ever had any surgery involving the use of metal implants, plates or clips?	☐	☐
	If **YES**, please provide details:		
8.	Have you had any surgery within the last two months?	☐	☐
	If **YES**, please provide details:		
9.	Have you EVER had any metal fragments in your eyes?	☐	☐
	If **YES**, please provide details:		
10.	Have you EVER had any metal fragments in any other part of your body? e.g. bullets, shrapnel, weld?	☐	☐
	If **YES**, please provide details:		
11.	Do you wear dentures, a dental plate with/without metal or a brace (NOT FILLINGS)?	☐	☐

	If YES, please provide details:		
12.	Do you have any of the following?		
	Tattoos	☐	☐
	Piercings/ Body Jewellery	☐	☐
	Limb or Prosthesis	☐	☐
	Medicine Patches e.g HRT, Nicotine replacement, Pain relief, Nitro patch	☐	☐

For female patients only:

13.	Is there a possibility that you could be pregnant?	☐	☐
14.	Are you breast-feeding?	☐	☐
15.	Do you have an IUD coil fitted? If YES, please provide details:	☐	☐

PATIENT DECLARATION

By signing below you acknowledge that:

1. You confirm that the information provided is accurate to the best of your knowledge.
2. You have had the opportunity to ask questions regarding the information on this form and regarding the MR procedure that you are about to undergo
3. BEFORE entering the Magnet Room you will remove ALL metal objects including coins, jewellery, hair pins, body piercing, false teeth, hearing aids, pens, tools, analogue watches and credit cards.
4. You may be advised or required to wear earplugs or other hearing protection during the MR procedure to prevent possible problems or hazards related to acoustic noise.
5. As a research site, your data maybe anonymised and added to the secure research data base at the University.

Signature: ……………………………………………… **Date:** ………………………………

(Office use only) Checked by: ………………………………… **Date:** ………………………………….

Appendix D. MRSinMRS checklist. Additional columns are provided for multi-site or multi-sequence studies if necessary.

Site: Swansea University, Singleton Campus, Clinical Imaging Facility 1. Hardware	
a. Field strength [T]	3T
b. Manufacturer	Siemens Medical Solutions
c. Model (software version if available)	Magnetom Skyra (software version XA30)
d. RF coils: nuclei (transmit/ receive), number of channels, type, body part	Siemens ^{1}H (transmit/receive), 32-channels, head coil, brain
e. Additional hardware	
2. Acquisition	
a. Pulse sequence	MEGA-PRESS (Marjańska et al., 2013) (provided by the CMRR at the University of Minnesota under a C2P agreement) Structural imaging: MPRage
b. Volume of Interest (VOI) locations	Right Dorsolateral Prefrontal Cortex (DLPFC). Anterior Cingulate Cortex (ACC), Supplementary Motor Area (SMA). Figure 8 in the main body.
c. Nominal VOI size [cm^3, mm^3]	(30x30x30mm) for the right DLPFC, ACC, and SMA VOIs
d. Repetition Time (TR), Echo Time (TE) [ms, s]	MRS: TR=2000ms, TE=68ms Structural MRI: TR=2200ms, TE=2.47ms
e. Total number of Excitations or acquisitions per spectrum In time series for kinetic studies i. Number of Averaged spectra (NA) per time-point ii. Averaging method (e.g. block-wise or moving average) iii. Total number of spectra (acquired / in time-series)	150 averages with water suppression (150 per on and 150 per off)), 16 averages without water suppression Block-wise averaging (gannet default was used)

f. Additional sequence parameters (spectral width in Hz, number of spectral points, frequency offsets) If STEAM:, Mixing Time (TM) If MRSI: 2D or 3D, FOV in all directions, matrix size, acceleration factors, sampling method	2000 Hz, 2048 complex data points, delta frequency -1.70ppm, Editing pulses edit-on 1.9, edit-off 7.5ppm-
g. Water Suppression Method	VAPOR
h. Shimming Method, reference peak, and thresholds for "acceptance of shim" chosen	automatic shimming: FASTEST map Reference peak: Water Thresholds for acceptance of shim:<15
i. Triggering or motion correction method (respiratory, peripheral, cardiac triggering, incl. device used and delays)	None
3. Data analysis methods and outputs	
a. Analysis software	GANNET 3.0 toolbox for MATLAB. SPM 12
b. Processing steps deviating from quoted reference or product	Standard processing steps, inbuilt models and assumptions for this software (details can be found at http://gabamrs.com). Utilized the relaxation and tissue correction method as described by Gasparovic et al. (2006)
c. Output measure (e.g. absolute concentration, institutional units, ratio)Processing steps deviating from quoted reference or product	GABA concentration measured and reported in institutional units, referenced to water. The concentrations are corrected for relaxation times and tissue composition.
d. Quantification references and assumptions, fitting model assumptions	The data was quantified using a model that treats the GABA peak as a single Gaussian, Glutamate and glutamine as a doublet, Glx.
4. Data Quality	
a. Reported variables (SNR, Linewidth (with reference peaks))	

b. Data exclusion criteria	GANNET Model fit was assessed based on visual inspection and FWHM within 3 *SD*s from the group mean per metabolite.
c. Quality measures of postprocessing Model fitting (e.g. CRLB, goodness of fit, SD of residual)	At least one of the neurotransmitters, GABA or Glx, was successfully fit according to visual inspection and FWHM falling within 3 SDs from the group mean.
d. Sample Spectrum	Sample Spectra for each VOI supplied in main body Figure 9

Appendix E

Calculation of SST on Stop Signal Trials

Participant Number	VG status	35ms	85ms	135ms	185ms	225ms	Slope	Intercept	SST
1	NVGP	1	0.8	0.8	0.6	0.4	-0.14	1.14	2.79
2	VGP	1	1	1	0.8	0.6	-0.1	1.18	4.30
3	NVGP	0.6	0.8	0.4	0.6	0.2	-0.1	0.82	0.70
4	VGP	1	0.8	1	0.8	0.8	-0.04	1	6.25
5	VGP	0.8	0.8	0.6	0.6	0.6	-0.06	0.86	1.83
7	VGP	1	1	1	1	1	0	1	0.00
8	NVGP	1	1	0.8	0.8	0.6	-0.1	1.14	3.90
9	NVGP	1	1	0.8	1	0.2	-0.16	1.28	3.31
10	NVGP	1	0.8	0.6	0.2	0.4	-0.18	1.14	2.17
11	NVGP	1	1	1	0.6	0.6	-0.12	1.2	3.75
14	VGP	1	1	1	0.8	0.8	-0.06	1.1	5.83
15	NVGP	1	0.8	0.6	0.6	0.2	-0.18	1.18	2.39
16	NVGP	1	1	1	0.8	0.4	-0.14	1.26	3.64
17	VGP	1	0.8	0.6	0.6	0.2	-0.18	1.18	2.39
18	NVGP	1	1	0.8	0.8	0.6	-0.1	1.14	3.90
19	VGP	1	1	1	0.8	0.8	-0.06	1.1	5.83
20	VGP	0.8	0.4	0.6	0.4	0.4	-0.08	0.76	0.13
21	VGP	0.6	0.8	0.2	1	0.4	-0.02	0.66	-4.50
22	VGP	0.8	0.6	0.6	0.6	0.2	-0.12	0.92	1.42
23	VGP	1	1	1	0.4	0	-0.26	1.46	2.73

24	VGP	1	0.8	0.4	0	0.2	-0.24	1.2	1.88
26	VGP	1	1	0.8	1	0.8	-0.04	1.04	7.25
27	NVGP	1	0.6	0.4	0	0.2	-0.22	1.1	1.59
28	NVGP	1	1	1	0.8	0.6	-0.1	1.18	4.30
29	VGP	1	0.8	0.8	0.4	0.6	-0.12	1.08	2.75
30	VGP	1	0.8	0.6	0.2	0	-0.26	1.3	2.12
31	NVGP	1	1	0.4	0.2	0.2	-0.24	1.28	2.21
32	VGP	1	1	1	1	0.6	-0.08	1.16	5.13
33	VGP	1	1	1	1	0.6	-0.08	1.16	5.13
34	VGP	0.8	1	0.6	0.2	0.2	-0.2	1.16	2.05
35	VGP	1	0.8	0.6	0.8	0.4	-0.12	1.08	2.75
36	VGP	0.8	1	0.8	1	0.4	-0.08	1.04	3.63
37	NVGP	1	0.6	0.6	0.4	0	-0.22	1.18	1.95
38	VGP	1	1	1	0.8	0.6	-0.1	1.18	4.30
39	NVGP	1	1	1	0.6	0.8	-0.08	1.12	4.63
40	VGP	1	1	1	0.4	0.4	-0.18	1.3	3.06
41	NVGP	0.6	0.2	0.4	0.4	0.2	-0.06	0.54	-3.50
42	VGP	1	0.8	0.6	0.8	0.2	-0.16	1.16	2.56
44	VGP	0.8	1	0.6	0.4	0.2	-0.18	1.14	2.17

Appendix F

Whole Sample Correlations of HRIT RT Data

		VG status	Years Experience	Subjective Rating	Incongruent RT	Congruent RT	Congruency Cost
VG status	Pearson Correlation	--					
	N	39					
Years Experience	Pearson Correlation	.590**	--				
	Sig. (2-tailed)	<.001					
	N	39	39				
Subjective Rating	Pearson Correlation	.707**	.669**	--			
	Sig. (2-tailed)	<.001	<.001				
	N	39	39	39			
Incongruent RT	Pearson Correlation	.084	.028	-.089	--		
	Sig. (2-tailed)	.611	.867	.591			
	N	39	39	39	39		
Congruent RT	Pearson Correlation	-.029	-.047	-.240	.753**	--	
	Sig. (2-tailed)	.863	.774	.141	<.001		
	N	39	39	39	39	39	
Congruency Cost	Pearson Correlation	.161	.106	.207	.393*	-.309	--
	Sig. (2-tailed)	.326	.519	.205	.013	.056	
	N	39	39	39	39	39	39

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Appendix G Supplementary Analyses

Mixed 2x5 ANOVA: Stop Timing

Table G1

Descriptive Statistics for Stop Timing By VG Status

		35ms		85ms		135ms		185ms		225ms	
		M	SD	M	SD	M	SD	M	SD	M	SD
VG Status	NVGP	.95	.14	.84	.23	.71	.24	.56	.27	.37	.23
	VGP	.93	.11	.88	.16	.77	.23	.66	.30	.46	.27

A mixed 2x5 ANOVA was conducted to examine the effects of VG Status (VGP vs. NVGP) and Timings (35, 85, 135, 185, 225) on proportion correct. Descriptive statistics are presented in Table G1. Sphericity was violated χ2(9)=.523,p=.006, therefore the Greenhouse-Geisser correction was used. Homogeneity of variance was observed by Levene's test (P>.05 across all levels). The within subjects factor of timings was significant (F(3.003,111.121)=54.360, p<.001, ηp2 = .595. However, the between subjects factor of VG status was not significant (F(1,37)=684.30, p=.322, ηp2 = .026). The interaction between Timings and VG status was likewise not significant (F(3.003,111.121)=.597, p = .619, ηp2 = .016.

Pairwise comparisons for Timings found significant differences between all levels of Timings (P<.009) as can be observed in Table G2.

Table G2

Pairwise Comparisons

Proportion Correct by Timings in Stop Task

(I) Timings	(J) Timings	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	.078*	.028	.008	.022	.134
	3	.203*	.031	<.001	.140	.267
	4	.331*	.051	<.001	.228	.434
	5	.524*	.042	<.001	.440	.609
2	1	-.078*	.028	.008	-.134	-.022
	3	.125*	.032	<.001	.060	.190
	4	.252*	.045	<.001	.161	.344
	5	.446*	.041	<.001	.362	.529
3	1	-.203*	.031	<.001	-.267	-.140
	2	-.125*	.032	<.001	-.190	-.060
	4	.127*	.045	.007	.036	.219
	5	.321*	.036	<.001	.249	.393
4	1	-.331*	.051	<.001	-.434	-.228
	2	-.252*	.045	<.001	-.344	-.161
	3	-.127*	.045	.007	-.219	-.036
	5	.193*	.042	<.001	.108	.279
5	1	-.524*	.042	<.001	-.609	-.440
	2	-.446*	.041	<.001	-.529	-.362
	3	-.321*	.036	<.001	-.393	-.249
	4	-.193*	.042	<.001	-.279	-.108

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Spearman correlations were conducted between VG status, Subjective rating of VG performance, Years experience, Congruent Go, Incongruent Go, and the 5 level of stop timings (35, 85, 135, 185, 225ms). No Go was removed from all correlations due to being a constant. Significant correlations were observed between Prop35 and Congruent Go (r=.36,p=.025), Prop 35 and Prop 85 (r=324,p=.044), prop35 and prop 135(r=.513,p<.001), Prop 85 and Prop135(r=.683,p<.001), prop85 and prop185 (r=.442,p=.005), prop 85 and prop225 (r=.453,p=.004). Prop 135 and Prop 185 (r=.492,p=.001), Prop 135 and prop 225 (r=.661, p<.001), and prop 185 and prop225(r=.580, p<.001). Additionally, the previously observed relationships between VG status and Years experience and subjective rating were observed.

UPPS & MRS

To assess the relationship between impulsivity as measured by the UPPSP and MRS data, Pearson correlations were conducted between the five subscales, total score, and the concentration of neuromatabolites in ACC (GLX), DLPFC (GABA, GLX), SMA (GABA, Glx). ACC Glx demonstrated a significant positive correlation with negative urgency (*r*(37) = .331, *p* = .039), suggesting that decreased levels of Glx in the ACC is associated with lower levels of negative urgency, the tendency to act rashly in response to negative affect. No other correlations were significant (*p* >.05). A Spearman correlation was conducted between ACC GABA and the measures obtained from the UPPSP. No correlation approached significance (all *p's* >.05).

Appendix H Spearman Correlations for ACC GABA and HRIT measures

Table H1

Spearman Correlation Matrix ACC GABA and HRIT measures

		Incongruent RT	Congruent RT	Congruency Cost	SST	ACC GABA
Incongruent RT	Correlation Coefficient	--				
	Sig. (2-tailed)	.				
Congruent RT	Correlation Coefficient	.720**	--			
	Sig. (2-tailed)	<.001	.			
Congruency Cost	Correlation Coefficient	.344*	-.306	--		
	Sig. (2-tailed)	.032	.058	.		
SST	Correlation Coefficient	.485**	.621**	-.041	--	
	Sig. (2-tailed)	.002	<.001	.806	.	
ACC GABA	Correlation Coefficient	-.104	-.186	.006	-.167	--
	Sig. (2-tailed)	.528	.256	.973	.310	.

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Appendix I Spearman correlations between Accuracy in congruent go and incongruent go trials with MRS data

Table I1

Spearman correlation matrix Congruent and Incongruent Go with MRS Data

		Incongruent Go	Congruent Go	ACC GABA	ACC Glx	DLPFC Gaba	DLPFC Glx	SMA GABA	SMA Glx
Incongruent Go	Correlation Coefficient	--							
	Sig. (2-tailed)	.							
Congruent Go	Correlation Coefficient	.290	--						
	Sig. (2-tailed)	.074	.						
ACC GABA	Correlation Coefficient	-.036	-.047	--					
	Sig. (2-tailed)	.826	.776	.					
ACC Glx	Correlation Coefficient	.104	-.032	.227	--				
	Sig. (2-tailed)	.529	.847	.165	.				
DLPFC GABA	Correlation Coefficient	.030	.096	.165	-.121	--			
	Sig. (2-tailed)	.854	.561	.315	.461	.			
DLPFC Glx	Correlation Coefficient	.119	.036	-.014	.525**	.083	--		
	Sig. (2-tailed)	.470	.826	.935	<.001	.617	.		
SMA GABA	Correlation Coefficient	-.017	-.202	.286	.126	.212	.019	--	
	Sig. (2-tailed)	.920	.238	.091	.464	.215	.912	.	
SMA Glx	Correlation Coefficient	-.109	-.095	.361*	.489**	.004	.464**	.280	--
	Sig. (2-tailed)	.528	.580	.030	.002	.983	.004	.098	.

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Appendix J

Spearman Correlation HRIT Accuracy and MRS data In Non-Video Game Players (NVGP)

			ACC Glx	DLPFC GABA	DLPFC Glx	SMA GABA	SMA Glx	ACC GABA	Congruent	Incongruent
Spearman's rho	ACC Glx	Correlation Coefficient	--							
		Sig. (2-tailed)	.							
		N	15							
	DLPFC GABA	Correlation Coefficient	-.164	--						
		Sig. (2-tailed)	.558	.						
		N	15	15						
	DLPFC Glx	Correlation Coefficient	.018	.121	--					
		Sig. (2-tailed)	.950	.666	.					
		N	15	15	15					
	SMA GABA	Correlation Coefficient	.538	.133	.119	--				
		Sig. (2-tailed)	.071	.681	.713	.				
		N	12	12	12	12				
	SMA Glx	Correlation Coefficient	.399	-.252	.811**	.427	--			
		Sig. (2-tailed)	.199	.430	.001	.167	.			
		N	12	12	12	12	12			
	ACC GABA	Correlation Coefficient	.618*	-.093	.175	.385	.622*	--		
		Sig. (2-tailed)	.014	.742	.533	.217	.031	.		
		N	15	15	15	12	12	15		
	Congruent	Correlation Coefficient	-.231	.349	-.046	-.132	-.055	-.004	--	
		Sig. (2-tailed)	.406	.202	.872	.683	.865	.989	.	
		N	15	15	15	12	12	15	15	
	Incongruent	Correlation Coefficient	.027	.188	-.085	.373	.103	-.038	.278	--
		Sig. (2-tailed)	.924	.502	.765	.232	.749	.892	.317	.
		N	15	15	15	12	12	15	15	15

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Appendix K

Spearman Correlation Matrix HRIT Accuracy and MRS Data In Video Game Players (VGP)

			ACC Glx	DLPFC GABA	DLPFC Glx	SMA GABA	SMA Glx	ACC GABA	Congruent	Incongruent
Spearman's rho	ACC Glx	Correlation Coefficient	--							
		Sig. (2-tailed)	.							
		N	24							
	DLPFC GABA	Correlation Coefficient	-.036	--						
		Sig. (2-tailed)	.869	.						
		N	24	24						
	DLPFC Glx	Correlation Coefficient	.702**	.074	--					
		Sig. (2-tailed)	<.001	.731	.					
		N	24	24	24					
	SMA GABA	Correlation Coefficient	.055	.219	-.030	--				
		Sig. (2-tailed)	.799	.304	.891	.				
		N	24	24	24	24				
	SMA_Glx	Correlation Coefficient	.577**	.153	.433*	.237	--			
		Sig. (2-tailed)	.003	.475	.035	.266	.			
		N	24	24	24	24	24			
	ACC GABA	Correlation Coefficient	-.016	.494*	-.112	.218	.229	--		
		Sig. (2-tailed)	.942	.014	.602	.306	.282	.		
		N	24	24	24	24	24	24		
	Congruent	Correlation Coefficient	.074	-.148	.124	-.222	-.053	-.123	--	
		Sig. (2-tailed)	.731	.490	.563	.297	.805	.568	.	
		N	24	24	24	24	24	24	24	
	Incongruent	Correlation Coefficient	.168	-.109	.244	-.176	-.137	-.098	.291	--
		Sig. (2-tailed)	.434	.612	.250	.410	.522	.649	.168	.
		N	24	24	24	24	24	24	24	24

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Appendix L

NVGP Spearman Correlation Matrix RT and SST HRIT data and MRS Data

			ACC GABA	Incongruent RT	Congruent RT	Congruency Cost	SST
Spearman's rho	ACC GABA	Correlation Coefficient	--				
		Sig. (2-tailed)	.				
		N	15				
	Incongruent RT	Correlation Coefficient	-.264	--			
		Sig. (2-tailed)	.341	.			
		N	15	15			
	Congruent RT	Correlation Coefficient	-.325	.757**	--		
		Sig. (2-tailed)	.237	.001	.		
		N	15	15	15		
	Congruency Cost	Correlation Coefficient	-.007	.039	-.561*	--	
		Sig. (2-tailed)	.980	.889	.030	.	
		N	15	15	15	15	
	SST	Correlation Coefficient	.064	.542*	.727**	-.449	--
		Sig. (2-tailed)	.820	.037	.002	.093	.
		N	15	15	15	15	15

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Appendix M

VGP Spearman Correlation Matrix HRIT RT, SST, and MRS Data

			ACC GABA	Incongruent RT	Congruent RT	Congruency Cost	SST
Spearman's rho	ACC GABA	Correlation Coefficient	--				
		Sig. (2-tailed)	.				
		N	24				
	Incongruent RT	Correlation Coefficient	.010	--			
		Sig. (2-tailed)	.961	.			
		N	24	24			
	Congruent RT	Correlation Coefficient	-.138	.702**	--		
		Sig. (2-tailed)	.519	<.001	.		
		N	24	24	24		
	Congruency Cost	Correlation Coefficient	.007	.468*	-.191	--	
		Sig. (2-tailed)	.974	.021	.371	.	
		N	24	24	24	24	
	75 % Acc	Correlation Coefficient	-.289	.429*	.539**	.146	--
		Sig. (2-tailed)	.172	.036	.007	.495	.
		N	24	24	24	24	24

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).