A Virtual Reality (VR) Exploration of Inhibitory Control and Working Memory in Adults with ADHD

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Contents

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Statement of Contribution

Experiment design: Fjorda Kazazi, Professor Peter Howell

Experiment build-up: Fjorda Kazazi

Data collection: Fjorda Kazazi, Jo Ma, Nur Afini Hamzah, QNJL0

Data analysis and interpretation: QNJL0, with support from Fjorda Kazazi and Professor Peter Howell

Write-up: QNJL0, with support from Professor Peter Howell

Abstract

Background: Inhibitory control deficit is associated with socio-economic consequences such as difficulty in social interaction and poor academic/working performance. Previous studies have found inhibitory control problems in ADHD. But most studies concentrated on response inhibition and children with ADHD.

Aim: This study aimed to investigate inhibitory control ability and working memory capacity in adults with ADHD and the relationship between inhibitory control and working memory.

Methods & Procedures: twenty-four participants were divided into control and ADHD group according to ASRS scores. Participants completed 10 VR tasks. Two response inhibition tasks (go/no-go task and antisaccade task) and one attentional inhibition task (inattentional blindness task) were examined in this report. Commission error rate and reaction time were analyzed for two response inhibition tasks, direction error rates were additionally calculated for the antisaccade task. Counting accuracy, detection of unexpected stimulus and mean gaze distance were analyzed for the inattentional inhibition task. UNWR scores were measured for all participants.

Results: The results failed to prove inhibitory control deficit in ADHD. But they showed a significant lower phonological working memory capacity in ADHD and indicated a negative correlation between UNWR scores and the commission error rate of the antisaccade task.

Introduction

Attention deficit hyperactivity disorder (ADHD) is one of the most common psychiatric disorders, characterized by the presence of inappropriate levels of hyperactivity, impulsivity, and inattention. Inhibitory control has long been considered a major neurocognitive deficit in ADHD since ADHD typically exhibit certain impairments in common inhibition paradigms compared to their typical peers (Barkley, 1997; Fosco et al., 2019; Lipszyc & Schachar, 2010). Inhibition has been a construct central to etiologic theoretical accounts of ADHD and other developmental psychopathology. Recent studies also suggest that inhibitory control deficit is associated with socio-economic consequences such as difficulty in social interaction and poor academic/working performance (Kofler et al., 2017).

ADHD is a developmental disorder that often arises relatively early in childhood and it was once thought to "disappear" as people grow age. Clinic-based longitudinal studies, however, reported that symptoms and associated psychosocial impairments of this childhood disorder often persist into adulthood (Kooij et al., 2010; Rowland et al., 2002; Shaffer, 1994). Our experiment, therefore, adopted the Adult ADHD Self-Report Scale (ASRS) to assess ADHD traits in adult participants and involve both response and attentional inhibition tasks. Also, previous empirical studies were mostly conducted in laboratory scenarios with low ecological validity. The immersive effect of Virtual Reality (VR) scenarios can significantly enhance individual's attention as well as behavioural performance compared to experiments conducted with 2D monitors (Berger & Davelaar, 2018; Li et al., 2020). Therefore, head-mounted VR display was applied in our experiment to make participants feel more presented in the tasks.

In the introduction, literature on two dimensions of inhibitory control, their representations in adults with ADHD, and the relationship between working memory and inhibitory control were reviewed.

Inhibitory Control

Broadly speaking, inhibitory control refers to the capacity to suppress a behavioural or internal response so as to achieve a goal (Nigg, 2000). It is an umbrella term that covers multiple subtypes of inhibitory processes at both behavioural (e.g. inhibition of motor response) and cognitive levels (e.g. suppression of prepotent mental representations) (Marton et al., 2007; Tiego et al., 2018). The definition of inhibition often varies across authors and sometimes the concept of inhibition in theoretical approaches is not very clear. Nigg (2000) attempted to establish an overarching taxonomy of inhibition and distinguished eight kinds of inhibitory processes in a wide range of cognitive processes. This report, however, follows a rather generalized taxonomy that distinguishes two significant inhibitory processes under the rubric of inhibition: response inhibition and attentional inhibition (Tiego et al., 2018).

Response Inhibition

Response inhibition is an aspect of inhibitory control that describes the ability to suppress, cancel or postpone a goal-irrelevant prepotent motor response (Tiego et al., 2018). It is also known as "behavioural inhibition" or "behavioural self-control" in other literature (Diamond, 2013; Friedman & Miyake, 2004), implying that self-regulation and performance monitoring are also involved in successful response inhibition. This top-down cognitive process allows people to resist impulsivities and temptations, thereby preventing people from indulging in illegal (e.g. morally wrong) pleasure or being shortsighted to choose short-term benefits over greater delayed rewards.

Previous studies have developed several experimental tasks to measure the countermanding process of response inhibition. The go/no-go task is one of the most frequently used behavioural paradigms in investigating response inhibition. It requires participants to press the button when Go cues show up and stop when they see No-Go cues. The task contains a much higher frequency of Go cues (e.g.80%) compared to No-Go cues (e.g.20%). Since participants may adopt a prepotent tendency for automatic response from the repetitive Go cues, if this tendency can be suppressed when the next

No-Go cue occurs, it means that response inhibition has successfully played its role. Stop signal task (SST) is similar to go/no-go tasks and they are sometimes interchangeably used to assess response inhibition. In SST, however, the go cue always appears first, and then the stop signal (usually a sound) appears just as the participant is about to respond (Lipszyc & Schachar, 2010). The outcome of SST trials comes from a competition between the go process and stop process and it is more about individual's ability to cancel a response. Go/no-go task, on the other hand, emphasizes more on suppressing a response. Thus the two task designs actually measure different aspects of response inhibition.

Another frequently used paradigm to assess response inhibition is the antisaccade task. Antisaccade task is designed to assess visual response inhibition. The natural oculomotor tendency is to look toward the same direction of a salient stimulus (i.e. prosaccade). On the contrary, the antisaccade task asks participants to inhibit their natural tendency and look away to the opposite direction of the stimulus instead. A successful performance involves two steps. First, the participant must withhold the prepotent prosaccadic response and then convert it into a voluntary motor command of antisaccade. Previous saccade study indicates that correct antisaccades are initiated later than prosaccades and people are more prone to errors in antisaccade tasks, but these errors are usually initiated earlier than the correct responses (Munoz & Everling, 2004).

Attentional inhibition

Attentional inhibition is the ability that enables us to resist irrelevant stimuli in the external environment and selectively attend to what we choose to focus on (Tiego et al., 2018). External salient stimuli such as visual motion or acoustic signals will arouse bottom-up involuntary attention, and attentional attention helps us to voluntarily ignore such unwanted interferences. Failure to inhibit unnecessary information (i.e. distractors) would undermine the efficiency of information processing and cause more mistakes. In a broader perspective, attentional inhibition refers to cognitive inhibition that not only helps us suppress external distractors, but also prevents us from the interference of prepotent mental representations such as proactive memories and unwanted thoughts

(Anderson & Levy, 2009; Diamond, 2013). In some other studies, attentional inhibition is also called interference control or inhibition of attention (Diamond, 2013; Nigg, 2000).

Attentional inhibition is closely correlated with selective attention. Selective attention is applied when individuals choose to concentrate on one aspect of simultaneous resources (Pashler et al., 2001). Lavie et al. (Cartwright-Finch & Lavie, 2007; Lavie, 2010) proposed a load theory delineating the mechanism of perceptual selection attentional inhibition. The involuntary process of attentional inhibition can be explained by perceptual load theory, which consists of two mechanisms. The first is perceptual load theory, which suggests that attentional inhibition of interferences depends on the perceptual load of task-relevant processing. Higher perceptual load requires greater intensity in information processing. The theory presumes that the attentional resources are limited, therefore when processing a task with high perceptual load, more attentional resources would be allocated to the task, and distractors and interferences would be less likely to intrude into working memory as there is not much capacity left for task-irrelevant stimulus processing. In contrast, when the perceptual load is low, attentional resources would spill over to process task-irrelated interferences. The other process involved is the cognitive control mechanism. As executive control requires working memory to suppress interferences and distractors, greater working memory load would lead to greater distractor interference.

Perceptual load theory has gained its support from inattentional blindness paradigms. As individuals only selectively attend to task-related information processing, other competing resources would be involuntarily retained, hence even an obvious salient stimulus may fail to be detected. This phenomenon is termed inattentional blindness. Inattentional blindness often happens when the observers are engaged in attentionally demanding tasks. Inattentional blindness paradigm display attentional inhibition and selective attention functioning in individuals. Different variations of inattentional blindness tasks have been developed to investigate the ability to detect unexpected events. The most popular inattentional blindness task is the invisible “gorilla”, in which participants are required to watch a video and count the times of ball passing among a group of players, and a “gorilla” walks past the players during the task. Approximately 50% of the participants failed to notice the “gorilla” (Simons & Chabris, 1999). A gradient model of selective spatial attention suggests the strongest facilitatory attention effect and accordingly greater attentional inhibition at the locus of the attention, and they would decrease with growing distance (Newby & Rock, 1998). Consequently, there is a lower rate of inattentional blindness when extraneous stimulus appears within the attended region compared to when it is presented further away from the locus of attention (Thakral & Slotnick, 2010). Nevertheless, attentional inhibition and the spatial effect are the only factors that mediate inattentional blindness, difficulty of the task, salience degree of the unexpected stimulus, working memory load, etc. may influence the inattentional blindness effect as well.

Other popular tasks used to assess attentional inhibition include the Stroop task and flanker task. The Stroop task demonstrated that the reaction time of naming the color word with incongruent color is longer compared to the color word with congruent color (Macleod, 1991). The flanker task requires participants to selectively attend to the stimulus presented in the center and ignore the flanking stimuli. And similar to the findings of the Stroop task, participants reacted slower when the center stimulus was incompatible with flanking stimuli.

Inhibitory Control and ADHD

The precise cause of ADHD has not yet been fully uncovered, but the exploration of causal determinants of ADHD has shifted its major focus from “inattention” to “disinhibition” (Nigg, 2001) since Barkley (1997) raised a unifying theory of ADHD. Barkley (1997) suggested that poor response inhibition would result in secondary impairments of other cognitive functions that depend on it for their effective execution. Consequently, people with ADHD will show decreased control over motor behaviour and a poor ability to maintain prolonged attention (i.e. sustained attention) because of their lack of behavioural control.

Correspondingly, there is an increasing number of both behavioural and neural imaging empirical studies aiming to examine the relationship between inhibitory control and ADHD. In behavioural studies, commission error rates and reaction times (RTs) are commonly considered as the standard measure for the assessment of behavioural inhibition in classic go/no-go tasks (Littman & Takács, 2017). Commission error here refers to when subjects respond to non-target stimuli (no-go cues). It is well supported by previous studies that people with deficits in behavioural inhibition often commit higher commission error rates (Aron & Poldrack, 2005; Trommer et al., 1988). Slow and variable reaction times (RTs) on speeded tasks represent a prominent characteristic of ADHD as well and it has commonly been used as a significant indicator of inhibitory control (Fosco et al., 2019; Karalunas et al., 2012). More specifically, the drift diffusion model decomposed ADHD effects on RT, indicating that the slower RT was due to a slower drift rate (slower and less efficient information processing) in the ADHD group (Karalunas et al., 2012; Karalunas & Huang-Pollock, 2013). The antisaccade paradigm shows similar patterns in ADHD. People with ADHD typically exhibit more direction errors (look into the wrong direction) and anticipatory saccade errors (errors resulted from premature saccades) (Feifel et al., 2004; Munoz et al., 2003).

Neural imaging studies also give evidence of inhibitory control deficit in people with ADHD. ERP studies reported attenuated amplitudes of N200 and P300 in response inhibition trials in children with ADHD (Liotti et al., 2010). fMRI studies revealed reduced activation in response inhibition trials in the ventrolateral and dorsolateral prefrontal cortical areas, premotor area, and supplementary motor area in children with ADHD compared to the control group (Passarotti et al., 2010). However, there are two main limitations. The first is that previous research focuses mainly on the domain of response inhibition. Literature on attentional inhibition in the ADHD population is quite limited. Meanwhile, behavioural and neuropsychological evidence for deficits in response inhibition in children with ADHD has witnessed a robust increase, but research on adult ADHD is relatively insufficient.

Working Memory

Working memory is a cognitive function that can temporarily hold information in mind and mentally process information so as to guide behaviour (Miyake & Shah, 1999). It includes three major components: a domain-general central executive (CE), and two subsystems for temporarily storing and rehearsing modality-specific phonological (PH) and visuospatial (VS) information (Baddeley, 2007). Meta-analytic reviews have provided strong evidence of working memory deficits in both children and adults with ADHD (Alderson et al., 2013; Huang-Pollock et al., 2009; Kofler et al., 2010). A functional working memory model of ADHD hypothesized working memory deficits as a core feature of the disorder. Empirical studies found larger deficits in CE and VS compared to PH (Alderson et al., 2013; Rapport et al., 2008).

Working memory and inhibitory control

There is an extensive discussion on the relationship between inhibitory control and working memory in previous literature. Inhibitory control and working memory are both essential executive functions and they are highly correlated (Diamond, 2013). Duncan et al. (2008) compared the performance of two groups of participants. One was presented with instructions on two tasks but participants were told to ignore one task because the experiment only involves the other task. Another group was presented with only instruction on the involved task. The result indicated that the second group performed better than the group that was shown instruction on two tasks. Also, the experiment shows that in the group that was presented with two task instructions, individuals with higher working memory capacity had better performance. It implies that inhibitory control can aid working memory by helping us rule out irrelevant information and leaving enough workspace for working memory to process information that matters. Alternatively, better working memory capacity increases the possibility of holding the goal-related information in mind and thereby decreases the rate of inhibitory error.

Some theories suggest that working memory plays a role in defining the relationship between response inhibition and attentional inhibition. Friedman & Miyake (2004) suggested that the two aspects of inhibitory control are strongly correlated and could be regarded as a unitary inhibition ability called “Response-Distractor inhibition”. The logic underlying the proposal is that the ability to resist task-irrelevant responses and selectively attend to goal-related stimuli work together to protect the contents of working memory from being disrupted by external distractors and proactive interferences, therefore the two aspects of inhibitory control can be attributed to the same unidimensional factor of active goal maintenance.

Other studies, on the contrary, suggest that response inhibition and attentional inhibition are empirically independent constructs. Wilson and Kipp (1998) consider that response inhibition is an active process while attentional inhibition occurs passively. They performed an experiment and found that the inhibition of response could not be recalled but can be recognized when the stimulus was shown to participants afterwards. Interfering items on the other hand cannot be recognized. In their account, response inhibition involves a process of encoding information into working memory and then rejecting the unwanted part from working memory. But attentional inhibition occurs before the stimulus could enter working memory. Participants would be unable to recognize the interference item since they are not being encoded in the first place. This theory can also account for the inattentional blindness effect mentioned earlier.

A third view is that working memory is regarded as a higher-order factor compared to response and attentional inhibition in the cognitive process. A relatively recent study raised a hierarchical regression model of inhibitory control (Tiego et al., 2018). They regressed the two inhibitory control factors onto working memory capacity as a higher-order factor. The regression model further confirms the share empirical reliance of response inhibition and attentional inhibition on working memory capacity, though working memory capacity explained the variance of response inhibition significantly better than attentional inhibition factors, which is to some extent consistent with Wilson and Kipp's (1998) theory of working memory and two factors of inhibitory control. But that nearly significant association between response inhibition and attentional inhibition comes from their shared empirical association with working memory capacity. Therefore response inhibition and attentional inhibition are two independent lower-order constructs when controlling the variance of higher-order working memory capacity.

The Present Study

This study investigated the following aspects: 1) Response inhibition and attentional inhibition ability in adults with ADHD. 2) The working memory capacity in adults with ADHD. 3) The relationship between working memory and two dimensions of inhibitory control.

Participants were divided into ADHD and control group according to ASRS scores. Go/no-go task and antisaccade tasks in VR environment to assess response inhibition, and an inattentional blindness task in a virtual club scenario to assess attentional inhibition. Behavioural data were collected and analysed for two response inhibition tasks, and eye tracking data were analyzed for the antisaccade task and attentional inhibition task. The Universal Non Word Repetition (UNWR) test was adopted to examine phonological working memory (Howell et al., 2016). We hypothesized that adults with ADHD would have poorer performances in adults with ADHD in three inhibitory control tasks and in the nonword repetition test, and there would be a positive correlation between working memory capacity and performance in inhibitory control paradigms.

Methods

Participants

A total of 32 participants were recruited for the study, then we filtered participants with ASRS scores above 16 (include 16) into ADHD group (Mean age = 24.3, SD = 3.77) and participants with ASRS score below 12 (include 12) into control group (Mean age = 22.2, SD = 2.18). Both groups have 12 participants. The ADHD group includes 6 males and 6 females, and the control group includes 9 males and 3 females. Participants were recruited from the UCL SONA system and personal networks. All participants have gained an undergraduate or above degree. Participants were required to have good vision (or corrected vision), unimpaired hearing, and no other mental health diagnoses. The study was approved by UCL Research Ethics Committee.

Design

We used a 2 × 3 mixed design with one two-level between factor (control vs. ADHD) and one within-subject factor (go/no-go task vs. antisaccade task vs. inattentional blindness task). Ten tasks were designed in total and EEG and eye movement data were collected for all tasks. But due to technical issues and time limits, only three tasks and related data from behaviour, eye movement, and questionnaires were analyzed in this study. The dependent variables were mean reaction times (RTs) and commission error rate (pressed when "3" appears) in the go/no-go task; mean RTs, commission error rate (press the button of same direction), direction error rate (looked into the wrong direction) in antisaccade task; accuracy, detection rate of the unexpected stimulus, mean distance (distance from the averaged gaze position to the avatar in the middle of the conversation) in inattentional blindness task.

Materials

Apparatus

The experiment was conducted in an acoustic laboratory on campus. Equipment includes a laptop, VIVE Pro Full Kit VR headset with nine embedded EEG electrodes and a pair of Pulil Labs eye trackers, and a controller with a trigger button and a rounded button. Pre-screening and assessment forms were done over the computer. Three experimental tasks and all questionnaires were completed in the VR environment.

Pre-screening

Essilor vision test[1] was conducted on the computer screen to measure visual acuity. The letter "E" was presented at different orientations in each trial and the size of it decreased over trials. There were six trials for each eye, twelve trials in total. Participants were marked as having normal vision if the direction of the letter "E" was correctly distinguished on all trials. The hearing test was done through a headphone. Contact lenses were allowed during the experiment. Sound bands were played at six frequencies (250Hz, 500 Hz, 1kHz, 4kHz, 8kHz) for both ears and individual's hearing threshold of each frequency was measured. If participants could hear sounds at all frequencies with an intensity below 25 dB they are considered as having normal hearing.

Assessments

ASRS form of each participant was collected before they came to the lab. The ASRS form contains six items and is consistent with DSM-5 criteria (Ustun et al., 2017). It was reported to have high sensitivity (91.4%) and specificity (96.0%) in identifying adults with ADHD among the general population. The ASRS score has a range from 0 to 25, and 14 was used as a threshold to identify ADHD in previous literature (Ustun et al., 2017). Also, theoretical models suggest that inhibitory control deficits were more exclusively to be an ADHD hyperactive-impulsive type problem rather than a problem for the predominantly inattentive type (Barkley, 1997). Therefore in this study, we classified participants with total ASRS scores at or above 16 as well as participants with ASRS Hyperattention scores at or above 5 into the ADHD group. Participants with ASRS scores below 16 in total and below 5 in hyperattention scores were considered as controls.

The UNWR was used to assess phonological working memory (Howell et al., 2016). Pseudowords are played through headphones and participants were asked to repeat the word as correctly as possible. The test contained four sets of pseudowords

[1] Essilor Vision Test https://www.essilor.com/en/vision-tests/test-your-vision/

with increasing syllable lengths. There were twelve pseudowords available in each set. Eight were randomly selected for each level. If the participant repeated all eight pseudowords correctly for the level, the test would enter into the next level. The test terminated when participant failed to repeat the word. The score represents the total number of correctly repeated words.

The Stuttering Severity Instrument 3 (SSI3) and The Liebowitz Social Anxiety Scale (LSAS) were used to evaluate the stuttering severity and anxiety level of each participant respectively, but the current study did not employ these two measurements.

Tasks

The go/no-go task was placed in a lecture hall. There was a lecturer talking about how to create a project on Unity and other students sitting there listening to him in the hall (Figure 1). During the task, participants would hear some noises such as people coughing, sneezing, typing, writing, paper flipping, etc. and in the middle of somewhere a paper plane would fly from left back to left front. There was a book on the table in front of the participants showing random numbers from 1 to 9 consecutively (Figure 2). The task for the participant was to press the trigger button of the controller for all numbers except for the number “3”. This meant that participants were required to withhold their response when number “3” appeared. Each number was presented 25 times and 225 (25*9) numbers were presented in total. Each number appeared for 1.15 seconds followed by a delay of 1.15 seconds. The task lasted for approximately 8 minutes to complete.

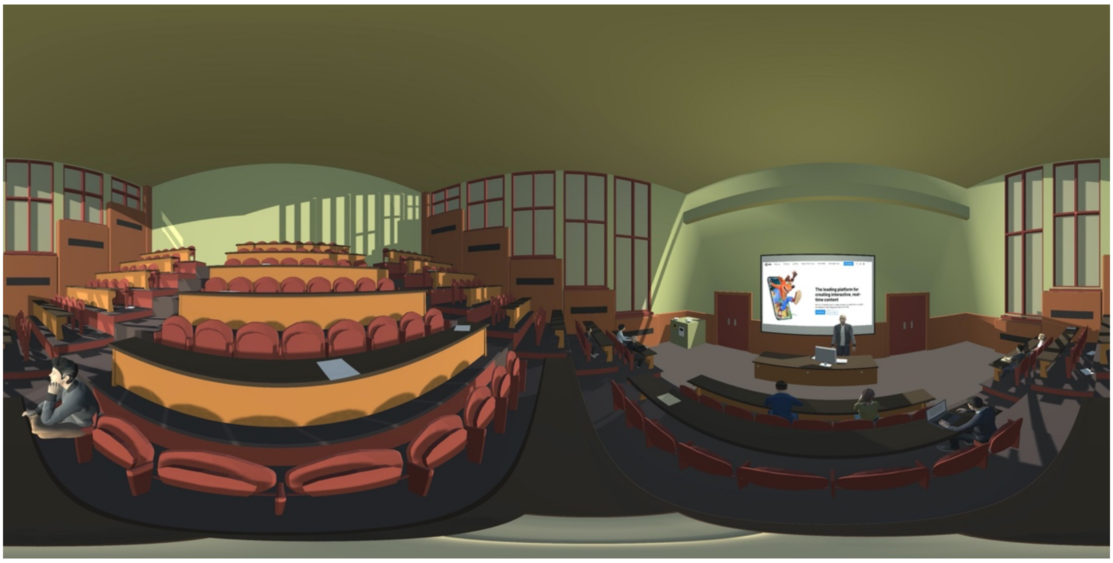

Figure 1. A panorama view of the lecture hall in VR.

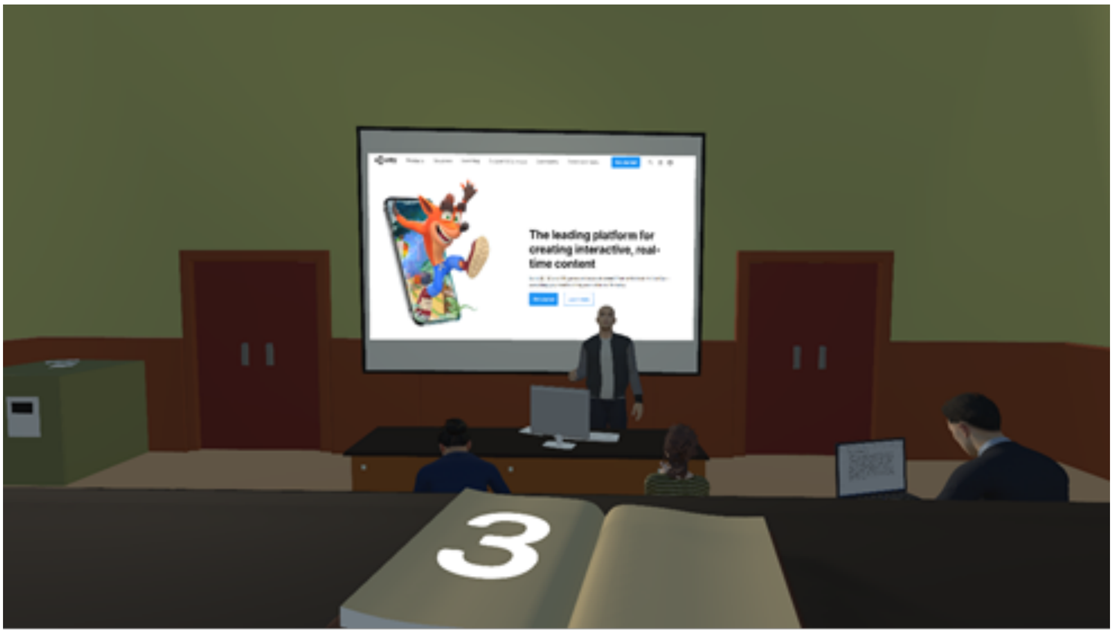

Figure 2. View in front of the participants.

The antisaccade task was set in a city environment (Figure 3). There were city ambient sounds, people talking and baby crying sounds from afar, and birds sound during the task. In front of the participants were two roads (Figure 4). There was also a plane flying across the sky at some point. Cars with different colors would randomly occur on either of the roads. The car would show up at the left/right bottom of the road and disappear at the end of the road. In the task, participants were required to look in the opposite direction to the car and press the opposite direction on the rounded button as soon as a car stimulus showed up. For example, if the car appeared on the left, the participant should look onto the right road and press the right button. Participants should look back to the light in the center of the park when the car disappeared. Fifty cars were presented in total, with twenty-five cars on each road. Each car was presented for 1.15 seconds and there followed a 3.15 seconds delay before the appearance of the next car. The task lasted for approximately 3.5 minutes.

Figure 3. A panorama view of the streets in VR.

Figure 4. Street view in front of the participants.

The setting of the attentional blindness task was in a bar (Figure 5). There were three human avatars in front of the participant having a conversation over the topic of “brain capacity”. There were bar music sounds, people talking sounds, and other people dancing. Participants were required to count how many times the word “capacity” appeared in the conversation among the three avatars. At a certain point in the task, an alien-looking creature walked in and out of the bar. Participants were not informed to expect the creature before the task. The task was around 1.5 minutes long.

Figure 5. A panorama view of the bar in VR.

Figure 6. Club view in front of the participants.

Questionnaires

There was one questionnaire following each VR task. All questionnaires included self-assessment questions on participants' performance in the task, their sense of presence, and whether they found the task similar to real-life scenarios. For the go/no-go task, apart from the common questions, participants were also asked whether pressing the wrong button would influence their performance and whether they felt distracted by the environment interferences. For the antisaccade task, participants were asked whether they found it difficult to look at the opposite side and press the opposite button in addition. For the attentional inhibition task, the count of the word "capacity" and detections of the alien-looking creature were reported in the questionnaire.

Procedure

Consent forms, information sheets, and ASRS forms were collected prior to the experiment. During the experiment, participants sat on an adjustable chair in front of the laptop. First, they would finish the pre-screening, and then began the experiment if they had normal vision and hearing. The order of LSAS form, stuttering evaluation, and VR experiment was counterbalanced. For the VR experiment, the order of the task was fully counterbalanced for the controls. Half of the controls did the tasks in the order from one to ten, half did the task in the reversed order. However, only one ADHD participant did the task in the reversed order.

Results

<u>Go/no-go task</u>

In the Go/no-go task, the commission error rate was the number of presses for digit "3" divided by how many times digit "3" appears in total (n = 25). RT measures the short period from the onset of the stimuli to when the participant press the button. Mean RT of each participant was calculated using the sum of RTs divided by the number of correctly responded trials (total press number minus presses for digit "3").

We analyzed the group effect on commission error rate and RT using an ANOVA with single independent-sample factor of group (2 levels: ADHD and control). For the different group effect on commission error rate, though ANOVA results showed no significant effect of group with $F(1, 22) = 1.20$, $p = .285$, pairwise comparison indicated a slightly higher mean commission error rate in control group (*Mean* = 0.163, *SD* = 0.089) compared to ADHD group (*Mean* = 0.123, *SD* = 0.089). For RT, there was also no evidence for significant difference between groups, $F(1, 22) = 0.73$, $p = .402$, but ADHD mean RT (*Mean* = 590, *SD* = 79.6) was longer than control mean RT (*Mean* = 565, *SD* = 59.6). Figure 7 shows the distribution and mean of commission error rate and RT across two groups.

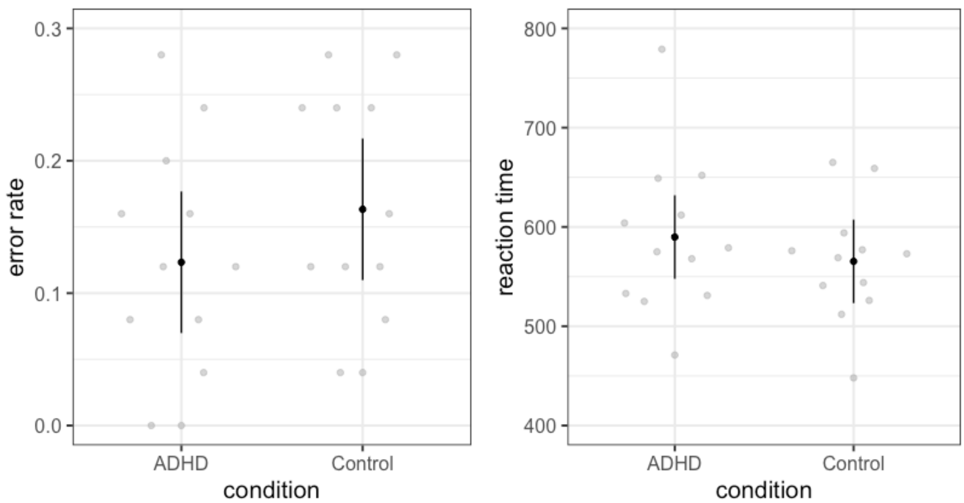

Figure 7. Distributions of commission error rate and RT for each condition. Grey points in the background show the aggregated data of each participant. Black points in the foreground show the condition means with error bars denoting 95% confidence intervals.

Antisaccade task

In the antisaccade task, the commission error rate was the number of failed trials (unable to press the button for the opposite direction) divided by the total presses of each participant. There should be fifty presses in total but there was an effect of both subjective omission and technical recording issues, so only four participants have a full recording of fifty presses. Two participants (one ADHD, one control) were filtered because they had a total press number below twenty. When measuring the direction error, besides the above filtering, the highest direction error rate in both groups was removed as it was equal to one or was approaching one. Mean RT is measured by the sum of RT divided by the total press number of each participant as well.

Three One-way ANOVAs were conducted to examine group effect on commission error rate, direction error rate, and RT. The effect of group difference on commission error rate in this task was not significant, $F(1, 20) = 2.06$, $p = .166$. Pairwise comparison showed that ADHD group had a slightly higher commission error rate (*Mean* = 0.054, *SD* = 0.064) than controls (*Mean* = 0.144, *SD* = 0.199). The group effect on direction error rate was not but approaching significance, $F(1, 18) = 4.07$, $p = .059$. The ADHD group exhibited a higher direction error rate (*Mean* = 0.546, *SD* = 0.328) compared to control (*Mean* = 0.310, *SD* = 0.272). The ADHD group showed a significantly shorter RT (*Mean* = 760, *SD* = 128) compared to controls (*Mean* = 913, *SD* = 201), $F(1, 20) = 4.5$, $p = .047$. Figure 7 shows the distribution and mean of commission error rate, direction error rate and RT across two groups.

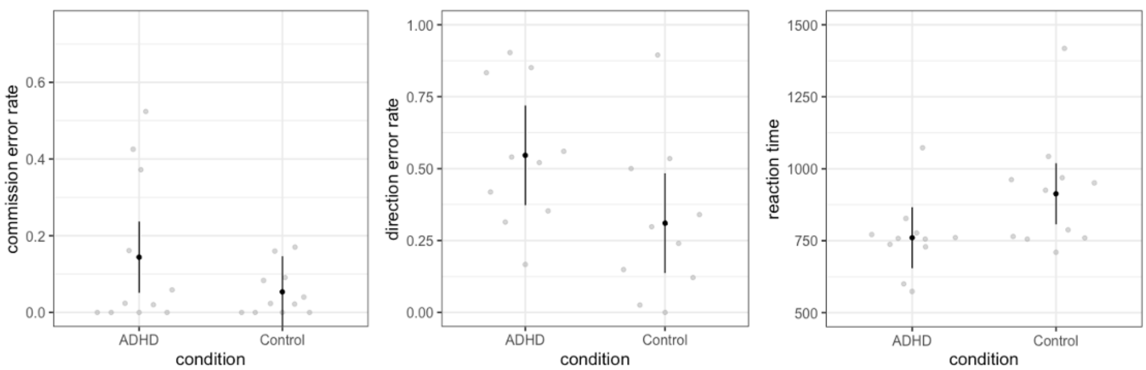

Figure 8. Distributions of commission error rate, direction error rate, and RT for each condition. Grey points in the background show the aggregated data across trials of each participant. Black points in the foreground show the condition means with error bars denoting 95% confidence intervals.

<u>2 × 2 mixed ANOVA</u>

We also tested the task effect on commission error rate and RT using a mixed ANOVA with two independent-sample factors, group (ADHD and control) and task (go/no-go task and antisaccade task). For RT, ANOVA revealed a significant main effect of task difference on RT. The RT in the antisaccade task was significantly longer than that in the go/no-go task, $F(1, 20) = 40.09$, $p < .001$. Main effect of the group difference on RT was close to significance, $F(1, 20) = 3.49$, $p = .077$. There was also a possible interaction, $F(1, 20) = 4.16$, $p = .055$. No evidence showed main effect of task difference ($F(1, 20)$, $p = .510$) nor group difference ($F(1, 20)$, $p = .148$) on commission error rate. Figure 9 and Figure 10 show a group curve that differed across the two tasks.

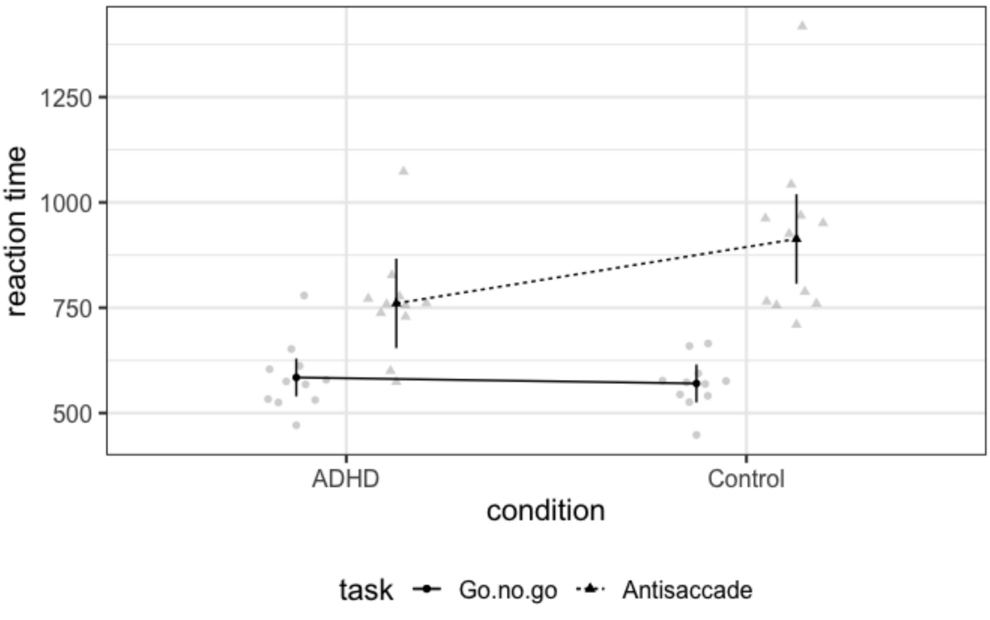

Figure 9. Distributions of RT in two groups (ADHD and control) across the two tasks (go/no-go and antisaccade task). Grey points in the background show the mean of RT of each participant. Black points in the foreground show the group means with error bars denoting 95% confidence intervals.

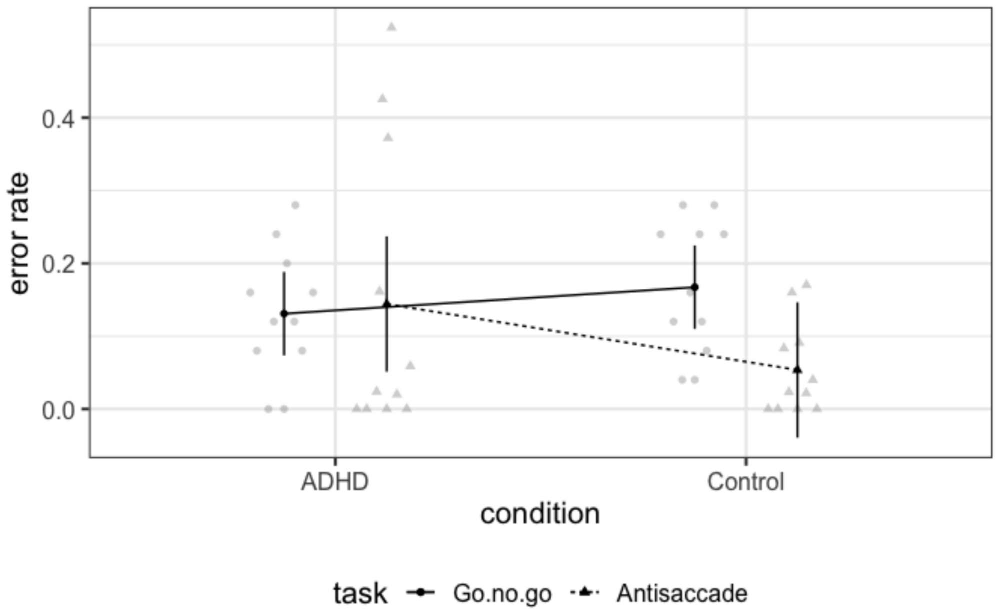

Figure 10. Distributions of commission error rate in two groups (ADHD and control) across the two tasks (go/no-go and antisaccade task). Grey points in the background show the commission error rate of each participant. Black points in the foreground show the group means with error bars denoting 95% confidence intervals.

<u>Inattentional blindness task</u>

In the inattentional blindness task, 75% of ADHD correctly counted the total times the word “capacity” occurred, while only 58.3% of controls counted it right. A chi-square test of independence showed that there was no significant association between correct count and groups, $X^2(1, N = 24) = 2$, $p = .157$. As for the unexpected “alien”, only two ADHD (17%) and one control (8%) successfully detected the unexpected “alien”. Chi-square test indicated no evidence of significant association between unexpected stimulus detection and different groups, $X^2(1, N = 24) = 2$, $p = .157$.

Also, we calculated the group means of the distance from the averaged gaze position to a stimulus in the VR scenario. First, we filtered the gaze positions with the confidence level above 0.6. Second, we averaged the x, y, and z coordinates of the gaze positions across the task for each participant, then counted the distance from the averaged coordinates to the coordinates of the avatar in the middle (x = 1.69, y = -1.97, z = 0.38). The longer the distance implies that the participant focused less on the conversation. The results showed that the mean distance of ADHD was shorter (Mean

= 2152, SD = 2807) than controls (*Mean* = 2618, *SD* = 2604), but the difference was not significant according to ANOVA test, $F(1, 22) = 0.18$, $p = .678$.

<u>UNWR</u>

A one-way ANOVA was employed to investigate working memory capacity in different groups. Results indicated that the ADHD group exhibited significantly lower UNWR scores (Mean = 12.5, SD = 3.68) compared to the controls (Mean = 20.4, SD = 4.17), $F(1, 22) = 24.34$, $p < .001$.

<u>Working Memory and Response Inhibition</u>

A Pearson product-moment correlation coefficient was computed to assess the relationship between working memory and commission error rate in the antisaccade task. Two participants with total presses below twenty in the antisaccade task were removed. We found a significant negative correlation between UNWR scores and the overall commission error rate, $r(20) = -.450$, $p = .036$. This means that increases in UNWR scores were correlated with decreases in commission error rate. Figure 11 shows a scatterplot summarizing the results.

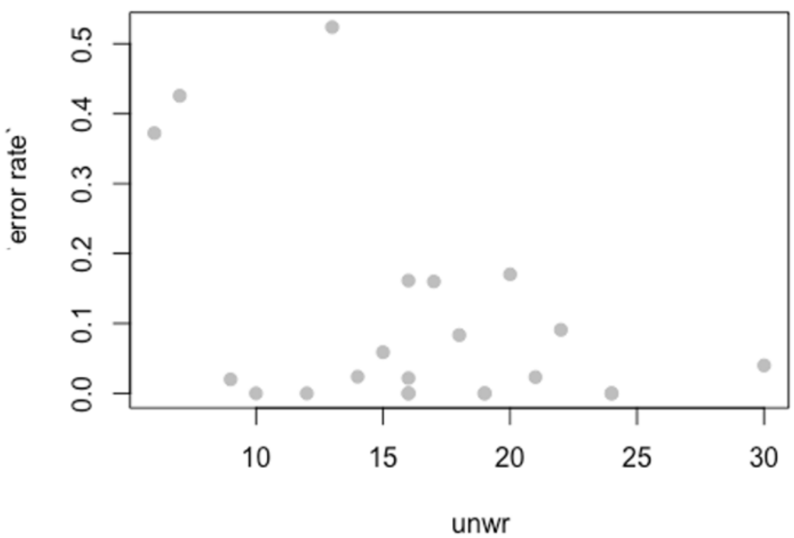

Figure 11. A scatterplot showing the correlation between UNWR scores and commission error rate. Note that some participants have the same error rate and UNWR scores so some grey points in the scatterplot may have overlapped.

The correlation coefficient was also assessed between working memory and RT in the antisaccade task. Similarly, two participants with total presses below twenty were removed. There was a positive but not significant correlation between UNWR scores and the overall RT, $r(20) = .387$, $p = .075$. This indicated a possible trend that higher UNWR scores were correlated with longer RT. Figure 12 shows a scatterplot summarizing the results.

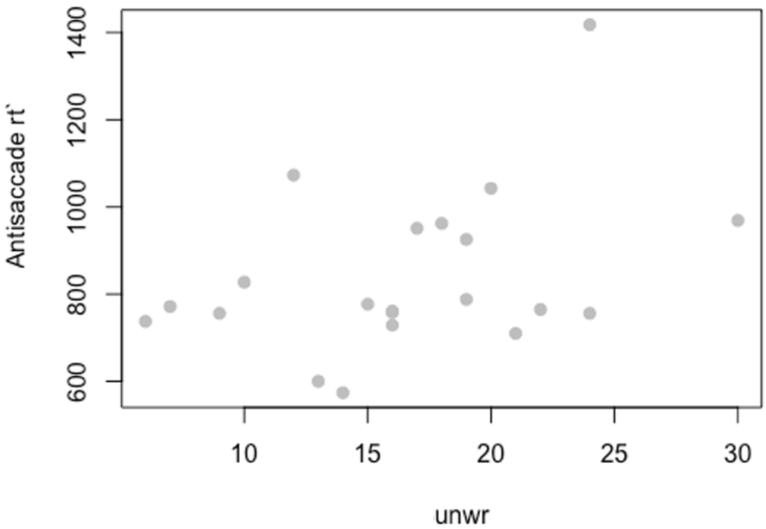

Figure 12. A scatterplot showing the correlation between UNWR scores and RT.

<u>Working memory and Attentional Inhibition</u>

A one-way ANOVA was applied to examine whether there was a UNWR scores difference between the participants who counted the word "capacity" correctly and who failed. No significant difference was found between groups, $F(1, 22) = 0.91$, $p = .350$, however, the mean UNWR scores of participants who counted correctly (*Mean* = 15.7, *SD* = 4.91) were slightly lower than the participants who counted wrong (*Mean* = 18, *SD* = 6.82).

We also examined the correlation between working memory and mean gaze distance. The correlation coefficient indicates a possible but not statistically significant trend of negative correlation, $r(22) = -.258$, $p = .223$. There was a possibility that increased working memory capacity was correlated with decreased mean gaze distance. Figure 13 shows a scatterplot summarizing the results.

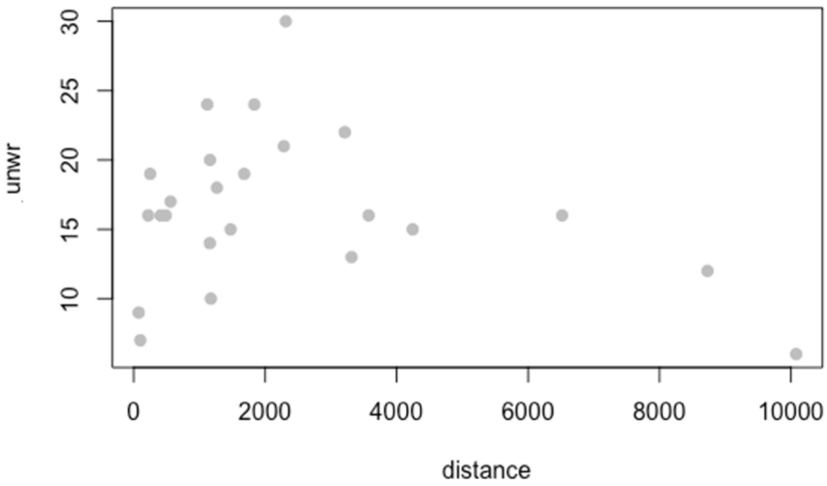

Figure 13. A scatterplot showing the correlation between UNWR scores and mean gaze distance.

Discussion

This study investigated response inhibition, attentional inhibition, and working memory capacity in adults with ADHD and controls.

Inhibitory Control Ability in ADHD

The first research question of the study was to investigate the inhibitory control ability in adults with ADHD. Our first hypothesis was that ADHD would perform significantly worse in both response inhibition (higher commission and direction error rates, longer mean RT) and attentional inhibition tasks (lower chances in correct word count, higher chances in unexpected stimuli detection, longer mean gaze distance). However, in our experiment, the results were partly contradictory to our hypothesis. Only the marginally higher direction error rates of ADHD in the antisaccade task can weakly support the hypothesis.

For response inhibition, in the go/no-go task, pairwise comparisons showed that ADHD had a slightly lower mean commission error rate and higher RT compared to controls though there was no statistical significance. In the antisaccade task, we found a significant shorter RT and a higher but not significant commission error rate in ADHD. The results showed a possibility of the speed-accuracy operating characteristic (SAOC). SAOC is a representation of the tradeoff between speed and accuracy. It suggests a relationship that individuals make fewer errors when they respond slowly and vice versa. In this experiment, the ADHD group had a tendency for better performance in the go/no-go task might because they chose accuracy over speed (they had a tendency of taking a longer time to react), while they have a tendency of performing worse in the antisaccade task as they chose speech over accuracy (ADHD have significantly longer reaction time) in this task. Therefore, since the observed difference might result from the personal willingness of the response speed rather than the group difference, it lacked evidence to conclude a less efficient information processing in response inhibition in ADHD.

Even though SAOC was found in both groups, we expected that the two groups would have consistent performance in go/no-go and antisaccade tasks as they both tested the response inhibition. However, the two groups seem to choose different speed-accuracy strategies in the two tasks and this led to inconsistent results. A comparison of group performances in the two tasks was done to figure out the underlying reasons. The comparison showed a significant main effect of task difference on RT, with RT of the antisaccade task being significantly higher than that of the go/no-go task, and also task difference had a greater effect on controls compared to ADHD.

First, inconsistent performances might come from the different difficulty levels of the two tasks. Successful response inhibition in the go/no-go task only involves two steps: 1) identify the stop signal “3”, 2) competition between go process and no-go process, 3) make a response decision (withhold the response); but the antisaccade task involves more complicated procedures: 1) identify the direction of the signal, 2) simultaneous competition between inhibition and reflexive motor and visual response, 3) press the button of the opposite direction and initiate an antisaccade. The antisaccade task required subjects to maintain more procedures in mind and thereby increased working memory demands. The non-word repetition test showed that ADHD had significantly lower working memory capacity. This meant that ADHD may require more effort to finish the task of the same difficulty level compared to controls. Therefore, though the go/no-go task was of low difficulty level, the ADHD group was more engaged in the task, and thereby had similar performance to controls and even a tendency for better performance in the go/no-go task. Since the antisaccade task was more difficult, it required both ADHD and control groups to be highly engaged in the task and it would take both groups a longer time to react. As both groups had a high engagement in the antisaccade task, the antisaccade task might be a better indicator of response inhibition difference between groups in this experiment.

Second, though one-way pairwise comparisons cannot provide sufficient evidence of response inhibition deficit in the ADHD group, the inconsistent performance of the two groups between tasks might to some extent reflect poorer response inhibition (behavioural self-control) in ADHD. The comparison of the two response inhibition tasks showed that the RT of ADHD had a smaller increment compared to controls. This means that task difference had more influence on the RT of controls and controls were more sensitive to task difficulty and more cautious when processing tasks with increasing working memory demands. One possible reason was that controls adopted a performance adjustment strategy by intentionally slowing the RT to increase the possibility of successful inhibition and to maintain higher accuracy when the task was more demanding. Being able to adaptively shift one's relative emphasis on speed versus accuracy according to various task demands is critical for successful behavioural inhibition (Fosco et al., 2019). The results were consistent with previous studies that ADHD have difficulty in adjusting their behaviour for better performance monitoring in tasks with changing demands compared to their typical peers (Mulder et al., 2010).

For attentional inhibition, the hypothesis was that ADHD would have deficits in attentional inhibition, meaning that they would behave worse in the counting task, be more likely to detect the unexpected "alien", and have longer mean gaze distance in the inattentional blindness task. However, the results were contradictory to the hypothesis. Though there was no statistical significance between groups, more ADHD successfully did the counting task while fewer controls gave the correct answer, and ADHD had a shorter mean gaze distance compared to controls, indicating that ADHD had a tendency of focusing more on the conversation. The results has several interpretations.

First, the results of this experiment may indicate an attentional advantage in ADHD. In this task, participants perceived both auditory and visual information, which thereby increased the working memory load. We expected to see increased interference and decreased performance as the increased cognitive demand may disrupt the efficient inhibition of distractors. However, no significant group differences were found, and ADHD had a tendency for even better performance. It seems that ADHD can attend to the auditory task and catch the unexpected visual stimulus at the same time. Therefore, the results revealed no attentional inhibition deficits in ADHD but rather implied an attentional privilege that people with ADHD may have advantages in dealing with dual tasks or attending to multiple sources simultaneously. The findings were consistent with the sociological theory that people with ADHD were more like "hunters" that can attend to multiple targets simultaneously while controls were more like "farmers" that can maintain their attention on one target (Hartmann, 1995). It also supported previous evidence on ADHD having superior divided attention abilities relative to their typical peers (Koschack et al., 2003).

Second, for the unexpected “alien”, there was a floor effect as only three participants successfully detected the “alien”. The floor effect may come from the scenario design as the “alien” was a bit “invisible” against the dim background and its shape much resembled other avatars in the club. Maybe participants noticed but did not report the “alien” as they didn’t find it “unexpected”. If the above reason does not cause biased results, the result would be consistent with perceptual load theory. As the perceptual load of the task was high and most attentional resources were allocated to the counting task, there was no capacity left to process the task-irrelevant “gorilla”.

Phonological Working Memory in ADHD

The second research question of this study was to investigate the phonological working memory capacity in ADHD. The hypothesis was that ADHD would have a significantly lower working memory capacity. A significant group difference was found in phonological working memory capacity. ADHD had significantly lower UNWR scores compared to the controls, indicating a lower phonological working memory capacity in the ADHD group. Though previous studies suggested that CE and VS were the major impaired components in working memory, this study provided evidence that ADHD had impairment in PH as well. This finding also suggests that future research, diagnosis and treatment of ADHD might also include phonological working memory deficit as a symptom of ADHD.

Phonological Working Memory and Inhibitory Control

The third research question was to discuss the relationship between working memory and two dimensions of inhibitory control. Correlations between working memory and response/attentional inhibition were done respectively. For the response inhibition and working memory, the correlation coefficient between commission error rates of the antisaccade task and UNWR scores was calculated as the antisaccade task can better represent response inhibition ability in both groups according to the previous discussion. A significant negative correlation was found between response inhibition and working memory, meaning that higher working memory capacity was correlated with lower commission error rates. As the non-word repetition task mainly tested the phonological working memory, the results can give support to Barkley's (1997) theory of speech internalization effect on behavioural inhibition. Barkley suggests that internalized speech can reinforce the power of messages to actually control motor response and create new rules in guiding behaviour (e.g. performance monitoring and adjustment in this experiment). And the motor execution of such verbal rules appears to be partially dependent on the capacity to maintain them in working memory (i.e. phonological working memory) and to inhibit prepotent or task-irrelevant responses that compete with the rule (Zelazo et al., 1995). Therefore, deficits in phonological working memory would lead to poorer response inhibition performance.

There was no significant difference in the UNWR scores between participants who correctly did the counting task and those who failed, and there was no evidence for a significant correlation between UNWR scores and mean gaze distance. This means that though ADHD is accomplished with verbal working memory deficit, such deficit would not influence their performance in the attentional inhibition task. The findings can reflect Wilson and Kipp's (1998) theory that response inhibition is an active process but attentional inhibition occurs passively. Since involuntary attentional inhibition occurs before the stimuli could enter the working memory, attentional inhibition ability would show no correlation with working memory capacity.

Limitations and Future Research

There are several limitations of the study. First of all, the sample size of the experiment was not large enough, and the data of several participants in the antisaccade task were removed because of technical issues. So effects observed from our data might not be powerful enough to be applied to the overall ADHD population. Also, ADHD participants included in our experiment were not clinically diagnosed, and the self-report ASRS scores may lack objectivity. Second, the tasks were not fully counterbalanced. Most participants did the tasks in the order of go/no-go task, antisaccade task, and last the inattentional blindness task, and increased fatigue could influence the performance of the later tasks. Third, the experiment design cannot fully exclude the task impurity problem. For example, in the response inhibition task, there were lots of distractors in the environment, so it also requires the employment of attentional inhibition to successfully complete the response inhibition task. However, this design can better simulate the real environment, where response and attentional inhibition combine together to help us better achieve the goal, and it is always tricky to balance ecological validity and task purity. Meanwhile, though commission error rates and mean RT can reflect inhibitory control, they are often interpreted as indicators of multiple cognitive problems in ADHD as well. Thus, whether these measures should be considered separately in cognitive theories or whether they can be considered to reflect a single process remains unclear.

For future studies, research could investigate inhibitory control ability in different ADHD subtypes respectively. This study did not specify subtypes of ADHD. Previous studies mostly regard response inhibition as a major deficit in ADHD hyperactive subtype and attentional inhibition mostly a deficit in the inattentive subtype (Barkley, 1997; Kofler et al., 2010). However, one subtype may have a comorbidity of two dimensions of inhibitory control deficits. Further studies on inhibitory control in ADHD subtypes could enrich theoretical accounts of ADHD and be beneficial to clinical ADHD diagnosis and treatment.

Also, future studies can consider other measures in the antisaccade task. In our experiment, as gaze direction data were collected only when participants pressed the button, it cannot precisely reflect the antisaccade errors as there might be trials when participants did not press the button but looked in the required direction. Also, since the timestamps of the behavioural data we collected were not accurate to milliseconds and we had no stimulus onset time, there would be a great deviation if we calculate the anticipatory saccade error rate (resulting from a premature saccade, e.g. in which the participant took less than 80 ms to start the saccade) and latency (saccadic reaction time, the time from the occurrence of stimulus to the onset of the primary saccade) (Júlio et al., 2019). Future studies could assess these measures in the antisaccade tasks and evaluate inhibitory control ability in ADHD in a more comprehensive way.

When designing the inattentional blindness paradigm, future research can investigate modality differences (visual vs. verbal) effects on working memory load on attentional inhibition. In our experiment, participants were required to remember how many times they hear the word “capacity”. The working memory load was verbal information processing. In the conventional “gorilla” paradigm (Simons & Chabris, 1999) participants were asked to count the times of ball passing. It used the visual modality of working memory load. And there might be a bias of different modalities on the performance of attentional inhibition.

Last but not least, when investigating the relationship between working memory and inhibitory control, future research can take all three components of working memory (CE, VS and PH) into account. This study only measured PH and it could not represent the overall working memory capacity of an individual. Relationships between CE, VS and inhibitory control would be worthwhile to investigate in the future studies as well.

Conclusion

In conclusion, this study aimed to investigate inhibitory control ability and working memory capacity in adults with ADHD and the relationship between inhibitory control and working memory. In the response inhibition task, speed-accuracy tradeoff effects were found in both groups. However, controls were more able to adaptively adjust speed versus accuracy strategies and monitor their performances according to the task difficulties, which implied a potential deficit in behavioural inhibition (i.e.self-regulation) in ADHD. Second, no attentional inhibition deficit was found in the ADHD group. And the results suggested a trend of attentional advantage in ADHD that ADHD may have superior ability in multi-resources processing. Third, ADHD exhibited significantly lower working memory capacity compared to their typical peers. Fourth, phonological working memory capacity was negatively correlated with response inhibition performance, but there was no evidence of correlation between working memory and attentional inhibition.

References

Alderson, R., Kasper, L., Hudec, K., & Patros, C. (2013). Attention-Deficit/Hyperactivity Disorder (ADHD) and Working Memory in Adults: A Meta-Analytic Review. *Neuropsychology*, *27*, 287–302. https://doi.org/10.1037/a0032371

Anderson, M. C., & Levy, B. J. (2009). Suppressing Unwanted Memories. *Current Directions in Psychological Science*, *18*(4), 189–194. https://doi.org/10.1111/j.1467-8721.2009.01634.x

Aron, A. R., & Poldrack, R. A. (2005). The cognitive neuroscience of response inhibition: Relevance for genetic research in attention-deficit/hyperactivity disorder. *Biological Psychiatry*, *57*(11), 1285–1292. https://doi.org/10.1016/j.biopsych.2004.10.026

Baddeley, A. (2007). *Working Memory, Thought, and Action*. OUP Oxford.

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin*, *121*(1), 65–94. https://doi.org/10.1037/0033-2909.121.1.65

Berger, A. M., & Davelaar, E. J. (2018). Frontal Alpha Oscillations and Attentional Control: A Virtual Reality Neurofeedback Study. *Neuroscience*, *378*, 189–197. https://doi.org/10.1016/j.neuroscience.2017.06.007

Cartwright-Finch, U., & Lavie, N. (2007). The role of perceptual load in inattentional blindness. *Cognition*, *102*(3), 321–340. https://doi.org/10.1016/j.cognition.2006.01.002

Diamond, A. (2013). Executive Functions. *Annual Review of Psychology*, *64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Duncan, J., Parr, A., Woolgar, A., Thompson, R., Bright, P., Cox, S., Bishop, S., & Nimmo-Smith, I. (2008). Goal neglect and Spearman's g: Competing parts of a complex task. *Journal of Experimental Psychology: General*, *137*(1), 131–148. https://doi.org/10.1037/0096-3445.137.1.131

Feifel, D., Farber, R. H., Clementz, B. A., Perry, W., & Anllo-Vento, L. (2004). Inhibitory deficits in ocular motor behavior in adults with attention deficit/hyperactivity disorder. *Biological Psychiatry*, *56*(5), 333–339. https://doi.org/10.1016/j.biopsych.2004.06.019

Fosco, W. D., Kofler, M. J., Matt Alderson, R., Tarle, S. J., Raiker, J. S., & Sarver, D. E. (2019). Inhibitory Control and Information Processing in ADHD: Comparing the Dual Task and Performance Adjustment Hypotheses. *Journal of Abnormal Child Psychology*, *47*(6), 961–974. https://doi.org/10.1007/s10802-018-0504-9

Friedman, N. P., & Miyake, A. (2004). The Relations Among Inhibition and Interference Control Functions: A Latent-Variable Analysis. *Journal of Experimental Psychology: General*, *133*(1), 101–135. https://doi.org/10.1037/0096-3445.133.1.101

Hartmann, T. / J. R. (1995). *ADD Success Stories: A Guide to Fulfillment for Families with Attention Deficit Disorder: Maps, Guidebooks, and Travelogues for Hunters in this Farmer's World* (1st ed.). Underwood Bks.

https://www.biblio.com/book/add-success-stories-guide-fulfillment-families/d/1336455353

Howell, P., Tang, K., Tuomainen, O., Chan, S. K., Beltran, K., Mirawdeli, A., & Harris, J. (2016). Identification of fluency and word-finding difficulty in samples of children with diverse language backgrounds. *International Journal of Language and Communication Disorders*, *52*(5), 595–611.

Huang-Pollock, C. L., Mikami, A. Y., Pfiffner, L., & McBurnett, K. (2009). Can executive functions explain the relationship between Attention Deficit Hyperactivity Disorder and social adjustment? *Journal of Abnormal Child Psychology*, *37*(5), 679–691. https://doi.org/10.1007/s10802-009-9302-8

Júlio, F., Caetano, G., Januário, C., & Castelo-Branco, M. (2019). The effect of impulsivity and inhibitory control deficits in the saccadic behavior of premanifest Huntington's disease individuals. *Orphanet Journal of Rare Diseases*, *14*, 246. https://doi.org/10.1186/s13023-019-1218-y

Karalunas, S. L., Huang-Pollock, C. L., & Nigg, J. T. (2012). Decomposing attention-deficit/hyperactivity disorder (ADHD)-related effects in response speed and variability. *Neuropsychology*, *26*(6), 684–694. https://doi.org/10.1037/a0029936

Kofler, M. J., Rapport, M. D., Bolden, J., Sarver, D. E., & Raiker, J. S. (2010). ADHD and Working Memory: The Impact of Central Executive Deficits and Exceeding Storage/Rehearsal Capacity on Observed Inattentive Behavior. *Journal of*

Abnormal Child Psychology, *38*(2), 149–161. https://doi.org/10.1007/s10802-009-9357-6

Kofler, M. J., Sarver, D. E., Spiegel, J. A., Day, T. N., Harmon, S. L., & Wells, E. L. (2017). Heterogeneity in ADHD: Neurocognitive predictors of peer, family, and academic functioning. *Child Neuropsychology*, *23*(6), 733–759. https://doi.org/10.1080/09297049.2016.1205010

Koschack, J., Kunert, H. J., Derichs, G., Weniger, G., & Irle, E. (2003). Impaired and enhanced attentional function in children with attention deficit/hyperactivity disorder. *Psychological Medicine*, *33*(3), 481–489. https://doi.org/10.1017/S0033291702007067

Lavie, N. (2010). Attention, Distraction, and Cognitive Control Under Load. *Current Directions in Psychological Science*, *19*(3), 143–148.

Li, G., Anguera, J. A., Javed, S. V., Khan, M. A., Wang, G., & Gazzaley, A. (2020). Enhanced Attention Using Head-mounted Virtual Reality. *Journal of Cognitive Neuroscience*, *32*(8), 1438–1454. https://doi.org/10.1162/jocn_a_01560

Liotti, M., Pliszka, S. R., Higgins, K., Perez, R., & Semrud-Clikeman, M. (2010). Evidence for specificity of ERP abnormalities during response inhibition in ADHD children: A comparison with Reading Disorder children without ADHD. *Brain and Cognition*, *72*(2), 228–237. https://doi.org/10.1016/j.bandc.2009.09.007

Lipszyc, J., & Schachar, R. (2010). Inhibitory control and psychopathology: A meta-analysis of studies using the stop signal task. *Journal of the International*

Neuropsychological Society, *16*(6), 1064–1076. https://doi.org/10.1017/S1355617710000895

Littman, R., & Takács, Á. (2017). Do all inhibitions act alike? A study of go/no-go and stop-signal paradigms. *PLoS ONE*, *12*(10), e0186774. https://doi.org/10.1371/journal.pone.0186774

Macleod, C. (1991). Half A Century of Research on the Stroop Effect—An Integrative Review. *Psychological Bulletin*, *109*, 163–203. https://doi.org/10.1037/0033-2909.109.2.163

Marton, K., Kelmenson, L., & Pinkhasova, M. (2007). Inhibition control and working memory capacity in children with SLI. *Psikhologyah : Ketav ’et Mada’i Yisre’eli Le-’iyun Ule-Mehkar*, *50*(2), 110–121. https://doi.org/10.2117/psysoc.2007.110

Miyake, A., & Shah, P. (Eds.). (1999). *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control*. Cambridge University Press. https://doi.org/10.1017/CBO9781139174909

Mulder, M. J., Bos, D., Weusten, J. M. H., van Belle, J., van Dijk, S. C., Simen, P., van Engeland, H., & Durston, S. (2010). Basic impairments in regulating the speed-accuracy tradeoff predict symptoms of attention-deficit/hyperactivity disorder. *Biological Psychiatry*, *68*(12), 1114–1119. https://doi.org/10.1016/j.biopsych.2010.07.031

Munoz, D. P., Armstrong, I. T., Hampton, K. A., & Moore, K. D. (2003). Altered Control of Visual Fixation and Saccadic Eye Movements in Attention-Deficit

Hyperactivity Disorder. *Journal of Neurophysiology*, *90*(1), 503–514. https://doi.org/10.1152/jn.00192.2003

Munoz, D. P., & Everling, S. (2004). Look away: The anti-saccade task and the voluntary control of eye movement. *Nature Reviews Neuroscience*, *5*(3), 218–228. https://doi.org/10.1038/nrn1345

Newby, E. A., & Rock, I. (1998). Inattentional blindness as a function of proximity to the focus of attention. *Perception*, *27*(9), 1025–1040. https://doi.org/10.1068/p271025

Nigg, J. T. (2000). On inhibition/disinhibition in developmental psychopathology: Views from cognitive and personality psychology and a working inhibition taxonomy. *Psychological Bulletin*, *126*(2), 220–246. https://doi.org/10.1037/0033-2909.126.2.220

Pashler, H., Johnston, J. C., & Ruthruff, E. (2001). Attention and performance. *Annual Review of Psychology*, *52*, 629–651. https://doi.org/10.1146/annurev.psych.52.1.629

Passarotti, A. M., Sweeney, J. A., & Pavuluri, M. N. (2010). Neural correlates of response inhibition in pediatric bipolar disorder and attention deficit hyperactivity disorder. *Psychiatry Research*, *181*(1), 36–43. https://doi.org/10.1016/j.pscychresns.2009.07.002

Rapport, M. D., Alderson, R. M., Kofler, M. J., Sarver, D. E., Bolden, J., & Sims, V. (2008). Working memory deficits in boys with attention-deficit/hyperactivity disorder (ADHD): The contribution of central executive and subsystem processes. *Journal of Abnormal Child Psychology*, *36*(6), 825–837. https://doi.org/10.1007/s10802-008-9215-y

Simons, D. J., & Chabris, C. F. (1999). Gorillas in Our Midst: Sustained Inattentional Blindness for Dynamic Events. *Perception*, *28*(9), 1059–1074. https://doi.org/10.1068/p281059

Thakral, P. P., & Slotnick, S. D. (2010). Attentional inhibition mediates inattentional blindness. *Consciousness and Cognition*, *19*(2), 636–643. https://doi.org/10.1016/j.concog.2010.02.002

Tiego, J., Testa, R., Bellgrove, M. A., Pantelis, C., & Whittle, S. (2018). A Hierarchical Model of Inhibitory Control. *Frontiers in Psychology*, *9*. https://www.frontiersin.org/articles/10.3389/fpsyg.2018.01339

Trommer, B. L., Hoeppner, J.-A. B., Lorber, R., & Armstrong, K. J. (1988). The Go—No-Go paradigm in attention deficit disorder. *Annals of Neurology*, *24*(5), 610–614. https://doi.org/10.1002/ana.410240504

Ustun, B., Adler, L. A., Rudin, C., Faraone, S. V., Spencer, T. J., Berglund, P., Gruber, M. J., & Kessler, R. C. (2017). The World Health Organization Adult Attention-Deficit/Hyperactivity Disorder Self-Report Screening Scale for DSM-5. *JAMA Psychiatry*, *74*(5), 520–526. https://doi.org/10.1001/jamapsychiatry.2017.0298

Wilson, S. P., & Kipp, K. (1998). The development of efficient inhibition: Evidence from directed-forgetting tasks. *Developmental Review*, *18*(1), 86–123. https://doi.org/10.1006/drev.1997.0445

Zelazo, P. D., Reznick, J. S., & Piñon, D. E. (1995). Response control and the execution of verbal rules. *Developmental Psychology*, *31*(3), 508–517. https://doi.org/10.1037/0012-1649.31.3.508

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