Assessing Executive Function Impairments and Comorbidity between ADHD and Stuttering

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Declaration

I, Fjorda Kazazi, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signed: Fjorda Kazazi, March 2023.

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Abstract

Stuttering and ADHD are often considered ‘comorbid’ because different types of symptoms and processing issues occur in, for example, fluency, attention and working memory. This thesis addresses whether or not these shared factors signify fundamental similarities between stuttering and ADHD that distinguish them from typical controls. This is done in two main ways: First, a comparison is made of details of performance on attention capabilities using a range of behavioural and physiological measures in various test environments, including Web and VR approaches; Second, modelling analyses are conducted that compare networks representing participants’ performance across groups.

Using the Load Theory of Attention methodology (Chapter 2), which addresses how to focus attention and ignore distractions up to a point where load exceeds perceptual capacity, it was observed that the performance of participants who stutter was significantly lower from the performance of controls in the auditory selective and divided attention tasks. The results showed that tasks in which attention demands enhanced were effective in detecting limitations in audio processing by PWS. Extending the task in the visual, audio and audio-visual domains in a virtual reality environment in people who stutter, (PWS) as well as people with ADHD (PWADHD) it was found that while audio was more affected in PWS, audio and audio-visual domains were affected in PWADHD. Lastly, Network Models (NMs) from the measures examined showed that comorbidity between PWS and PWADHD is limited.

For better clinical assessments of attention, fluency and working memory problems, a Linear Mixed Model (LMM) was included in chapter 3 to understand if gender imbalance affected the results of PWS, PWADHD and controls in a selective attention task. LMM correctly determined that the gender imbalance did not affect the participants performance and PWS performed significantly worse from PWADHD showing that the groups were not comorbid and PWS is impaired in selective attention tasks.

Further investigations were made in chapter 4 on PWS, PWADHD and controls in which data collected was extended to behavioural as well as physiological measures in a selective attention task implemented in a Virtual Reality (VR) environment. Although both PWS and PWADHD differed from controls with lower performance on the task, impulsive behaviours were only present in PWADHD (higher NOF) while inattentiveness was observed only in PWS (lower FD, higher theta activity). The architecture of NMs was different between PWS and PWADHD in task performance confirming again that comorbidity between groups is overstated while the frontal cortex is impaired in both groups as shown by NMs from EEG measures.

While previous chapters showed that selective and divided attention tasks in Executive Function (EF) can correctly assess attention problems in PWS, chapters 5, 6 and 7 aimed at understanding which attention type in EF is impaired in PWADHD and can correctly assess attention problems in this group. An extensive investigation was made from 10 VR tasks that drew upon different attention types on behavioural measures and responses from questionnaires (chapter 5), eye measures (chapter 6) and brain activity (chapter 7). PWADHD were compared to controls on all the measures. NMs showed that sustained attention tasks in all domains and switched attention task only in the visual domain assessed ADHD traits in PWADHD on the measures examined. Furthermore, prefrontal cortex was impaired as shown from NMs in EEG measures.

Finally, NMs were compared between controls, PWADHD and PWS in chapter 8 on cognitive factors including attention, fluency and working memory. NMs confirmed previous findings that the comorbidity of symptoms of both disorders is overstated. NM architecture between controls and PWADHD was similar, but both differed from PWS. Working memory was a strong factor that affected attention in all groups but the way it affected attention differed between PWS and PWADHD.

Impact Statement

The studies in this thesis have important theoretical and practical contributions to the research. In the first instance, this is the first research (to our knowledge) to examine comorbidity between stuttering and ADHD utilizing contemporary analysis with network models. As reported in the introduction, statistical tests used to assess comorbidity between both disorders to date have significant flaws. Given the strong evidence from the literature on utilizing network models (Cramer et al., 2010a), clinicians not only would achieve a better explanation of what is causing mental disorders but also would help them to develop new treatment strategies.

Previous research falls short in methodological aspects, utilizing approaches that have little meaning to participants affecting their performance on tasks which can significantly impact the data collected and the reliability of the results. Utilizing contemporary technologies such as Virtual Reality with powerful eye tracking and EEG devices would not only help capture behavioural and physiological responses with precise control but can also make training and testing engaging and enjoyable (Schultheis & Rizzo, 2002). In addition, the technology is safe to use, and the environment is controlled and the same for all participants allowing for more credible findings. For example, pupil diameter can be affected by light changes in traditional task assessments causing confounding results, but in VR the light of the task in a 3D environment is constant for all participants.

The thesis also aimed at tapping into different attentional systems in PWS and PWADHD in contrast to testing particular attentional abilities, as seen in previous studies. There is only one study (Doneva et al., 2017) that assessed PWS in different attentional tasks, but no study has assessed PWADHD in all attentional abilities to date. The findings provide significant implications for researchers to gain a better understanding of the right attention task to diagnose and train attention problems in PWS and PWADHD. Furthermore, empirical findings on the right physiological measures of the right attentional ability would allow the next studies to correctly assess inattentiveness in PWS and PWADHD. We suggest that PWADHD and PWS would benefit from therapies that aim to strengthen attention in the executive function in the frontal cortex. For PWS, training in attentional demanding selective tasks would help them focus their attention on relevant information such as the information they would like to express instead of concentrating on distractions including their speech disfluency or people's reactions. Training PWS in divided attention tasks would train their cognitive processing capacity and, subsequently, their speech. For PWADHD, training in sustained attention tasks would help them focus on a specific visual or auditory information for longer periods of time. Furthermore, the ability of PWADHD to switch their visual attention from one information to the next would be enhanced if this group is trained in attentional switching ability.

Overall, the work in this thesis provides practical solutions that can be used to assess and train attention, fluency and working memory problems in individuals who stutter and/or have ADHD. Employing the instruments and approaches developed and utilized in this thesis would significantly enhance the quality of life of participants who suffer from these disorders.

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Abbreviations

ADHD	Attention Deficit Hyperactivity Disorder
ADHD-PI	Attention Deficit Hyperactivity Disorder - Primarily Inattentive
ADHD-C	Attention Deficit Hyperactivity Disorder - Inattentive and Impulsive
AI	Artificial Intelligence
aMCI	amnestic Mild Cognitive Impairment
ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
AOI	Area of Interest
APA	American Psychiatric Association
ASRS	Attention Deficit Hyperactivity Disorder Self Report Scale
AST	Attention Skills Training
AVLT	Auditory Verbal Learning Task
AWADHD	Adults with Attention Deficit Hyperactivity Disorder
AWNS	Adults who do not stutter
AWS	Adults who stutter
BCI	Brain Computer Interfaces
BMI	Brain Machine Interface
CBT	Cognitive Behavioural Therapy
CL	Clutter
CPT	Continuous Performance Test
CS	Critical Stimulus
CWADHD	Children with Attention Deficit Hyperactivity Disorder
CWASD	Children with Autism Spectrum Disorder

CWNS	Children who do not stutter
CWS	Children who stutter
DAD	Directed Attention Dichotic
DS	Detection Sensitivity
DSM	Diagnostic Statistical Manual of Mental Disorders
DTD	Dual Task Decrement
EBIC	Extended Bayesian Information Criterion
EEG	Electroencephalography
EF	Executive Function
FD	Fixations Durations
fMRI	functional Magnetic Resonance Imaging
fNIRS	functional Near Infrared Spectroscopy
GAD	Generalised Anxiety Disorder
G/SMV	Gaze/Saccade Mean Velocity
GLASSO	Graphical Least Absolute Shrinkage and Selection Operator
HFT	High-Frequency Tasks
HMD	Head Mounted Display
IAD	Interaural Amplitudes Difference
IB	Inattentional Blindness
ITD	Interaural Time Difference
IVA	Integrated Visual and Auditory
LASSO	Least Absolute Shrinkage and Selection Operator
LFT	Low-Frequency Tasks
LMM	Linear Mixed-effect Model
LSD	Least Significant Difference

LVM	Latent Variable Model
MANOVA	Multivariate Analysis of Variance
MCI	Mild Cognitive Impairment
MRT	Mass Rapid Transit
MTBI	Mild Traumatic Brain Injuries
NCS-R	National Comorbidity Survey
NF	Neurofeedback
NFT	Neurofeedback Training
NIDC	National Institute on Deafness and Other Communication Disorders
NM	Network Model
NOB	Number of Blinks
NOF	Number of Fixations
NOS	Number of Saccades
NWR	Non-Word Repetition
OCD	Obsessive-Compulsive Disorder
PD	Pupil Diameter
PMRF	Pairwise Markov Random Field
PWADHD	People with Attention Deficit Hyperactivity Disorder
PWM	Phonological Working Memory
PWNS	People who do not stutter
PWS	People who stutter
RT	Reaction Times
SART	Sustained Attention to Response Tasks
SC	Superior Colliculus

SCP	Slow Cortical Potentials
SD	Standard Deviation
SLD	Speech-Like Disfluencies
SP	Speech Phobia
SPSS	Statistical Package for the Social Sciences
SSI-3	Stuttering Severity Instrument (version 3)
STAI	State-Trait Anxiety Inventory
TAP	Test of Attentional Performance
TD	Typically Developed
TEA	Test of Everyday Attention
TFT	Traditionally Formatted Tasks
TMT	Trail Making Test
T.O.V.A.	Test of Variables of Attention
SWM	Spatial Working Memory
UNWR	Universal Non-Word Repetition
VE	Virtual Environment
VR	Virtual Reality
VRET	Virtual Reality Exposure Therapy
WCST	Wisconsin Card Sorting Task
WM	Working Memory
WMC	Working Memory Capacity
WURS	Wender Utah Rating Scale

1. Chapter 1. Introduction

1.1 Overview of the introduction

People with Attention Deficit Hyperactivity Disorder (PWADHD) and people who stutter (PWS) have similar psychological, social and neural issues. Since the disorders share these features, it has been claimed that there is some commonality between them (referred to as comorbidity when these support a common cause). Past research suggests that attentional problems occur in PWS (Alm & Risberg, 2007; Bental & Tirosh, 2007; Donaher & Richels, 2012; Druker et al., 2019; Healey & Reid, 2003) as well as PWADHD (American Psychiatric Association, 2013; Chhabildas, Pennington & Willcutt, 2001). Speech disfluencies have also been reported in PWADHD (Engelhardt et al., 2010; Lee et al., 2017), as well as in PWS (American Psychiatric Association, 2013). These provide evidence of the possible comorbidity between ADHD and stuttering. Comorbidity rates of ADHD in PWS, loosely defined as those PWS who report attentional problems, reported in studies range from 4% to 26% (Arndt & Healey, 2001; Riley & Riley, 2000). The literature suggests, furthermore, that both disorders affect working memory (WM), (Jacquemot & Scott, 2006; Marchetta et al., 2008; Martinussen et al., 2005; Postma & Kolk, 1993). Using the stricter criterion for comorbidity of meeting DSM criteria for two disorders would only show that the surface characteristics of the two conditions are shared. Specifically, this does not show that the cognitive architecture of processes supporting fluency and attentional performance in people suffering from one or both disorders operate similarly. Focusing on attentional issues, no literature has explored whether symptoms of attention are impaired in the same way in groups of participants where the primary disorder is either stuttering or ADHD. For example, are all types of attention performance that are in deficit in PWADHD also affected in the same way in PWS? Similar questions arise when considering whether fluency is affected in similar ways across ADHD and stuttering. The two issues that have been highlighted, the need to compare ADHD, stuttering participants and controls for (1) attention and fluency issues (chapters 2, 3, 4, 5, 6, 7, 8), and (2) the way other cognitive processes that support attention and fluency are involved (chapter 2, 4, 5, 6, 7), are focussed on in the current thesis.

The current chapter starts by reviewing the literature on both disorders along with descriptions of their traits with an emphasis on documenting any similarities. After that, a review of the literature on WM and how it is affected when people have one or both disorders follows. Methodological and analysis approaches used in previous literature with PWS and PWADHD that addresses these similarities are then explored. Several statistical procedures have been used to understand the link between disorders including descriptive statistics, Pearson Correlations, Independent t-tests, One-Way analysis of variance (ANOVA), Mann-Whitney U tests and post-hoc paired comparisons tests. Conclusions drawn about comorbidities between the two conditions using such statistical analyses can be flawed and there is a need for contemporary analysis approaches. The way that comorbidity is examined in greater detail in these statistical models is examined, followed by an introduction of the network model (NM) approach to assessing comorbidity and a review of the pros and cons of NM based on work on other disorders. Next, the chapter focuses on Virtual Reality (VR), used in this thesis, as an emerging technology which has high relevance for the diagnosis and treatment of stuttering and ADHD. The last part of this chapter reviews previous literature on PWS and PWADHD in eye and EEG measures emphasizing similarities and inconsistences between studies.

1.2 Stuttering

Fluent speech production refers to the accurate articulation of phonemes (individual sounds) that make up spoken words. It requires phonological knowledge of speech sounds as well as the capacity to synchronise the movements of the articulators (jaw, tongue, and lips) with breathing and vocalisation. Individuals with speech production issues may have difficulty with the phonological understanding of speech sounds or in coordinating movements involved in speech.

According to DSM-5 (American Psychiatric Association, 2013), stuttering is a neurodevelopmental disorder, specifically one of the communication disorders, and is characterised by disturbances in normal speech fluency not appropriate for the individual's age and communication abilities. Stuttering can persist over time and is characterised by frequent and apparent occurrences of one (or more) of the following: 1) Repetition of sound and syllables; 2) Consonant as well as vowel sound prolongations; 3) Mispronounced words (e.g., pauses within a word); 4) Blocking that is audible or silent; 5) Word replacements to avoid difficult words; 6) Excessive physical stress in the production of words; and 7) Whole-word monosyllabic repetitions. According to Johnson et al. (1959), the signs of stuttering are: 1) interjections (pauses); 2) repetitions of words; 3) repetitions of phrases; 4) repetitions of part-words; 5) prolongations; 6) broken words; 7) unfinished phrases; and 8) revisions.

Howell (2004) divided speech problems into those that involved parts of words (part-word dysfluencies) and those that involved whole words or pauses (otherwise called stallings). According to Howell (2004), dysfluencies result from difficulties in coordinating the time between the motor planning process and linguistic levels that lead to either part-word dysfluencies or stallings involving pauses or whole words. From this perspective, stuttering occurs if linguistically difficult words are being produced and the output of the speech motor system is set to a high a rate. When this happens, people who stutter, PWS, need to adjust speech rate before they say the word. Prolongations are considered a trait in stuttering in older speakers who have had the disorder for a long time (Conture, 1990). Howell argued that stallings were the dominant characteristic of stuttering in young speakers. In speakers who recovered, the incidence of these and other dysfluencies decreases.

Approximately 1% of the adult population is affected by stuttering and many children who stutter recover before adulthood (Bloodstein, 1995). However, the prevalence of stuttering is significantly higher, with estimates ranging from 4% to 5% of the population having stuttered at some point over early development (Andrews & Harris, 1964). Craig et al. (2002) reported that most children who stutter started before adolescence, most typically between the ages of 2 and 5, with the largest peak at around 4 years old (called developmental stuttering). An injury to the brain (such as stroke or trauma) can result in brain damage and lead to stuttering. However, this is not in line with DSM-5 which points out that speech difficulties are not attributable to brain damage (making brain injury-based forms a different type of stuttering). Stuttering can lower a person's overall quality of life by causing them to have negative emotions about themselves due to their speech impairment (Craig & Tran, 2006) and this leads to lowering the chances of psychological and educational development (Andrews & Craig, 1988; Bloodstein, 1995; Craig et al., 2003) and even limiting employment prospects (Klein & Hood, 2004). PWS may be more susceptible to bullying (Langevin & Hagler, 2004) and have more difficulty establishing friendships with peers than children who do not stutter (Davis et al., 2002). According to Dworzynski et al. (2007), boy-to-girl ratios range from around 2:1 for young children, to 5.33 males to each female for older children. Howell et al (2008) reported that males were more likely to stutter than females, and the overall recovery rates for both genders were about 50%. The late (10-11 years old) and very late (12 years old) groups had a recovery rate that was around 12% greater than the early age group (8-9 years old).

1.3 ADHD

Attention Deficit Hyperactivity Disorder, ADHD is a neurodevelopmental disorder characterised by a persistent combination of inattentive, impulsive, and hyperactive behaviours (American Psychiatric Association, 2013; World Health Organization, 2018).

According to DSM-5 (American Psychiatric Association, 2013), inattention and disorganisation are defined as the inability to stay on task, listening issues that are not in accordance with one's age or developmental level (American Psychiatric Association, 2013; Kofler et al., 2008). Inattentive behaviour is linked to a variety of underlying cognitive processes, and people with ADHD (PWADHD) may struggle with attention, executive function, or memory assessments. Overactivity, fidgeting, difficulty in staying seated, intruding into other people's activities, and inability to wait are all indicators of hyperactivity-impulsivity. When attentional difficulties or hyperactivity exceed what is generally seen in people of equivalent mental age, an attention-deficit/hyperactivity disorder (ADHD) diagnosis should be considered. People with ADHD can have a combined presentation, a presentation predominantly on attention, or a presentation predominantly on hyperactivity-impulsivity. ADHD is a condition that begins in childhood. The requirement that five or more symptoms of inattention and 5 or more symptoms of hyperactivity must be evident before the age of 12 years and persistent for at least 6 months emphasising the significance of a clinical presentation in childhood. Symptoms must impact academic and social performance and should be persistent in at least 2 settings (such as home, school or in different social activities). ADHD frequently persists throughout adulthood, resulting in social, intellectual, and occupational problems. ADHD is linked to a higher chance of suicide attempts by early adulthood, especially when combined with mood, behaviour, or substance use disorders. According to population surveys, ADHD affects roughly 5% of children and 2.5% of adults in most countries. In the general population, males are more likely than females to have ADHD, with a ratio of approximately 3:1 in children (Biederman et al., 2002) and 1.6:1 in adults (Stibbe et al., 2020). Females are more prone than males to have inattentive traits (Biederman et al., 2004) or a combined ADHD subtype (Simpson, 1969) whilst males have more hyperactive/impulsive symptoms (Ramtekkar et al., 2010). Interestingly, the ratio drops as age increases with more females diagnosed with ADHD than males. Such differences may be because hyperactive symptoms in males may decline with age. Whereas for females, it is possible that some form of adult-onset of ADHD has not been recognised due to focusing only on childhood onsets of presentations of this disorder, but this has yet to be studied. However, in children with ADHD, studies using clinic-referred samples may only accurately reflect a specific subtype, leading to the claim that research in clinically referred adults with ADHD may be more representative (Williamson & Johnston, 2015). In addition, many studies have only focused on people with clinical conditions. Research may benefit from the use of non-clinical populations as in clinical populations there are problems like referral bias (Levy et al., 1997). Hence, in this thesis PWADHD were assigned in the ADHD group from three different backgrounds: 1- Some participants had an ADHD clinical diagnosis; 2- some participants had a self-reported ADHD diagnosis; 3- some participants reported symptoms of inattentive and hyperactivity in line with the DSM-5 criteria for having a presentation of ADHD. Most studies draw conclusions between the groups without taking into consideration gender differences. Chapter 3 addresses this to determine whether gender imbalances affect the interpretation of results about cognitive abilities in PWADHD as well as in other groups.

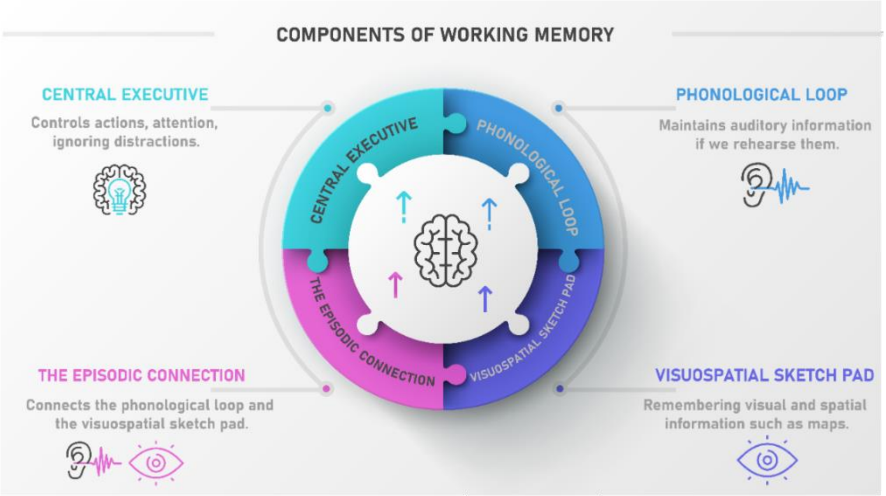
The symptoms of ADHD decrease in PWADHD under various interventions. The interventions include whether they receive rewards for appropriate behaviour, are under close supervision, are engaged in a novel setting or interesting activities, have consistent external stimulation or are interacting in one-on-one situations.

1.4 Working Memory issues in PWS and PWADHD

The above literature suggests that PWS and PWADHD are both likely to exhibit symptoms characteristics of the other disorder suggesting comorbidity. Other symptoms, like WM impairments, may be present in both disorders. However, no literature has assessed how WM links to fluency and attention and how these differ across PWS and PWADHD. Network models (Cramer et al., 2010a) were used to investigate how WM hooks up with cognitive abilities for PWADHD and PWS (Chapter 8) including how WM problems are affected in PWADHD and PWS. According to Cowan (2013), WM refers to a limited capacity mechanism that temporarily stores and processes information required to accomplish difficult cognitive tasks such as learning and problem-solving. WM is a cognitive system that provides access to information needed for ongoing cognitive processes whereas Working Memory Capacity (WMC) represents a person's restricted capacity for using WM. Given that WM is involved in numerous cognitive processes, assessing it offers a convenient method to consider and test issues of comorbidity i.e., in the way it links with activities across ADHD and stuttering. WM is made up of several components, one of which is the phonological loop which is responsible for managing linguistic and auditory information (Baddeley, 2003, see Figure 1.1). The phonological store maintains verbal information and rehearsal can refresh that information.

Figure 1.1

Working Memory Components including: 1-central executive related to attention and ignoring distractions; 2-phonological loop related to maintaining auditory information; 3-visuospatial sketchpad that allows visual information such as maps to be remembered; and 4-the episodic connection which connects the phonological loop and the visuospatial sketch pad.



Communication disorders have been linked to impairments in phonological memory and central executive functioning although little research has been conducted on the potential role that these working memory elements may play in stuttering. The attention to phonological encoding in PWS (Melnick et al., 2005) encourages investigating the degree to which phonological working memory components are implicated in the disorder. Daneman (1991) reported a link between fluency and WM, and it has been suggested that phonological working memory (PWM) is involved in planning and producing speech (Jacquemot & Scott, 2006). WM is central in phonological encoding and planning speech and involves accessing linguistic information to build articulatory plans (Gathercole & Baddeley, 1993). Stuttering is linked to poor phonological encoding, which leads to errors in speech planning (Postma & Kolk, 1993). Phonological encoding relies mostly on phonological loop activities when it comes to accessing phonological information from storage to create articulatory plans during speech planning (Levelt, 1989). According to the EXPLAN model of stuttering (Howell & Au-Yeung, 2002), dysfluencies may occur if linguistic planning (PLAN) processes do not provide motor execution (EX) processes with output in time. The speaker attempts the word before they are ready rather than hesitating before it, which causes the transition from stalling to part-word stuttering. Howell (2004) reported that among adults who stutter, both phonetic and metrical elements are determinants of stuttering. These explanations show that if PWM is damaged in a person, verbal preparation and production should also be impaired, resulting in fluency issues.

Literature supports the link between poorer PWM performance using non-word repetition (NWR) tasks in PWS. NWR tasks require people to listen to non-words with two or more syllables, remember the order of the syllables, and repeat them accurately. It is suggested that in non-words, speakers rely on the memory part of the phonological loop (Gathercole et al., 1994), which handles phonological storage, encoding, and retrieving without the interference of prior linguistic knowledge (Montgomery, 2004). In people with language deficits, non-word repetition has been validated as a reliable indicator of phonological encoding deficits (Baddeley & Wilson, 1988). Hakim and Ratner (2004) utilised the Children's Test of non-word repetition (Gathercole et al., 1994) to investigate the performance of eight children who stutter (CWS) and eight children who do not stutter (CWNS) and to determine whether

WM was an indicator of language problems among CWS. The researchers also gave their participants the same items with changed (non-English) stress patterns (increasing the proportion of unfamiliar syllables in the non-words) to assess whether atypical word stress had an impact on the accurate recall from phonological memory. Word repetitions were evaluated for overall correctness and phoneme errors in incorrect answers. The results showed that CWS had lower accuracy and generated more phoneme errors than the fluent children, with statistically significant group differences. In repeating words with unfamiliar stress patterns, all participants' performance deteriorated, but CWS showed a more drastic decline. According to Hakim and Ratner's (2004) analysis, children with particular linguistic impairments performed worse in their study when phonological memory was assessed. The same results were obtained in CWS in Bakhtiar et al. (2007) and in adults (Byrd et al., 2015),where CWS and adults who stutter (AWS) performed worse than controls in NWR tasks. This indicates that NWR can be utilised to investigate PWM impairments in PWS.

WM deficiencies have also been linked to ADHD. According to Rapport's (2001) model, ADHD symptoms are characterised by disorganised behaviour, related to WM problems. The model suggests that the capability of WM to: (1) retain the received stimulus; (2) search long-term memory for similarities; and (3) obtain and hold suitable responses to stimuli are all required for organised behaviour. WM deficits should impair these processes, resulting in improper behavioural responses, which could appear in PWADHD as symptoms of inattention, disorganisation, and impulsivity. In a meta-analysis, Martinussen et al. (2005) found evidence for WM impairments in adults with ADHD and in a review of 26 studies. Marchetta et al. (2008) investigated four areas of executive functioning between controls and PWADHD: 1-interference control, 2- concept shifting, 3-verbal fluency, and 4-verbal working memory. The auditory verbal learning task (AVLT) was used to test verbal working memory. In this task, 15 commonly used monosyllabic words were presented sequentially, one word every two seconds, in a fixed order. Participants repeated as many words as possible after words were presented (immediate recall). For the AVLT, there were significant performance differences across the groups with the ADHD group having significant lower scores than the controls. Such evidence suggests that PWM is also affected in PWADHD.

These results suggest that PWS and PWADHD may have PWM deficits and, therefore, it is appropriate to investigate whether PWS and PWADHD have WM deficits using NWR tasks. However, NWR tasks prioritize the language for which they were designed, which can be problematic when presented to people that can speak other languages. For example, Greek-speaking people who also speak English did better on a Greek NWR than on an English NWR one (Masoura & Gathercole, 1999). The universal NWR (UNWR) of Howell et al. (2016) partly tackles this issue because it is applicable to 20 commonly spoken languages in the UK. The UNWR can be used to identify fluency issues in linguistically diverse samples. The UNWR task (Howell et al., 2016) was employed in this thesis to understand how WM affects attention and whether WM performance differs between PWADHD and PWS compared to controls.

1.5 Previous Approaches to assessing attention and stuttering

Several statistical analyses have been used to understand the link between disorders including descriptive statistics, Pearson Correlations, Independent t-tests, One-Way ANOVA, Mann-Whitney U tests and post-hoc paired comparisons tests. Critics have argued that conclusions drawn about comorbidities between the two conditions using such statistical analyses can be flawed and there is a need for contemporary analyses (Jeon 2015; Lash et al., 2007). Studies using these approaches are reviewed in this section.

In Donaher and Richels' (2012) empirical investigation, 36 parents of 36 CWS completed the ADHD Rating Scale to evaluate whether their child showed the typical signs of ADHD. Cramer's V test was used to assess whether participants who met the requirements for psychological evaluation due to ADHD symptoms had significantly higher values on the dependent measures (e.g., gender, family history, concomitant diagnoses, etc.). Pearson correlation was used for comparisons of dependent measures within-groups. Cramer's V is a good choice for evaluating the relationship of referral criteria and non-parametric dependent factors such as gender and family history. Pearson correlation, on the other hand, allows within-group comparisons of dichotomous variables and indicates the strength of the relationship between them. However, this approach does not show cause and effect between variables, and it does not account for confounding factors that could influence the correlation results. It was reported that 58% of CWS met the criteria for ADHD referral. Additionally, the existence of a concomitant diagnosis was strongly positively linked to a family history of recovered stuttering.

In Biederman et al. (1993) 84 adults with ADHD (AWADHD), 140 children with ADHD (CWADHD) and matched controls completed structured self-report interviews. The findings from the chi-square tests suggested that 4% of CWADHD had a significant history of stuttering, compared to 2% in the control group. Also, 18% of AWADHD had a significant history of stuttering compared to only 3% of the control group. These findings suggest that ADHD when comorbid with stuttering is more persistent than when there is ADHD alone. Due to the gender inequality in the ADHD group compared to the other groups, chi-square tests are a good choice because they allow for the examination of matched categorical and continuous data. However, interpretations of the results can be difficult if there are many categories in the dependent and independent variables. Furthermore, in a large sample even insignificant associations can be statistically significant, and the chi-square does not indicate that there is a direct causal relationship between the two variables.

Alm and Risberg (2007) administered the Wender Utah Rating Scale (WURS), a 25-item self-report questionnaire for the assessment of ADHD symptoms, to 32 AWS and 28 controls. From the independent samples t-test, AWS had higher ratings of ADHD traits during childhood than did controls. Independent t-tests compare the means between groups when the dependent variable is continuous. However, independent t-tests are sensitive to small and unequal sample sizes. Hence, since the study used a limited sample size, this may have had an effect on the validity of the results from the independent t-tests.

Riley and Riley (2000) assessed physical concomitants in 50 school-aged CWS. 26% of their sample had an Attending Disorder, which was characterised by poor attention and high impulsivity, which are both symptoms of ADHD. Descriptive statistics were used to make robust comparisons across obtained information from the normative test results and clinical judgement translated to a 7-point Likert scale. In a prior study on 176 CWS (Riley & Riley, 1979) therapeutic outcomes were improved if clinicians addressed the attention issues before beginning speech therapy. From the factor analysis and descriptive analysis, results suggested that attending disorders were observed in 36% of CWS. Factor analyses are helpful for clustering a large number of variables into a smaller number of factors that are essential to the development of the Component Model. The interpretation of the identified factors, on the other hand, is participative. Descriptive statistics give some fundamental information, such as the percentage of patients with concurrent conditions and treatment outcomes. Such analyses are appropriate for a specific variable, but there are limitations in generalizing the findings despite a large sample size.

Arndt and Healey (2001) conducted a survey to investigate the incidence of comorbid disorders in CWS. The results from their descriptive analysis suggested that 109 of the 262 school-aged children with a fluency disorder also had ADHD further supporting a link between stuttering and attention abilities. In this context, descriptive analysis can be used to summarise a vast amount of data and present the survey results in a logical form but no significant findings can be established from such analysis.

Blood et al. (2007) used a visual attention test to investigate attentional functioning in 19 CWS and 19 CWNS. T-tests on overall scores showed no significant differences between the groups. However, 58% of the CWS scored higher on the risk-taking subscale of the task than did non-stuttering children. This implies increased impulsivity. In addition, from a continuous performance test (CPT), 16% of the stuttering group showed a co-occurring link between stuttering and impaired attention. The sample size is limited but t-tests are sensitive and appropriate for comparing means between the stuttering and non-stuttering groups. T-tests, on the other hand, could not examine potential confounding variables such as socioeconomic status differences across groups.

Bosshardt (1999) compared 9 AWS with 10 adults who do not stutter (AWNS) on two dual tasks where participants repeated a sequence of words vocally and continuously whilst performing mental calculations. When AWS read and memorised similar words at the same time, they exhibited considerably higher stuttering rates during word repetition. A minority of the AWS were impaired in the mental calculation task, possibly because such activities provided many strategic possibilities. The two experiments used factor analysis and revealed that the speech of PWS is vulnerable to interference from concurrent attention-demanding cognitive functioning, especially when phonological processing is involved.

In Engelhardt et al.'s (2010) study, 194 PWADHD completed a sentence generation task in which participants were given two pictures and a verb and were asked to create a sentence involving all these materials. This task evaluated the effect of inhibition on incorrect speech. As task demands increased, PWADHD produced more disfluencies based on the significant group differences using a one-way ANOVA and paired-comparisons tests. The results showed that the production system relies on inhibitory control to prevent language production errors. One Way ANOVA is appropriate for studies with more than two groups, i.e., Controls, ADHD-Primarily Inattentive (ADHD-PI) and ADHD- Inattentive and Impulsive (ADHD-C) but the analysis might not be reliable since the data were not normally distributed.

Heitmann et al. (2004) examined the attentional abilities of nine PWS, eight participants who clutter (CL) and nine fluent controls in a series of attention tasks. The stuttering group had significantly longer reaction times compared to CL and the control group as analysed by descriptive statistics using ANOVA followed by Fisher’s Least Significant Difference (LSD) to explore significant main effects and interactions. This supported the author’s hypothesis that stuttering is linked to an inability to remain focused. By employing Fisher's LSD, the researchers restricted the individual error rate to the specified significance level and investigated which group diverged in the ANOVA results.

A preliminary study of differences in treatment responsiveness for 185 CWS with and without ADHD symptoms was conducted by Druker et al. (2019). Participants completed the ADHD Rating Scale. The results from the non-parametric Mann-Whitney U tests revealed that approximately half of the participants had severe ADHD symptoms, and 25% of these children required more clinical intervention time to improve fluency performance. Mann-Whitney U tests are appropriate when the data among groups are not normally distributed. Non-parametric tests however have less power than parametric tests and can miss significant results.

During focused attention tasks, Ratcliff-Baird et al. (2002) looked at the differences in frontal area theta, and alpha activity between AWS (n=22) and AWNS (n=22) using electroencephalogram (EEG). The following six conditions were recorded: 1) baseline resting-eyes-open, 2) baseline resting-eyes-closed, 3) eyes-open focused attention, 4) eyes-closed focused attention, 5) eyes-closed backwards-counting math task, and 6) eyes-open auditory delayed non-match-to-sample task. The results from ANOVA and post-hoc analysis demonstrated that the stuttering group had higher theta activity and decreased alpha activity at frontal locations in all situations, supporting the attention-stuttering link.

Tucha et al. (2005) examined fluency in both phonemic and semantic tasks in 34 AWADHD compared to 34 controls. In the semantic tasks, participants produced verbally as many words as possible that belonged to some specific categories. In the phonemic task, participants had to say as many words as possible that started with a letter specified by the experimenter. PWADHD generated fewer words in both tasks as shown by t-tests. T-test is appropriate in this case as the groups were matched in number and the sample size was large enough to generate reliable results.

A similar study was conducted by Andreou and Trott (2013) who investigated fluency in 30 adults diagnosed with ADHD compared to matched controls in two verbal fluency tasks (phonemic and semantic) of Tucha et al. (2005). Paired sample t-tests showed that PWADHD had significantly lower scores than controls in the phonemic task. The results suggested that PWADHD had impairments in phonetic fluency possibly due to the cognitive demand that such a task requires and because it impacts more the functions on frontal lobe which is known to be impaired in PWADHD (Andreou & Trott, 2013).

Processing speed and reading fluency were examined by Jacobson et al. (2011) in 41 CWADHD and 21 controls. Several tests were conducted that assessed reading fluency, processing speed and verbal working memory. For the reading task, participants read out loud paragraphs where fluency score was calculated by combining the reading speed rate and accuracy. For processing speed, the authors examined children in a task with subtests including coding and symbol search (no further information was provided by the authors). In a verbal WM test, children repeated orally presented digits. The verbal WM was also assessed in another task in which participants memorised a sequence of letters and numbers and recalled the letters presented in alphabetic order whilst numbers were recalled in ascending order. Independent samples t-test showed that CWADHD had reduced verbal and processing fluency speed compared to controls in the tests. It was further concluded that processing speed was significantly correlated with the WM measures, and both were predictors of reading fluency.

Table 1.1

Summary of studies assessing attention and stuttering including methods, statistical approaches, conclusions, and limitations of tests.

Study	*Groups*	*Method*	*Statistical Approach*	*Findings*	*Statistical tests Limitation*
Donaher and Richels (2012)	36 parents of 36 CWS	ADHD Rating Scale	Cramer's V test; Pearson Correlation	58% of CWS met the criteria for ADHD.	Test don't show cause and effect between variables, and it does not account for confounding variables.
Biederman et al. (1993)	84 AWADHD; 140 CWS; matched controls	Self-Report Interviews	Chi-square tests	18% of AWADHD had a history of stuttering.	Test don't show cause and effect between variables, and even insignificant associations can seem statistically significant.
Alm and Risberg (2007)	32 AWS; 28 controls	Wender Utah Rating Scale	Independent samples t-test	AWS had higher ratings of ADHD than controls.	Independent t-tests are sensitive to small and unequal sample sizes.
Riley and Riley (2000)	50 CWS	7-point Likert scale	Descriptive statistics	26% of their sample had an Attending Disorder which are characterised by poor attention and high impulsivity.	Descriptive statistics are not appropriate to generalize the findings and draw conclusions.
Riley and Riley (1979)	176 CWS	7-point Likert scale	Descriptive statistics; Factor Analysis	36% CWS had an Attending Disorder.	The interpretations of the identified factors are participative
Arndt and Healey (2001)	262 CWS	Survey	Descriptive statistics	109 CWS had ADHD traits.	No significant findings can be established from such analysis.
Blood et al. (2007)	19 CWS; 19 controls	1-Visual attention test; 2-CPT	Independent samples t-test	1-58% of the CWS scored higher on risk-taking (increased impulsivity); 2- 16% of CWS showed attention impairments.	Independent t-tests are sensitive to small sample sizes.
Bosshardt (1999)	9 AWS; 10 AWNS	Two dual tasks	Factor Analysis	PWS is vulnerable to interference from concurrent attention demanding.	The interpretations of the identified factors are participative.

Study	*Groups*	*Method*	*Statistical Approach*	*Findings*	*Statistical tests Limitation*
Engelhardt et al. (2010)	194 PWADHD	Sentence generation task	One-way ANOVA; Paired-comparisons tests	PWADHD produced more disfluencies.	One Way ANOVA is appropriate for studies with more than two groups but cannot be reliable if data is not normally distributed.
Heitmann et al. (2004)	9 PWS; 8 participants who clutter; 9 controls	Attention tasks	One-way ANOVA; Fisher's Least Significant Difference (LSD)	The stuttering group had significantly longer reaction times compared to CL and the control group.	One Way ANOVA is appropriate for studies with more than two groups but cannot be reliable if data is not normally distributed.
Druker et al. (2019)	185 CWS	ADHD Rating Scale	Mann-Whitney U test	Half of the participants had severe ADHD symptoms.	Non-parametric tests have less power than tests that parametric tests.
Ratcliff-Baird (2002)	22 AWS; 22 controls	Focused attention tasks	ANOVA; post-hoc test	AWS had higher theta activity and decreased alpha activity at frontal locations (characteristics seen in PWADHD).	ANOVA is affected by data that is not normally distributed.
Tucha et al. (2005)	34 AWADHD; 34 controls	Semantic tasks	Independent samples t-test	PWADHD generated fewer words in tasks.	T-test is appropriate for this study.
Andreou and Trott (2013)	30 AWADHD; 30 controls	Two verbal fluency tasks (phonemic and semantic)	Paired sample t-tests	PWADHD had impairments in phonetic fluency.	Paired sample t-test is appropriate for this study.
Jacobson et al. (2011)	21 CWADHD; 21 controls	Fluency reading tasks	Independent samples t-test	Reduced verbal and processing fluency speed compared to controls.	T-test is appropriate for this study.

1.6 Summary and evaluation of studies looking at fluency and attention issues in PWS and PWADHD

A summary of all studies conducted with PWS and PWADHD is given in Table 1.1. Conclusions drawn from scales, questionnaires, and interviews suggested a large percentage of CWS and AWS with ADHD traits (Alm & Risberg, 2007; Arndt & Healey, 2001; Donaher & Richels, 2012; Druker et al., 2019; Riley & Riley, 1979; Riley & Riley, 2000), and 18% of AWADHD had stuttering symptoms (Biederman et al., 1993). In reading tasks, PWADHD generated disfluencies (Engelhardt et al., 2010; Jacobson et al., 2011; Tucha et al., 2005) while a substantial percentage of PWS had attention deficits and increased impulsivity (Andreou & Trott, 2013; Blood et al., 2007; Bosshardt, 1999; Heitmann et al., 2004; Ratcliff-Baird, 2002) as assessed in attention tasks. Almost all studies used similar inferential analysis techniques to analyse the data and drew conclusions about comorbidities between stuttering and ADHD. Based on the significance of the results from descriptive statistics, t-tests, ANOVA, Pearson correlations and multiple regression between PWADHD, PWS and controls, conclusions were drawn about comorbidities between the two conditions. Researchers sometimes fail to acknowledge or overlook the limits of statistical models. Lash et al. (2007) reviewed articles on how well researchers may expect to separate participants into groups (healthy and less healthy) given the variable that they are measuring comorbidity for, the measure of comorbidity they select, and the method they use. Medical records, assessments, self-report scales, and administrative databases are all used in comorbidity measures. The authors suggested that analyses based on these scales bring uncertainties that can be interpreted as measurement errors or misclassification issues, both of which can be handled using current analytic methodologies. Although the use of approaches like marginal structural models, multiple bias modelling, data augmentation, and multiple imputations has re-emphasized uncertainty assessment in epidemiology recently, these strategies can be used to address ambiguity emerging from comorbid disorder measurement errors. It was concluded that contemporary analytic methods are necessary to effectively use many sources of comorbidity data to improve assessment and address uncertainty. Similarly, according to Jeon (2015), previous approaches are faulted when used for determining comorbidities. For an accurate explanation or prediction of the causal links among variables, it is important to choose and use appropriate statistical models and to consider their limitations and strengths. The Network Model, NM was investigated here (Chapter 8) as it can allow any patterns across participant groups (controls, PWADHD, PWS) to be established.

1.7 Comorbidity

Returning to *Comorbidity* technically it is the presence of two (or more) disorders simultaneously in an individual (Angold et al., 1999). Approximately 45% of people who meet diagnostic criteria for a given mental disorder, receive additional diagnoses for other disorders (Kessler et al., 2005). Gadermann et al. (2012) suggested that this figure could be as high as 73.8 - 98.2% if chronic physical disorders are included as comorbid conditions too. The assessment tool used in these reports (Gadermann et al., 2012; Kessler et al., 2005) involved a replication of a US National Comorbidity Survey (NCS-R[1]). In NCS-R, disorders from DSM-IV were correlated with each other. In the adult psychiatric literature, there is a growing interest in comorbidity based on claims such as these and therefore the NCS-R was developed to investigate psychiatric diseases in the United States (Angold et al., 1999). It is important to determine multiple mental disorders in one person since, when they are present, they pose higher demands for professional treatment, more difficulty coping with ordinary life, and a higher rate of suicide (Albert et al., 2008).

As seen above, the literature suggests that symptoms of stuttering are comorbid with those in ADHD emphasizing that attention issues, disfluency and working memory problems can be present in PWS and in PWADHD. However, no literature has used appropriate statistical

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[1] A copy of the NCS is available in https://www.hcp.med.harvard.edu/ncs/

approaches to understand this comorbidity using better analysis procedures and improved specifications about the meaning of ‘comorbidity’. Furthermore, no literature has explored whether such symptoms of attention are impaired in the same way in groups of participants where the primary disorder is either stuttering or ADHD. For example, is attention comorbid with stuttering in the same way in PWS and PWADHD? Is WM impaired in the same way in both groups? For this reason, we introduce the network model in detail and explain why NM is a preferred approach to address comorbidity between disorders. Studies suggest similarities between PWADHD and PWS and throughout development, males continue to experience more symptoms of stuttering (Dworzynki et al., 2007) and ADHD (Biederman et al., 2002; Stibbe et al., 2020) than do females but the ratio drops with age in PWADHD from 3:1 in childhood (Biederman et al., 2002) to 1.6:1 in adults (Stibbe et al., 2020) whereas the opposite happens in PWS with 2:1 in childhood to 5:1 in adulthood (Dworzynki et al., 2007). There is a need to consider whether the pattern of cognitive deficits in adults with ADHD and stuttering differs by age as an alternative position to comorbidity.

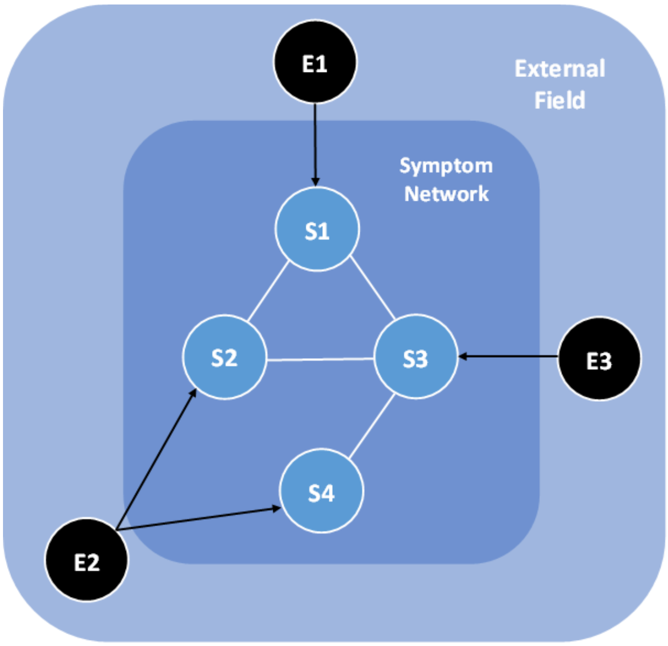
1.8 Network Model

Recent studies of comorbidity amongst disorders have focused on the relationships between symptoms in a network approach where symptoms are assigned to a single underlying cause (Borsboom & Cramer, 2013; Cramer et al., 2010a; Epskamp et al., 2017a; Epskamp et al., 2017b). Disorders are viewed as clusters of directly-related symptoms in this "network perspective." Fried et al. (2016) used this method to investigate the relationships between the symptoms of depression and reported that the essential symptoms in depression were recognised by the networks and provided information on which symptoms may be targeted during therapies. The network method assumes that symptoms can interact with one another and hence be causally linked (Cramer et al., 2010a) and is generally used to find and analyse statistical relationship patterns in multivariate psychological data (Borsboom et al., 2021).

Networks involve nodes and edges. Nodes represent the symptoms (in circles) in the network model whereas edges are the lines that connect the nodes. In a NM, symptoms that activate each other are connected whilst those that do not activate each other are not (see Figure 1.2 for an example).

Figure 1.2

A group of symptoms (S1-S4) that form a network. Symptoms that activate each other are connected by a line or otherwise known as an edge (e.g., S1-S2). Symptoms that are not directly connected to each other (e.g., S1-S4) may share a network neighbour (S3). The external factors (E1, E2, E3) presented in the external field are life events, genetic or social issues causing abnormal brain functioning known as mental disorders. Such factors can cause specific symptoms (e.g., E1, E3) or can cause more than one symptom (E2).

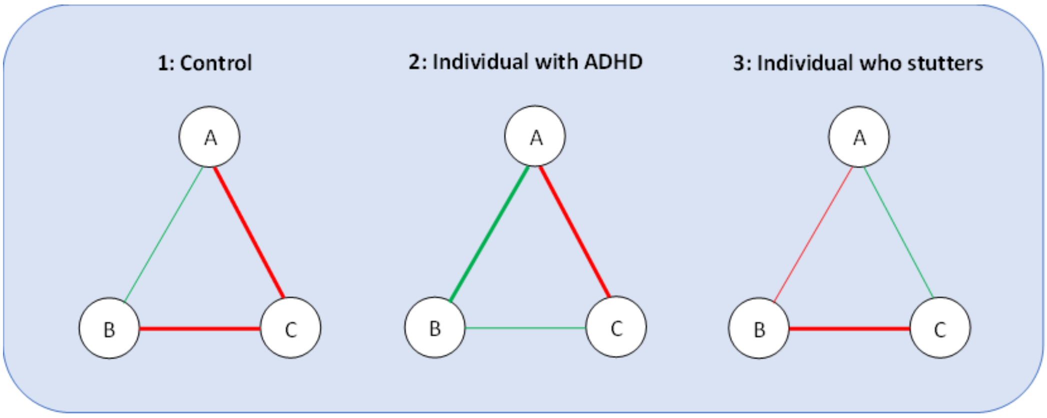


The network's edges that link two symptoms together, may or may not be directed (visualised with a line or a line arrow) positively or negatively (green for positive connections; red for negative connections in Figure 1.3) and may or may not be weighted for their strength (edges can have a value or no value). For example, losing a family member (external factor) can cause a symptom in the network (such as depression). This can activate other symptom neighbours such as anxiety, insomnia, eating disorder. In a network model, after nodes and connections have been established and a network has been built, the topology of the network can be studied using network science descriptive tools for the position of specific nodes inside the network. The network often represents the intensity of this conditional association as an edge weight that characterises the relationship between two nodes and their pattern characterised by green and red colours. The position of nodes in the network can be investigated using centrality measures. The most used centrality metrics are node strength, which sums the absolute edge weights of edges per node; closeness, which measures the distance between a node and all other nodes by averaging their shortest path lengths; and betweenness, which measures how often a node is on the shortest path connecting any two other nodes. The strength presents on average the strength of association between the relevant variable and other variables in the network. Network techniques apply to multivariate data and can be used to accomplish various objectives. First, if a strong prior theory about how variables are related is lacking, they can be used to investigate the structure of high-dimensional data. Second, because network representations provide excellent visualisations of statistical association patterns, they can be utilised to effectively explain multivariate patterns of reliance. Third, because network models describe statistical structures that may provide clues to causal dynamics, they can be used to construct causal hypotheses.

Network models can help us understand whether an individual who has met the DSM criteria for primary disorder A and has symptoms of another, secondary, disorder B, has a similar correlation or not for an individual who has a primary disorder B and has symptoms of a secondary disorder A. Furthermore, if we bring to this, the symptom C that can be found in both primary disorders A and B, we can understand whether symptom C is similarly correlated or not with disorders A and B. In an NM these two individuals can be compared with an individual who does not have A, B and C symptoms (known as control or a typical healthy participant). For example, for an individual who receives a diagnosis of ADHD (disorder A) and has symptoms of stuttering (disorder B), can this correlation in NM be the same for an individual who receives a diagnosis of stuttering (disorder B) and has symptoms of ADHD (disorder A)? Furthermore, is WM (disorder C) affected in the same way in both individuals? Finally, we can ask what is the pattern of these two individuals compared to the pattern in a healthy participant? See Figure 1.3 for a visualisation of this example.

Figure 1.3

Examples of NMs visualised for one control (left NM), one individual with ADHD (middle NM), and one individual who stutters (right NM) from the symptoms A: ADHD, B: Stuttering, C: Working Memory.



Mental disorders are described as an interconnected web of symptoms (here, attention, fluency and working memory represented as nodes) and according to network theorists, the disorders are emerging phenomena that originate from direct interactions amongst their symptoms, rather than underlying factors that cause symptoms to appear (Jones et al., 2019). Mental disorders often have many symptoms in common (shown in NM as nodes). For example, obsessive-compulsive disorder (OCD) symptoms, are associated with guilt, which in turn is a cause of depression (Kim et al., 2011). Experiencing certain symptoms of one disorder causes risk for other disorders, resulting in diagnostic comorbidity. NM has not been used to determine the comorbidity between ADHD and stuttering to date. Next, we introduce details about the pros and cons for NM based on work from other disorders.

1.8.1 Pros and Cons of NM

The network account of comorbidity derives strong support from work on clinical treatments. Cramer et al. (2010a) claimed that the NM reflects the processes of the more successful therapeutic treatments for mental disorders, which recognise the importance of relationships between symptoms. For example, in cognitive behavioural therapy (CBT; Beck, 1979), treatment focuses on the impact of cognition on symptoms—e.g., how ruminating might lead to a spiral of irrational thoughts and subsequent actions. Furthermore, treatments following the Latent Variable Model (LVM), approach that does not involve networks have yielded contentious results. The LVM approach to mental disorders embodies a traditional view of comorbidity. Comorbidity, in this context, is regarded as a relationship between multiple latent variables or due to a direct connection between two latent variables where the latent variables represent disorders (Neale & Kendler, 1995). Some researchers go even further, hypothesising that a direct relationship between two latent variables signifies the presence of a "super disorder". For example, in models in which the super disorder "negative affect" causes a number of mental disorders (such as depression), negative affect triggers observable symptoms in the various mental disorders (Barlow et al., 2004). As a result, associations between the various symptoms are merely covariance due to the same underlying cause (Cramer et al., 2010a). Historically, the assumptions behind such models have been the basis for diagnosis of mental disorders, in that disorders are seen as separate entities with unitary causes and definitive symptoms that can be used to identify the disorder a person has (e.g., 5th ed.; DSM-5; APA, 2013).

Cramer et al. (2010a) suggested that the LVM approach to comorbidity research has significant flaws and NM avoids these contentious issues. For example, antidepressants do not work for every patient (Cipriani et al., 2009), indicating that the latent variable assumed for depression (e.g., serotonin imbalances) does not explain the disorder for all patients. Thus, not only might the NM provide a better explanation for the causes of mental disorders, but it may also have positive implications for developing new treatment strategies. Cramer et al. (2010a) pointed out that clinical practice has commonly taken a network-style view to treatment (e.g., administering a range of treatments to patients besides antidepressants). Thus, the NM may advocate more of a psychometric rather than an applied, change in research perspectives.

NM has strong foundations in genetic and neural research. Davis and Plomin (2010) noted that genetic influences in psychological phenotypes (i.e., behaviour) can be well represented in a network approach due to similarities in implicated genetic factors between disorders and symptoms. Furthermore, a network approach is highly reflective of the anatomical and functional properties of the brain; brain imaging studies are progressively and consistently revealing the highly complex and interconnected nature of brain structure—termed the ‘connectome’ (e.g., Passoa, 2017). It seems likely, then, that comorbidity would function similarly in that symptoms correlate due to direct biological connections, such as shared genetic influences or neural networks.

However, the NM also falls short in some respects. Cramer’s analysis reveals that NM can be applied to DSM-4 Axis I symptom disorders (i.e., the most common disorders such as generalised anxiety disorder and major depressive disorder; ADHD and stuttering belong to this Axis). Other disorders, such as Axis II disorders (personality disorders and mental retardation), differ from Axis I disorders in many ways; for example, symptoms across these axes are very different. The extent to which NM applies to Axis II disorders is still limited. Thus, the application of network theory of comorbidity to all disorders may need modification (see attempts by Fried & Cramer, 2017).

Whilst NM is appropriate for determining comorbidity between ADHD and stuttering, NM has not been used for this purpose to date. Hence this thesis will also explore comorbidity between disorders using NM.

1.9 Virtual Reality

As mentioned earlier, this thesis set up to probe attention in ADHD and stuttering in more depth. VR was used to extend scenarios and to capture measures of physiological performance in attention tasks and to extend beyond the auditory modality. VR technology provides a technique to measure attention, oculomotor, and EEG activity simultaneously. VR is a technology of emerging popularity in rehabilitation (Keshner, 2004). VR apps have been in use since the early 1990s. A successful therapy approach is Virtual Reality Exposure Therapies (VRET; Walkom, 2016). This involves users communicating in three dimensions in VR applications so that they feel that they are part of the scene. VR offers the ability for the dynamic physical world to be transferred into a regulated environment. This technology allows us to create an artificial environment with precise control whilst recording a range of responses for analysis. Researchers can create practical VR situations that can make participants "forget" that they are being studied.

In addition, it is possible to monitor the stimuli that are presented. By building a simulated world, risky scenarios can be avoided, and VR has the potential to make testing and training enjoyable (Schultheis & Rizzo, 2002). According to Hendrikse et al. (2019), the benefits of using VR in the laboratory are that they have high reproducibility and power, and complete access to auditory and visual stimuli can be provided by VR engines. However, it can be argued that measurements with Virtual Environments (VEs) in the laboratory are less ecologically valid than field experiments. Constructing and designing practical VEs and explicitly developing applicable daily conditions that arise naturally in the field is difficult (Llorach et al., 2018). Bishop and Rohrmann (2003) stated that if people are familiar with the real world in which the VE was based, they might also accept it and adapt to the VE since they just need to be reminded of the environment and fill in the rest with their memory or imagination. It could be argued that not too much detail should be added to make space for the participants' imagination, even though the VE is not focused on a real setting. Care should be taken, however, to ensure that the VEs are not too sparse, making them unrealistic.

1.10 Eye Tracking

Eye movements can be tracked in VR headsets to determine what part of the scene is being viewed. Eye tracking techniques were first developed more than a century ago and are now a well-established tool in psychological studies, but recent advancements have made them more adaptable and affordable. VR and eye tracking, when used together, provide unprecedented monitoring and control of human behaviour in semi-realistic settings. The use of eye tracking and virtual reality allows researchers to measure the participant’s gaze in 3D space and monitor where they are looking during tasks. Clay et al. (2019) described various methodologies and tools that can be used in the implementation of experiments using eye tracking in VR. In addition to the technical details, the authors provided data that demonstrated the technology's usefulness and the types of results that can be obtained when employing eye tracking in virtual reality. They focused their research on the participant’s visual behaviour while exploring a city using VR technology which expands the data set available for analysing navigational behaviour. Microsaccades, saccades, fixations, blinks and pupil diameter have been associated with attention (Fried et al., 2014; Munoz et al., 2003; Laubrock et al., 2010; Pastukhov & Braun, 2010; Pastukhov et al., 2013). There are comparatively few studies that have explored some, or all, of the measures in PWADHD, PWS compared to controls and there are no studies comparing across groups. Since both PWS and PWADHD are often considered comorbid, the same eye tracking measures can be tested and compared between groups. Therefore, the measures reported in the thesis are: 1- saccades, 2- fixations, 3- fixation durations, 4- blinks, 5-saccade/gaze velocity, and 6-pupil diameter (see Table 1.2 for measures tested and the corresponding chapters and Table 1.3 in the next section for a review and summary of findings on eye movement in PWADHD and PWS).

Table 1.2

Eye measures obtained and analysed in this thesis including groups of participants and chapter. No. = number.

Measures	Participants
Chapter II	
Saccade/Gaze Velocity	Controls vs PWADHD vs PWS
Pupil Diameter	Controls vs PWADHD vs PWS
Chapter IV	
No. Saccades	Controls vs PWADHD vs PWS
Saccade/Gaze Velocity	Controls vs PWADHD vs PWS
No. Fixations	Controls vs PWADHD vs PWS
Fixations Durations	Controls vs PWADHD vs PWS
Chapter VI	
No. Saccades	Controls vs PWADHD
Saccade/Gaze Velocity	Controls vs PWADHD
No. Fixations	Controls vs PWADHD
Fixations Durations	Controls vs PWADHD
No. Blinks	Controls vs PWADHD
Pupil Diameter	Controls vs PWADHD

1.10.1 Saccades and Gaze velocity

Our eyes are never still. Small ocular movements that do not blur vision happen even when we fixate. The three different types of fixational eye movements are tremor, drift, and saccades. Small saccades are produced between one and two times per second during fixation (Martinez-Conde et al., 2013) by the optical network of the superior colliculus (SC) (e.g., Hafed et al., 2009; Hafed et al., 2013; Goffart et al., 2012). Gaze velocity also known as saccade velocity is the speed at which eyes move from one fixation point to another.

Microsaccades, which are small saccades during visual fixations, have also been associated with attention (Laubrock et al., 2010; Pastukhov & Braun, 2010; Pastukhov et al., 2013). Microsaccades are normally inhibited in response to perceptual events for a period of time depending on the stimulus characteristics and attention (Rolfs, 2009). Lower microsaccade rates correlate with a higher attentional load (Pastukhov & Braun, 2010).

Few studies have analysed microssacades, saccades and saccade velocity in PWADHD so far and there is a need for more research using these measures. In one study, a greater microsaccade rate was predicted in ADHD establishing a positive linear association between ADHD features and microsaccade rates using a prolonged fixation paradigm in which participants were asked to fixate on a target (e.g., Panagiotidi et al., 2017). Munoz et al. (2003) used a pro saccade, anti saccade task (first introduced by Hallett (1978)) and prolonged fixation task. In the pro saccade task, ADHD and control participants between 6 and 59 years of age looked first at a target stimulus when it appeared on the centre of the screen and then looked at another stimulus that appeared on the screen on the right or left side of the target stimulus. Supposing that the target stimulus appears at the centre of the screen. Then the other stimulus occurs on the right side of the target stimulus. In the pro saccade task, users had to look first at target stimuli then look at the other stimuli (on the right of the target stimuli). In the anti saccade task, users had to look first at the target stimuli then look on the left of the target stimuli (the opposite side of other stimuli). In the prolonged fixation task, participants fixated on a point. The authors hypothesised that participants with ADHD would have more difficulties suppressing reflexive saccades. In the pro saccade task, participants with ADHD showed longer response times, more reflexive saccades, lower peak velocities of saccades and longer saccade durations than participants in the control group. In the anti saccade task, they had more trouble inhibiting automatic saccades, had longer response times and greater variability. In the prolonged fixation task, people with ADHD generated more reflexive saccades.

In a CPT-test, Fried and colleagues (2014) conducted the Test of Variables of Attention (T.O.V.A.) in 22 PWADHD and 22 controls. The test consisted of a white square presented to the users with a small inner black square placed at the top for the target (22% of the trials) or at the bottom for the non-target (78% of the trials). Participants had to respond to targets by clicking the computer mouse and ignore the non-targets. Individuals with ADHD who were not taking medication displayed a greater saccade rate than controls. Recently, a review highlighted the relationship between saccades and the distribution of attention (Martinez-Conde et al., 2013). In summary, the pattern of saccadic response and rate to perceptual stimuli under attentional demands may be used to describe the attentional variables. Although these studies showed increased saccade rates in PWADHD, it was difficult to identify the factors that affected the results because of the different task conditions used in each study.

Saccades have not yet been explored in PWS. Although one study (Gkalitsiou et al., 2020) made a tentative move towards investigating saccade latencies in Adults Who Stutter, AWS and adults Who do not stutter, AWNS in a pro saccade (looking toward a target) vs anti saccade task (looking in the opposite direction to the target). Seventeen AWS and 17 AWNS were tested while eye movement measures were obtained. There was no difference between the groups. When comparing long to short distances and anti saccade to pro saccade trials, both AWS and AWNS showed higher saccade latencies. Although those results suggest no difference between groups, the authors only investigated saccade latencies while in this thesis both saccade rates and gaze velocities are reported. Since the literature suggests that attention is linked to saccadic rates and there is a shared comorbidity between PWS and PWADHD, it is therefore appropriate to investigate this measure in PWS as well as in PWADHD.

1.10.2 Fixations and fixations durations

Fixations are defined as the time the eyes remain fixed or still within an area of interest (AOI). Fixations take different forms and have different durations. The difficulty of the task is directly correlated with more frequent and prolonged fixations (longer fixation durations) (Just & Carpenter, 1980; Rayner, 2009). Dwell time is the amount of time a person's gaze remains fixed within a particular AOI, which may involve one or more fixations of different lengths. Longer dwell periods are positively correlated with task difficulty, reflecting the fact that dwell time represents the length of fixations on a stimulus as another separate signal of overall processing difficulty (Rayner, 1998). Another significant factor is the fixation number, which counts the instances during which the eyes have tried to collect information. The relationship between eye gaze and executive functions can be indicated by dwell time and the number of fixations.

Gould et al. (2001) compared children with ADHD and control children in a fixation task to determine whether eye movement data provided reliable criteria for diagnosing ADHD. Eye movement patterns showed that control children sustained focus on a fixation point that was steady for 30 seconds and then shifted back and forth on the computer screen. The children with ADHD had more trouble sustaining fixations than the control group due to their impulsive behaviour. Vakil et al. (2016) investigated group differences (controls vs PWADHD) in their fixations in a Stroop test. In this test rectangles with different colours and a text were presented one at a time. Participants gave the colour of the rectangle while not paying attention to the words. Results from this task suggested that there was a significant difference in the number of fixations and fixations durations between the groups with PWADHD having a higher number of fixations and fixations durations than controls. Fixation durations have also been linked to difficulty in maintaining fixation for a long time which is associated with ADHD traits (Falck-Ytter et al., 2020). Fixation duration is a reliable measure of attention (Papageorgiou et al., 2014). A study (Karatekin & Asarnow, 1999) compared CWADHD (N = 30) to controls (N = 26) to investigate fixation durations between groups in an image-based study. Participants looked at the images presented on the screen and answered three questions without making head movements while their eye movements were recorded. The results showed that CWADHD recorded shorter fixation durations compared to controls suggesting that attention problems are associated with shorter fixation durations.

The number of fixations and fixation duration have also been explored in PWS although no studies have explored fixations in attention tasks. Lowe et al. (2012) investigated number of fixations and fixation durations in PWS and controls. In their study, 16 AWS and 16 AWNS gave a 3-minute speech in front of an audience while eye movements were recorded. The audience members were taught how to express themselves in a positive, negative, and neutral manners. Between the stuttering and control participants, there was a significant difference in fixation time and number of fixations. Particularly, the PWS looked at any audience member for shorter periods of time (less fixation durations) in comparison to controls. Additionally, in relation to the background of the audience, the PWS had a lower number of fixations compared to controls.

Pelczarski et al. (2018) suggested different effects. In their study, 18 AWS and 18 AWNS read non-words under covert and overt scenarios. The number of fixations, dwell time, and response time were recorded. During overt reading, AWS showed significantly more fixations and longer fixation durations than AWNS. In the covert condition, while dwell-time differences were not apparent, the AWS had more fixations on the non-words than AWNS. Studies on PWS contradict each other on their results when it comes to the number of fixations and fixations durations. This may be because studies have used different tasks paradigms. The first study (Lowe et al., 2012) tested social anxiety in PWS and the second study (Pelczarski et al., 2018) tested phonological encoding. Since PWS and PWADHD share similar characteristics and inattention is linked to shorter fixation durations it is relevant to determine hypothesis around the first study (Lowe et al., 2012).

1.10.3 Blinks

The relationship between blink rates and attention raises the possibility that they have diagnostic significance for people with ADHD. For instance, it was reported that blink rates increased with prolonged periods of wakefulness (Barbato et al., 2007) and that they were negatively connected with arousal (Tanaka, 1999), presumably because inhibitory control was reduced.

There are a few studies investigating the blink rates between PWADHD and controls, and there is conflicting evidence from the research. No overall differences were observed in blink rates between controls and children with ADHD in tasks lasting between one and ten minutes (Caplan et al. 1996; Daugherty et al., 1993; Groen et al., 2015). However, in the microsaccades section of the same study, Fried et al. (2014) found that the blink rates were higher in the ADHD group, especially in the time interval around stimulus onset.

Similar to PWADHD, not much research has been done to investigate blink rates in PWS. However, one study (Conture & Kelly, 1991) tested 30 children who stutter and 30 controls in a 30-minute conversation whilst blinks were recorded. The results from this study suggested that children who stuttered produced more blinks compared to controls.

Blinks have not been extensively explored in PWS and PWADHD and therefore the analysis on blink rates between controls, PWS and PWADHD in this thesis is exploratory to address the question whether there are differences between the groups on this measure and, if so, in which direction.

1.10.4 Pupil Diameter

Pupil diameter is another ocular measure that has been linked to mental processes (Kahneman & Beatty, 1966). Pupil diameter responds to a variety of additional elements such as light in addition to its primary function. Thus, it is appropriate to record and analyse pupil diameter in VR environments because the light of the task that surrounds the user in 3D is controlled by the experimenter and is constant for all participants. Previous studies demonstrated that different cognitive demands affect pupil diameter (Kahneman & Wright, 1971; Simpson, 1968). The pupil diameter normally shows a brief increase in response to perceptual events, with a change that depends on many stimulus factors including surprise or repetition (Privitera et al., 2010). Additionally, one study reported that purposeful shifts in focus were connected to a change in pupil size (Daniels et al., 2012).

In Fried et al. (2014), besides microsaccades and blinks, the authors also examined pupil diameter. They reached to the conclusion that the pupil diameter decreased in both groups (more in PWADHD) during sessions although significant differences were absent. However, a limitation was identified in the study that might have potentially affected pupil diameter was light intrusion. Pupil size was measured during a visuospatial working memory task in ADHD and control participants by Wainstein et al. (2017) while the light effect was controlled. The task was completed by children with ADHD with and without medication. Without medication, smaller pupil sizes were recorded during the task. The findings suggested that pupil size might function as an ADHD biomarker positively correlated with attention. In Munoz et al. (2003), beside the results in microsaccades mentioned above, the authors also investigated pupil diameter. They concluded that PWADHD had reduced pupil diameter compared to controls. Whether such findings are mirrored in PWS has to be established. Despite only being investigated in PWADHD, these deficits may be generalizable to PWS since both groups have attentional deficiencies and are believed to have frontal dysfunction (Ratcliff-Baird, 2002). Thus, it is possible that pupil diameter is affected in the same way in PWS in attentional demanding tasks as in PWADHD. Table 1.3 shows findings from the literature on oculomotor measures for controls, PWS and PWADHD. Table 1.4 summarises findings from the literature for the eye measures, inconsistencies between studies and what measures will be addressed in this thesis.

Table 1.3

Past research findings in eye measures for PWADHD, PWS compared to controls. No. = number.

Study	Measures	Participants and Results
	Saccades and Gaze velocity	
Munoz et al. (2003)	No. Saccades	Controls < PWADHD
Munoz et al. (2003)	Saccade/Gaze Velocity	Controls > PWADHD
Gkalitsiou et al. (2020)	Saccade Latencies	Controls = PWS
	Fixations and fixations durations	
Gould et al. (2001)	No. Fixations	Controls > PWADHD
Vakil et al. (2016)	No. Fixations	Controls < PWADHD
Lowe et al. (2012)	No. Fixations	Controls > PWS
Pelczarski et al. (2018)	No. Fixations	Controls < PWS
Vakil et al. (2016)	Fixations Durations	Controls < PWADHD
Lowe et al. (2012)	Fixations Durations	Controls > PWS
Pelczarski et al. (2018)	Fixations Durations	Controls < PWS
	Blinks	
Caplan et al. (1996)	No. Blinks	Controls = PWADHD
Daugherty et al. (1993)	No. Blinks	Controls = PWADHD
Groen et al. (2015)	No. Blinks	Controls = PWADHD
Fried et al. (2014)	No. Blinks	Controls < PWADHD
Conture and Kelly (1991)	No. Blinks	Controls < PWS
	Pupil Diameter	
Fried et. al (2014)	Pupil Diameter	Controls > PWADHD
Wainstein et al. (2017)	Pupil Diameter	↓ PWADHD
Munoz et al. (2003)	Pupil Diameter	Controls > PWADHD

Table 1.4

A summary of findings from the literature on the eye measures including inconsistencies between studies and measures investigated in the thesis in which chapter and between which groups. Chapt. = Chapter.

	C-S	*C-A*	*C-S-A*	*Chapter/s*
NOS (Munoz et al., 2003)	NA	C < A	NA	C-S-A Chapt. 4 C-A Chapt. 6
GMV-SMV (Munoz et al., 2003)	NA	C > A	NA	C-S-A Chapt. 2 C-S-A Chapt. 4 C-A Chapt. 6
NOF (Gould et al., 2001)	NA	C > A	NA	C-S-A Chapt. 4
NOF (Vakil et al., 2016)	NA	C < A	NA	C-A Chapt. 6
NOF (Lowe et al., 2012)	C > S	NA	NA	
NOF (Pelczarski et al., 2018)	C < S	NA	NA	
FD(Karatekin & Asarnow, 1999)	NA	C > A	NA	C-S-A Chapt. 4
FD (Vakil et al., 2016)	NA	C < A	NA	C-A Chapt. 6
FD (Lowe et al., 2012)	C > S	NA	NA	
FD (Pelczarski et al., 2018)	C < S	NA	NA	
NOB (Caplan et al., 1996)	NA	C = A	NA	C-A Chapt. 6
NOB (Daugherty et al., 1993)	NA	C = A	NA	
NOB (Groen et al., 2015)	NA	C = A	NA	
NOB (Fried et al., 2014)	NA	C < A	NA	
NOB (Conture & Kelly, 1991)	C < S	NA	NA	
PD (Fried et al., 2014)	NA	C > A	NA	C-S-A Chapt. 2
PD (Wainstein et al., 2017)	NA	↓A	NA	C-A Chapt. 6
PD (Munoz et al., 2003)	NA	C > A	NA	

Note. NOS stands for number of saccades, NOMS for number of microsaccades, GMV is the gaze mean velocity, SMV is saccade mean velocity, NOF stands for number of fixations, FD are fixations durations, NOB is number of blinks and PD is the abbreviation of pupil diameter. C, S, A stands for controls, PWS and PWADHD respectively.

1.11 EEG

EEG signals from the brain are filtered into frequency bands specified in Hertz (Hz). EEG led to findings that certain frequency patterns are linked to specific brain functions. According to the German psychiatrist Hans Berger (Berger, 1929), who invented and recorded the first EEG equipment for studying the human brain, slow-frequency waves were associated with resting states, whereas quicker waves appeared in response to mental challenges (e.g., doing a math test). Low frequencies below 4 Hz (Delta waves) are related to deep sleep, while frequencies between 4 and 7 Hz (Theta) are linked to daydreaming, meditation, and reduced attentiveness. Alpha waves (8-12 Hz) emerge in relaxed/wakeful states. Fast 13 to 30 Hz waves (Beta) are associated with attention, and frequencies above 30 Hz are the Gamma waves that usually occur when the person is simultaneously processing information from different brain areas (hyper brain activity). EEG measures the electrical activity produced by the cerebral cortex (Lenartowicz & Loo, 2014), and EEG activity measures are attracting increased scientific and clinical attention (Loo & Makeig, 2012).

The EEG potentials obtained as points on the scalp reflect the amount of cortical activity resulting from the synchronous firing of large neuronal groups beneath the electrodes. Since the electrical potentials are registered on the scalp some distance from the cortical area from which the signals originate, only highly synchronous or spatially consistent electrical sources are detected in EEG signals. Recent research with high-density EEG recordings (with appropriate analysis) may provide useful, accurate information about complex aspects of cortical activity. In humans, the brain is the only organ which learns. This learning takes place via trillions of electrical signals that communicate and can be measured using EEG. The regular EEG actions are manifest in different ways, and they influence development and learning functions: functions of attention, vision, memory, executive function, speech/language, sensory/motor, and mood. Theta, alpha, and beta, either alone or relative to one another, are the frequency bands of most interest in attention (Loo & Makeig, 2012). There is no literature that compares the three groups together (PWADHD, PWS and controls) with regards to EEG but there is work that show significant differences in the measures between PWADHD and controls and PWS and controls. There is strong evidence from the literature to suggest that the frontal lobe region is responsible for cognitive skills or executive functions such as attention (Andreou & Trott, 2013; Fuster, 2008; Geurts et al., 2004; Ratcliff-Baird, 2002). On the other hand, many regions such as frontal, temporal and parietal lobes of cerebral cortex and interconnections such as cerebellum, basal ganglia and brain stem are involved in speech, making it difficult to understand the most important brain region involved in speech. This thesis is focused only on the frontal cortex of the brain since attention is measured in frontal cortex and PWADHD and PWS share comorbidities. Therefore, the measures reported in the thesis are: 1-Theta, 2- Alpha, 3 – Beta, and 4-Theta-Beta Ratio, TBR (see Table 1.5 for EEG measures tested and their corresponding chapters). The results should help us understand whether attention is involved in speech dysfluencies and whether the frontal cortex is the most important region involved in speech.

Table 1.5

EEG measures tested in the thesis including groups of participants and chapter.

Measures	Participants
Chapter IV	
Theta	Controls vs PWADHD vs PWS
Alpha	Controls vs PWADHD vs PWS
Beta	Controls vs PWADHD vs PWS
TBR	Controls vs PWADHD vs PWS
Chapter VII	
Theta	Controls vs PWADHD
Alpha	Controls vs PWADHD
Beta	Controls vs PWADHD
TBR	Controls vs PWADHD
Attention	Controls vs PWADHD

1.11.1 Theta, Alpha, and Beta

Theta, alpha, and beta, either alone or relative to one another, are the frequency bands of most interest in ADHD (Loo & Makeig, 2012). Findings have been mixed in ADHD studies involving alpha- and beta-band activities, with studies documenting decreased activity in both bands in people with ADHD compared to controls (El-Sayed et al., 2002 in a sustained attention task; Lazzaro et al., 1998 in a 2-minute resting eye open condition). Other studies reported an increase in frontal beta-band (rather than a decrease) in a subgroup of children with ADHD (Chabot & Serfontein, 1996 in a 20–30-minute eyes closed state; Clarke et al., 2011; Clarke, 2002, both studies compared participants in eyes closed resting state).

In Loo et al. (2009) EEG was used to assess cortical activity patterns under baseline and sustained attention conditions. Cortical behaviour was analysed separately for the first, middle, and last 5-minutes of the sustained attention task. In the frontal regions, patterns of activation in the alpha and beta bands differed between PWADHD and controls, indicating that increased cortical activation was associated with ADHD. In the ADHD group, it was observed that significant differences in EEG correlated to cognitive function, which were predominantly in frontal regions. Such results suggest that AWADHD may have a different neural organisation, especially in the frontal regions, resulting in a constant need for high levels of cortical activity in order to maintain sustained attention. Bresnahan and Barry (2002) compared 50 AWADHD to 50 non-ADHD participants (who were examined for ADHD traits but did not meet the diagnostic criteria) and 50 control participants. EEGs were obtained whilst participants were at rest with their eyes open. The higher theta activity was significantly different in the ADHD group from both the non-ADHD and control groups. The beta activity was similar between the ADHD and control groups, but relative theta was lower, and relative beta power was higher in the non-ADHD group compared to other groups.

Use of EEG has also been of interest in the diagnosis of speech disorders and stuttering. Strong connections have been reported between frontal regions and speech development

(Cieslak et al., 2015; Jäncke et al., 2004). Ratcliff-Baird (2002) examined theta and alpha activity differences assessed by EEG at frontal sites during concentrated attention tasks between PWS and controls. In comparison to controls, significantly more theta and lower alpha activities were reported at frontal sites for PWS. The authors proposed that neurofeedback (NF), which has proven to be effective in treating ADHD, may hold promise as a viable adjunct therapy to conventional stuttering speech therapies. EEG activity was compared during WM tasks between PWS and controls in a study by Baird (1996). In all conditions, PWS exhibited higher theta and alpha power than controls in frontal regions. It was also concluded that when attempting motor plans, PWS experience excessive sensory input, indicating stuttering may be an attention disorder.

1.11.2 Theta-Beta Ratio, TBR

Studies suggest that an increase of theta/beta ratio (θ/β,TBR) power has the potential to assess ADHD (Loo & Makeig, 2012; Monastra et al., 2001; Snyder & Hall, 2006). EEG research has attempted to define and measure ADHD, associating it with increased activity of the frontocentral theta band and increased power ratio of theta to beta bands (θ/β) during rest for people with ADHD relative to control participants (Loo & Makeig, 2012). An increase in TBR has been associated with faster reaction times and decreases in performance in adults with ADHD (Loo & Makeig, 2012; van Dongen-Boomsma et al., 2010). However, studies on TBR have been controversial (Loo & Makeig, 2012) showing that more research is needed to understand if TBR is positively correlated to impulsive and inattentiveness in ADHD group.

Jasper et al. (1938) described a slowing of EEG rhythms at front-central sensors as a predictor of irregular brain activity in a group of children with a behaviour problem identified as hyperactive and impulsive. Rajabi et al. (2019) combined cognitive WM training games conducted pre- and post-training, which involved an Integrated Visual and Auditory (IVA) performance task, and EEG was measured. The researchers determined whether the EEG theta/beta waves could give information about ADHD and whether computerised WM-training games would show an improvement in EEG activity. EEG measures showed reduced θ/β waves (WM-training normalized the pattern). Such results suggest that advances in technology provide an opportunity for interventions and that integrating cognitive WM-training games with NF may yield significant therapeutic effects on the symptomatology of brainwaves and ADHD. Other studies suggest that WM-training decreases the severity of symptoms of ADHD and increases frontal lobe function (Johnstone et al., 2017; Ten Brinke et al., 2017). Ogrim et al. (2012) did not replicate these findings when 62 CWADHD were compared to 39 controls in a go/no-go task while EEG data was recorded. The findings showed that TBR was not associated with ADHD symptoms or any cognitive performance in PWADHD possibly due to task differences.

Sengupta et al. (2019) investigated oscillatory cortical activity in AWS and AWNS during a single-word delayed reading task. The set of stimuli included a list of 80 (2 to 6 syllables long) complex, multisyllabic targets. The task included reading the target tokens aloud whilst EEG signals were being captured from the scalp. The stimuli were seen for 2 seconds each. A plus sign appeared after a pause of 0.5s (production prompt) that cued respondents to read the word immediately and aloud (within 2s). The EEG results suggested that AWS had an increase in theta-beta level as compared to AWNS. A summary of the findings from past literature on EEG measures for a comparison between controls, PWS and PWADHD is shown in Table 1.6 whereas Table 1.7 shows inconsistencies between studies and the measures investigated in this thesis.

Table 1.6

Results from past research in EEG measures for PWADHD, PWS compared to controls.

Study	Measures	Participants and Results
	Theta, Alpha, Beta	
El-Sayed et al. (2002)	Alpha	Controls > PWADHD
Lazzaro et al. (1998)	Alpha	Controls > PWADHD
Loo et al. (2009)	Alpha	Controls < PWADHD
Ratcliff-Baird (2002)	Alpha	Controls > PWS
Baird (1996)	Alpha	Controls < PWS
El-Sayed et al. (2002)	Beta	Controls > PWADHD
Lazzaro et al. (1998)	Beta	Controls > PWADHD
Chabot and Serfontein (1996)	Beta	Controls < PWADHD
Clarke et al. (2011)	Beta	Controls < PWADHD
Clarke (2002)	Beta	Controls < PWADHD
Loo et al. (2009)	Beta	Controls < PWADHD
Bresnahan and Barry (2002)	Beta	Controls = PWADHD
Bresnahan and Barry (2002)	Theta	Controls < PWADHD
Ratcliff-Baird (2002)	Theta	Controls < PWS
Baird (1996)	Theta	Controls < PWS
	Theta-Beta Ratio (TBR)	
Loo and Makeig, (2012)	TBR	Controls < PWADHD
Monastra et al. (2001)	TBR	Controls < PWADHD
Snyder and Hall (2006)	TBR	Controls < PWADHD
Sengupta et al. (2019)	TBR	Controls < PWS

Table 1.7

A summary of findings on EEG highlighting inconsistencies between studies and measures observed in the thesis (Chapt. = Chapter).

	C-S	*C-A*	*C-S-A*	*Chapter/s*
Alpha (El-Sayed et al., 2002)	NA	C > A	NA	C-S-A Chapt. 4
Alpha (Lazzaro et al., 1998)	NA	C > A	NA	C-A Chapt. 7
Alpha (Loo et al., 2009)	NA	C < A	NA	
Alpha (Ratcliff-Baird, 2002)	C > S	NA	NA	
Alpha (Baird, 1996)	C < S	NA	NA	
Beta (El-Sayed et al., 2002)	NA	C > A	NA	C-S-A Chapt. 4
Beta (Lazzaro et al., 1998)	NA	C > A	NA	C-A Chapt. 7
Beta (Chabot & Serfontein, 1996)	NA	C < A	NA	
Beta (Clarke et al., 2011)	NA	C < A	NA	
Beta (Clarke, 2002)	NA	C < A	NA	
Beta (Loo et al., 2009)	NA	C < A	NA	
Beta (Bresnahan & Berry, 2002)	NA	C = A	NA	
Theta (Bresnahan & Berry, 2002)	NA	C < A	NA	C-S-A Chapt. 4
Theta (Ratcliff-Baird, 2002)	C < S	NA	NA	C-A Chapt. 7
Theta (Baird, 1996)	C < S	NA	NA	
TBR (Ogrim et al., 2012)	NA	C = A	NA	C-S-A Chapt. 4
TBR (Loo & Makeig, 2012)	NA	C < A	NA	C-A Chapt. 7
TBR (Monastra et al., 2001)	NA	C < A	NA	
TBR (Snyder & Hall, 2006)	NA	C < A	NA	
TBR (Sengupta et al., 2019)	C < S	NA	NA	

Note. C, S, A stands for controls, PWS and PWADHD respectively.

1.12 Thesis Overview

Research suggests that PWADHD and PWS share common symptoms of attention impairments, stuttering and working memory problems. Different scales, surveys, interviews and tasks have been utilized with different statistical approaches to assess those issues between the groups (see Table 1.1 for a summary of all the studies). Results from scales, surveys and interviews indicate that many CWS (Arndt & Healey, 2001; Donaher & Richels, 2012; Druker et al., 2019; Riley & Riley, 1979; Riley & Riley, 2000) and AWS (Alm & Risberg, 2007) from their samples, had ADHD traits whilst 18% of AWADHD had a history of stuttering (Biederman et al., 1993). Attention tasks and fluency reading tasks have been utilised to investigate fluency impairments in PWADHD and attention problems in PWS. Results suggested that a high percentage of PWS have attention impairments and increased impulsivity (Andreou & Trott, 2013; Blood et al., 2007; Bosshardt, 1999; Heitmann et al., 2004; Ratcliff-Baird, 2002) whereas PWADHD produced disfluencies (Engelhardt et al., 2010; Jacobson et al., 2011; Tucha et al., 2005).

The literature suggests that working memory impairments also occur in PWS and PWADHD. NWR tests have investigated the performance of phonological working memory in both disorders. Several studies in PWS (Baddeley & Wilson, 1988; Bakhtiar et al., 2007; Byrd et al., 2015; Hakim and Ratner, 2004) suggest that NWR tasks can be reliable indicators of working memory impairments in PWS. Similar findings have been discovered in PWADHD (Marchetta et al., 2008; Martinussen et al., 2005; Rapport's, 2001) suggesting phonological working memory deficits.

The statistical approaches utilised to generate the findings have been similar across studies. Authors have drawn conclusions based on the significance of the results from descriptive statistics, independent t-tests, ANOVA and chi-square tests. There are however limitations with these tests. For example, descriptive statistics are not appropriate to draw conclusions on the significance of the results, t-tests are sensitive to small and unequal sample sizes, ANOVA cannot be reliable when data is not normally distributed and therefore non-parametric tests need to be conducted but non-parametric tests have less power than parametric tests. Chi-square tests do not show cause and effect between variables and even insignificant results can seem significant. There are many limitations that need to be taken into consideration before making analyses based on these tests. It has been suggested that these tests can be unreliable and contemporary analytic methods need to be applied to understand comorbidities between disorders (Jeon 2015; Lash et al., 2007). Recent studies have utilised NM to investigate comorbidity between disorders (Borsboom & Cramer, 2013; Cramer et al., 2010a; Epskamp et al., 2017a; Epskamp et al., 2017b) but no studies have assessed comorbidity between PWS and PWADHD in an NM approach to date. Furthermore, contemporary analytical methods have not been applied in contemporary technologies. Virtual Reality is an emerging technology that can be utilised to create controlled and safe artificial environments (Keshner, 2004). When combined with powerful eye tracking and EEG devices, precise user behavioural responses and physiological measures can be obtained. Studies have assessed oculomotor and brain activity measures alone in PWS and PWADHD.

As seen in Table 1.4 oculomotor measures such as number of saccades (NOS), gaze/saccade mean velocity (G/SMV), number of fixations (NOF), fixations durations (FD), number of blinks (NOB) and pupil diameter (PD) are the most used measures to indicate attention and fluency problems. However, there are contradictory results across studies and no study tests all those measures together and between PWS and PWADHD. While NOS and SMV are higher in PWADHD compared to controls, NOF is lower in PWADHD (Gould et al., 2001) and PWS (Lowe et al., 2012) in some studies and higher in PWADHD (Vakil et al., 2016) and PWS (Pelczarski et al., 2018) compared to controls in other studies. FD has been reported in one study as lower in PWADHD (Karatekin & Asarnow, 1999) and higher in another study (Vakil et al., 2016) compared to controls. Similarly as in PWADHD, for PWS one study suggests that FD is lower (Lowe et al., 2012) and another study suggests the opposite (Pelczarski et al., 2018). Three studies (Caplan et al., 1996; Daugherty et al., 1993; Groen et al., 2015) reached the conclusion that no difference was observed in NOB for PWADHD compared to controls while for Fried et al. (2014) NOB were higher in PWADHD and for Conture and Kelly (1991), NOB was higher in PWS. Results in PD suggest that PWADHD have lower PD when compared to controls (Fried et al., 2014; Munoz et al., 2003) and when tested only in PWADHD (Wainstein et al., 2007).

Similar to Table 1.4, Table 1.5 summarises previous studies that have investigated EEG measures in PWADHD and PWS. The focus in PWS and PWADHD have been around alpha, beta, theta and Theta-Beta Ratio (TBR) measures in frontal area of the brain because the frontal lobe has been linked to attention. Similar to eye tracking measures, studies on EEG in PWS and PWADHD contradict each other, and no study has assessed brain activity in both groups. With regards to alpha measures, PWADHD (El-Sayed et al., 2002; Lazzaro et al., 1998) and PWS (Ratcliff-Baird, 2002) have lower alpha activity compared to controls whilst other studies suggest the opposite for PWADHD (Loo et al., 2009) and PWS (Baird, 1996). No studies have investigated beta activity in PWS but for PWADHD, beta has been lower in PWADHD compared to controls as suggested by some studies (El-Sayed et al., 2002; Lazzaro et al., 1998) higher than controls in other studies (Chabot & Serfontein, 1996; Clarke, 2002; Clarke et al., 2011; Loo et al., 2009) and no difference was observed in one study (Bresnahan & Berry, 2002). Results on theta and TBR are similar across studies. Studies recorded higher theta activities in PWADHD (Bresnahan & Berry, 2002) and PWS (Baird, 1996; Ratcliff-Baird, 2002) and higher TBR in PWADHD (Loo & Makeig, 2012; Monastra et al., 2001; Snyder & Hall, 2006) and PWS (Sengupta et al., 2019) compared to controls. There was one study however (Ogrim et al., 2012) that showed no difference between PWADHD and controls in TBR activity in a sustained attention task.

This thesis investigates behavioural and physiological measures in PWADHD and PWS compared to controls in different VR and web attention tasks. The results are analysed based on several statistical approaches including contemporary analyses such as NM to investigate comorbidities between disorders including symptoms of attention, fluency and working memory problems. The focus of this thesis is to understand if there are comorbid features between the groups and what is their pattern. Since previous studies have shown conflicting results, approaches in this thesis utilize powerful devices and contemporary technologies in different attention tasks to test with precision behavioural and physiological responses.

2. Chapter 2. The Load Theory of Attention

Chapter Summary

It is important to understand which attention skill is affected in which group (PWADHD, PWS) and on what measure/s in order that the appropriate attention task can be selected by researchers to diagnose and train stuttering, attention and working memory problems. The results from Experiment 1 suggest that when the cognitive load was enhanced, PWS's performance declined, suggesting that auditory selective and divided attention tasks can be used to assess stuttering. Training PWS in the Load Theory of attention would train their cognitive processing capacity and, subsequently, their speech. Such findings were supported in Experiment 2 in which performance of controls was compared to PWS and PWADHD in audio, visual and audio-visual domains. Results suggested that for the performance decrease under high load in selective attention tasks, audio was more affected in PWS, whereas audio and audio-visual were affected in PWADHD. The results from NM (network modelling), indicated that measures of accuracy and gaze velocity in selective attention tasks were similar in controls and PWADHD but different from PWS suggesting that PWS and PWADHD are not comorbid based on these measures. The findings of Experiment 2 support the idea that compared to controls, PWADHD and PWS have symptoms of attention, stuttering and working memory problems but further NM analysis are conducted in Chapter 8 to understand whether such symptoms are comorbid in PWS and PWADHD.

2.1 Introduction

Literature indicated that in PWS, most of the studies assessed attention in PWS in rating scales and surveys (see Table 1.1). Studies that examined attentional abilities in PWS by utilizing attention tasks were limited in several ways including that most of these studies tested attentional abilities in the visual domain. Furthermore, attentional functioning in PWS has not been assessed in terms of the popular Load Theory of Attention in the auditory domain which assesses attention of participants when they operate under conditions where perceptual load in the primary task is varied. A load theory paradigm was chosen and investigated for this purpose with PWS in Experiment 1.

The attentional mechanism is described as a limited capacity system and there are different views concerning what constitutes an attentional capacity. One view assumes that all sensory modalities share central attentional resources (Broadbent, 1952) with different modalities drawing from the same attentional capacity. Attention may be modality-specific due to the differences between the auditory and visual perception systems. However, studies have provided evidence with tasks that draw on resources from different modalities (Allport et al., 1972; Wickens, 1981) supporting the notion of a supramodal attentional mechanism.

Whereas most studies on attention in PWS have focused on audition, the majority of studies on PWADHD have focused on assessing attentional performance in the visual domain (Berwid et al., 2005; Stern & Shalev, 2013; Tucha et al., 2009). The latter usually report that PWADHD perform significantly worse than controls. Aylward et al. (2002) examined attentional performance in PWADHD on a sustained CPT with standardised visual and auditory tasks in conjunction with each other. Participants (634 children with ages 5-17) clinically diagnosed with ADHD were required to press a button if number 1 was followed by number 9 in the visual task and when the numbers were heard whilst visual stimuli were not visible in the auditory task. CWADHD performed worse in the auditory task and were correct more often with less commission errors as age increased. Draeger et al. (1986) assessed CWADHD (predominantly hyperactive) and controls in visual and auditory tasks. No significant differences were observed between groups in either task. However, the focus of the study was to assess performance of children when an experimenter was present or absent. Furthermore, the tasks involved only minimally interacting with the experimenter who only monitored the children, their vocalization and body movements. Therefore, the results of this investigation were limited by the use of incompatible visual and auditory attentional tasks. Lin et al. (2014) assessed audio and visual sustained attention in 50 CWADHD, and 50 controls in CPT, and in T.O.V.A. tasks. Participants responded to targets while inhibiting a response to the non-targets. The results showed that CWADHD had poorer performance in the visual domain compared to the audio domain contradicting Aylward et al. (2002). Also, CWADHD performed significantly worse in the visual domain compared to their typically developed peers whilst in the auditory domain no difference between groups was observed.

Studies with PWS have assessed either the audio or the visual domain and compared results to controls. In the visual domain, Blood et al. (2007) failed to find a significant difference between PWS and controls in a visual sustained attention task in which children pressed a button for any letter apart from letter X. Doneva et al. (2017) conducted a study between 50 age-gender matched PWS and controls in test of everyday attention (TEA) which consists of eight subtests including sustained attention, selective attention (visual and auditory), divided attention (dual task) and attentional switching. In contrast to Blood et al (2007), this study showed a significant difference in visual selective and visual-audio divided attention tasks between groups with PWS performing worse. There was a trend for poorer performance of PWS in the auditory selective attention task although not significant. Such results suggest that stuttering is affected in certain attentional tasks and attentional dysfunction is at the root of this disorder.

Studies show contradictory results, but this can be due to the attentional task chosen. There are four main different types of tasks to assess attentional ability: 1-selective attention, 2-sustained attention, 3-attentional switching, and 4-divided attention (the entire set is explored in detail in Chapters 5, 6 and 7). Different types of attention tasks might show different results across sensory modalities for PWS and PWADHD and across task. Studies are also limited by the statistical approaches conducted to understand which modality is affected in PWS and PWADHD. Hence, Experiment 2 assessed differences in behavioural and physiological measures in controls, PWADHD and PWS in Fairnie's load task in VR scenarios using audio, visual and audio-visual modalities. NMs were conducted to understand modality and group differences.

2.2 Experiment 1

Previous research showed that PWS have attentional problems. Lavie et al.'s (2004) load theory of attention provides a theoretical basis for investigating this as it addresses how to focus attention and ignore distractions up to a point where load exceeds perceptual capacity. Tasks with low load leave spare attention capacity that allows attention shifts towards distractors in secondary tasks. On the other hand, when the load in a task is high, the available perceptual capacity, and the perception of distractions is reduced or even eliminated (Forster et al., 2014). Many papers support the theory by suggesting that an increase in perceptual load results in reduced distractor processing (Fairnie et al., 2016; Forster et al., 2014; Lavie et al., 2014; Lavie, 2005).

Fairnie et al. (2016) developed an auditory load task and applied it to 20 controls. An array of stimuli was presented in auditory space (participants heard a dog or lion sound as well as several distractor animals sounds appearing simultaneously at random points in space). Load was varied by including different numbers of distractors for each level (four levels were used). On half of the trials, a critical stimulus (CS) for the second task (a car) was presented concurrently. The primary task was to decide which of two possible targets (a dog or a lion) was present in the array. The secondary task was to assess whether the CS (car) was presented. The results showed that higher loads led to increased reaction times (RTs) and decreased accuracy for the primary task, and decreased detection sensitivity (DS) for the secondary task. These findings indicated that the load theory applies in the auditory domain.

Experiment 1 tested whether there were differences between PWS and controls groups on accuracy, RTs and DS as load increased in an implementation of this same paradigm. It was predicted that as load level increased, accuracy in the primary task should decrease for both groups, and PWS should be less accurate than controls. As load level increased, RTs in the primary task should increase for both groups, with PWS having higher RTs than controls. DS in the secondary task should decrease as load level increased for both groups with lower DS in PWS compared to controls. Based on the prediction that PWS have attention problems, the hypotheses were: H1: Accuracies will decrease as load level increases and there should be differences between controls and PWS. H2: RT will increase as load level increases and there should be differences between controls and PWS. H3: DS will decrease as load level increases and there should be differences between controls and PWS.

2.3 Methods

2.3.1 Participants

Twenty-eight controls (Mean age: 28.14, SD: 10.18, 13 Females and 15 Males) volunteered through the UCL SONA participant pool, and the majority were therefore students. Twenty-five PWS (Mean age: 31.08, SD: 9.78, 6 Females and 19 Males) from self-help groups in London and Manchester volunteered. Participants in both groups were matched for age and gender. UCL Research Ethics Committee approved the study (6252/002). All participants were given an information sheet and signed an informed consent form. Control participants were given 1 credit through UCL SONA and were told they could withdraw from the study at any time. With 25 PWS and 28 Controls, power analysis showed that with a large effect size of 0.8, there is a 95% chance of detecting an actual effect in repeated measures ANOVA within-between interactions.

2.3.2 Design

A mixed design was used, with the independent variables as the four load levels (indicated in Table 2.1; within-participants) and the type of the participant (Controls and PWS; between-participants). The dependent variables were: 1. and 2. Accuracy and RT in the primary task, 3. DS of the critical stimulus in the secondary task.

2.3.3 Materials

A program was set up on the Unity[2] platform using C# programming language (link: https://fjordakazazi.github.io/AuditoryAttentionTrainingWebApp/).Participants were supplied with a pair of Optimus Nova 626 headphones. All sounds lasted for 100ms and had 10ms fade-ins and fade-outs. Sounds were positioned spatially around participants (Figure 2.1) by varying interaural time difference (ITD) and interaural amplitudes difference (IAD; see Appendix A for an explanation of ITD and IAD). Data were stored in an excel file. Stimulus parameters for each trial were 0/1 for Dog/Lion, 1-4 for load level, and 0/1 for participant type. Response parameters for each trial were 0/1 for dog/lion, 0/1 for car present/absent, and RT for the dog/lion response. Accuracy, RT and DS were examined across load levels. RT data were cleaned before analysis by excluding incorrect trials and RTs > 3 sec. For DS analysis, responses from the secondary task were coded as hit, miss, correct rejection, and false alarm. Non-parametric DS analyses (Zhang & Mueller, 2005) were used because the hit and false alarm rates were not normally distributed. The formula used to calculate DS is given in Figure A2.1 in Appendix A.

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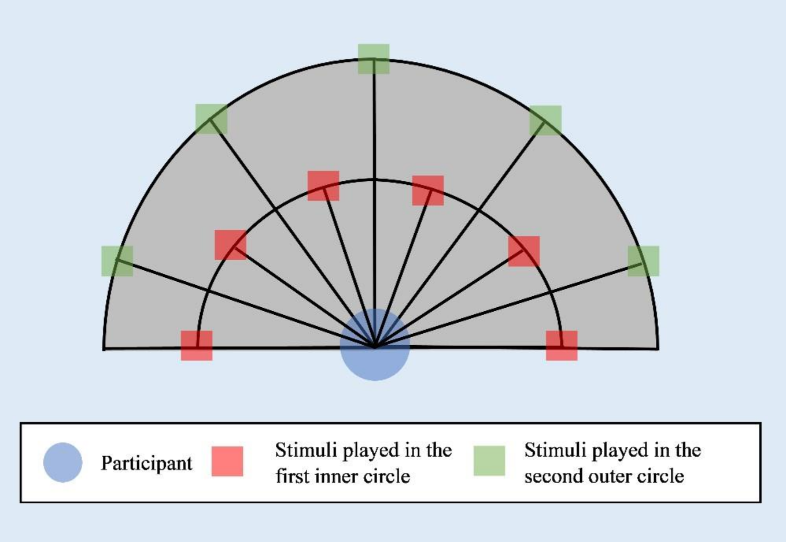
[2] Unity platform for developing applications: https://unity.com/

Figure 2.1

Stimulus positions spatially distributed relative to the participant. Participant is positioned in the middle (blue circle) and the auditory stimuli are presented in a 180-degree angle around the user. In the first, inner, circle (red squares) target and non-target stimuli were played. In the second, outer, circle (green squares), the critical stimulus was played. All sounds on outer ring were 6db lower in level compared to sounds on the inner ring. All stimuli were presented in a random and counterbalanced order.



2.3.4 Procedure

Fairnie's paradigm was adopted. Participants opened the program on their own computers/PCs at their homes while the experimenter monitored them through the laptop webcam. Data were automatically stored in a google drive folder. Participants made two responses to each auditory scenario. In the primary task, participants indicated whether they heard a dog or a lion (each of these occurred 50% of the time in random order) while other animal noises were played simultaneously. In the secondary task, participants indicated whether or not they had heard a car sound (CS) whilst they performed the first task. Task trials consisted of 72 trials each at the four task blocks (Table 2.1). As the levels increased, the number of distractors (animals) increased. Simultaneously in the scenarios, the car sound (the CS) occurred 50% of the time (25% each on dog and lion trials) in random order. Participants pressed one of two keys to indicate whether or not they heard a dog (key Z) or lion (key X) sound and then a 2nd set of keys (key N/M) to indicate whether or not a car had occurred. After the instructions, participants played all sounds and their combinations in practice blocks. Practice blocks were conducted at four levels of distractors (similar to the way shown in Table 2.1). Participants were allowed to take a rest after 36 trials of the test blocks.

Table 2.1

Load levels and the number of targets and distractors shown for each level.

LOAD 1	LOAD 2	LOAD 3	LOAD 4
One Target	One target + One Non-Target	One target + Three Non-Targets	One target + Five Non-Targets

2.4 Results

2.4.1 Experiment 1 Results

Table 2.2

Descriptive Statistics for accuracy, RT and DS.

	Outliers	Shapiro-Wilks	Levene's Test	Independent t-test	Mann-Whitney U test
H1: Accuracy	None	$p < 0.01$	$p = 0.630$	$p = 0.003$	$p = 0.002$
H2: RT	25-30% of the data were excluded	$p = 0.049$	$p = 0.77$	$p = 0.020$	$p = 0.038$
H3: DS	Some outliers were cleaned	$p < 0.01$	$p = 0.06$	$p = 0.019$	$p < 0.001$

Table 2.3

Hypothesis and results for accuracy, RT and DS for audio condition.

	Repeated Measures Anova			**Hypothesis Met?**
	Levels* (1 vs 4)	**Groups***	**Groups*Levels**	
H1: Accuracies will decrease as load level increases and there should be differences between controls and PWS.	$p < 0.001$	$p = 0.008$	$p = 0.149$	**Accepted**
H2: RT will increase as load level increases and there should be differences between controls and PWS.	$p = 0.001$	$p = 0.04$	$p = 0.60$	**Accepted**
H3: DS will decrease as load level increases and there should be differences between controls and PWS.	$p = 0.003$	$p < 0.001$	$p = 0.337$	**Accepted**

H1: Accuracies will decrease as load level increases and there should be differences between controls and PWS.

Descriptive statistics (Table A2.1 in Appendix A) showed that overall, controls were more accurate than PWS, and correct responses decreased as the load level increased for both groups. Data were checked for outliers using box and whiskers plots (none found). Data were checked for normality. Shapiro-Wilks showed that data was not normally distributed ($p < 0.01$) and Levene's Test of Equality of Variances was met ($p = 0.630$). Independent samples t-test ($t(210) = 2.995$, $p = 0.003$) and Mann-Whitney U test ($p = 0.002$) showed that groups differed significantly (Table 2.2). Accuracy data are shown in Figure 2.2 separately for the two groups at the four load levels (abscissa). Accuracy decreased as load increased for both groups, with PWS showing bigger drops. A four (load level) by two (type of participant) repeated-measures ANOVA with a Greenhouse-Geisser correction was conducted to investigate the impact of groups and load levels on accuracy (Table 2.3). There was a significant main effect within levels $F(2.1,104.6) = 66.246$, $p< 0.001$, $\eta p2 = 0.565$. This showed that as levels increased, the accuracies of both groups decreased significantly. There was also a significant main effect of groups F(1,51) = 7.730, p = 0.008, $\eta p2$ = 0.132, suggesting that mean accuracy differed significantly between PWS and controls. These findings support H1. However, there was no interaction of groups*levels for the dependent variable accuracies F(2.1,104.6) = 1.934, p =0.149, $\eta p2$ = 0.037, suggesting that mean accuracies between groups did not vary differentially as a function of the level.

H2: RT will increase as load level increases and there should be differences between controls and PWS.

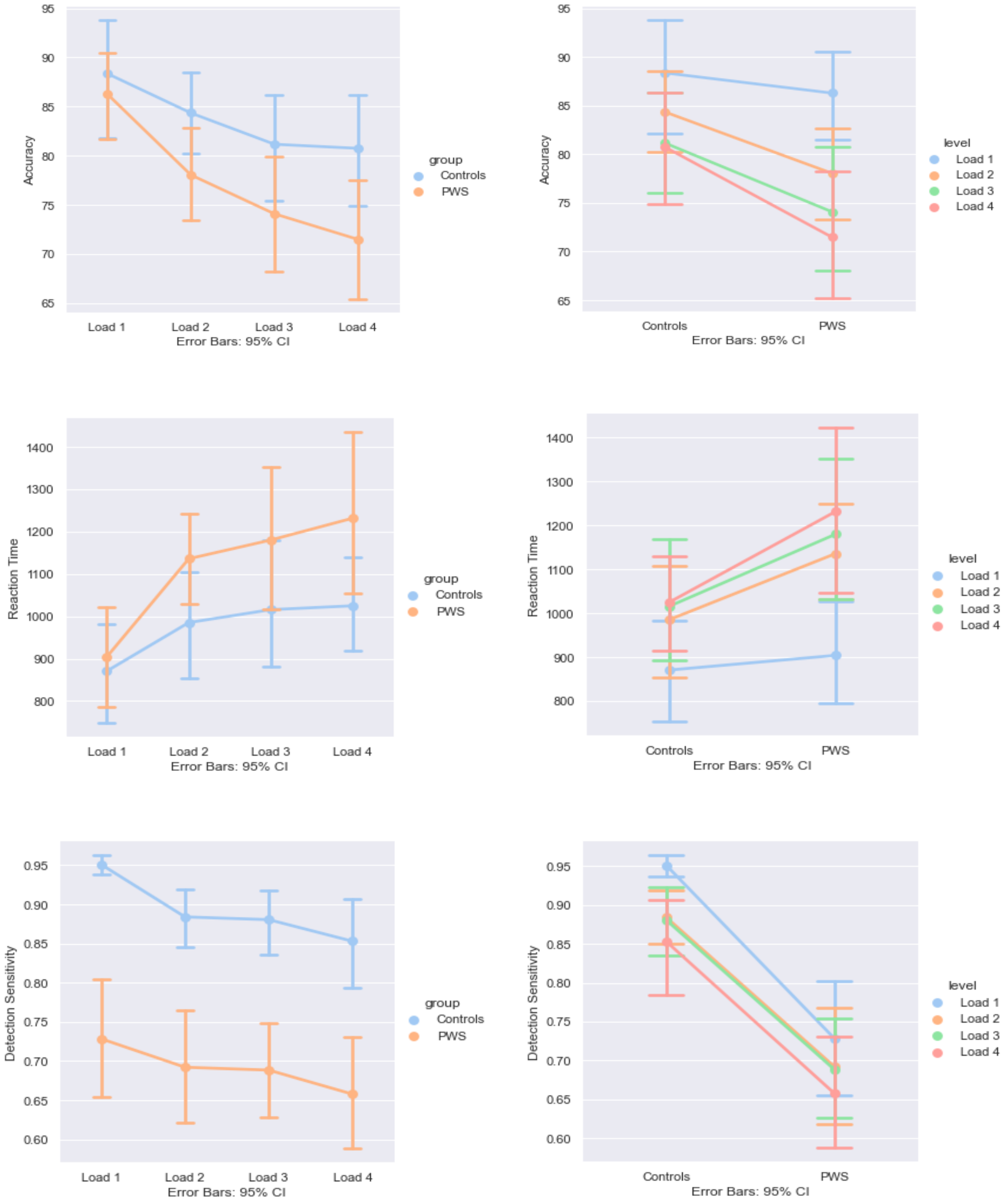
No participant data were missing, but approximately 25-30% of the RTs > 3 seconds were excluded after data cleaning. From the descriptive statistics, RTs increased in both groups as load-level increased, and PWS were significantly slower than controls (Table 2.2 provides more information and Figure 2.2 provides a visual representation of the results). The repeated measures ANOVA (Table 2.3) showed that there was a significant main effect on RTs across levels. This indicated that as the load level increased, RTs increased significantly. There was a significant main effect of groups which showed that RT of PWS was significantly longer than controls. Hence, H2 was supported. However, there was no interaction of levels throughout groups on RT. This suggests that RTs were not impacted by levels at different rates for the two participants groups.

H3: DS will decrease as load level increases and there should be differences between controls and PWS.

The box plot confirmed that were some outliers which were cleaned from the data. The descriptive statistics showed that DS decreased in both groups as load levels increased (see Figure 2.2 for a visualisation of the results). Results (Table 2.2) confirmed that groups differed significantly. There was a significant difference on DS across levels (Table 2.3) and a significant main effect of groups showing that DS differed significantly across groups. Hence, H3 was accepted. The interaction between groups and levels was not significant for DS as with RT and accuracy.

Figure 2.2

Mean accuracy (top row), RT (middle row), DS (bottom row) between PWS vs controls at each load level. Line graphs with error bars show mean accuracies throughout load levels (left line graph in each row) and groups (right line graph in each row). Error bars in the last row represent ± 2 Standard Error [SE].



2.5 Discussion

Selective attention tasks under high load levels in the Fairnie et al. (2016) task have been investigated previously but not for PWS. In this experiment, a selective attention task was investigated in an auditory dual-task and the performance of PWS and controls was compared on accuracy, RT (primary task) and DS (secondary task). Since data in the measures tested was not normally distributed, as assessed from Shapiro Wilks, results from both parametric (Independent t-test) and non-parametric tests (Mann-Whitney U test) were reported. The results indicated that as load levels in the primary task increased, accuracy for the PWS significantly decreased, and there was a significant difference between the groups. Furthermore, as the load level in the primary task increased, RTs significantly increased, with PWS being significantly slower than controls. As load level increased, DS in the secondary task significantly decreased and was significantly lower for PWS. Finally, DS showed that load theory is supported because a higher perceptual load was followed by a reduction in sensitivity for detecting the CS in the secondary task. These results are consistent with previous studies that have suggested that PWS have attentional issues (Alm & Risberg, 2007; Bental & Tirosh, 2007; Donaher and Richels, 2012; Druker et al., 2019; Healey & Reid, 2003). The performance of PWS was impaired when the cognitive load increased, indicating that auditory selective attention tasks can be utilized for the diagnosis and potentially for treating stuttering. No group by load interactions were observed, indicating that levels did not affect accuracy, RTs and DS at different rates for controls and PWS.

Although the results in Experiment 1 are promising, one limitation of this experiment was testing the hearing ability of participants other than self-report. As the hearing ability was not measured for this experiment, this can impact the results and be a confound in the analysis. Since participants conducted this study in their homes, testing for hearing was not possible. Participants chose the most comfortable audio level of the program as an automated audiometry solution. After the experimental trials, participants conducted a control block with 64 trials in which they were asked to focus on detecting only the CS (car stimuli) and ignore targets (dog bark or lion roar). This block was vital to ensure that an error in detecting the CS in the main trials was due to auditory load and not underlying inability such as lack of hearing the CS. Results from the control blocks in detection sensitivity of CS showed that all participants detected CS with 90% accuracy and no differences were observed between set sizes indicating that the hearing ability of participant did not have an impact on the results of experimental trials. Testing participants' hearing with an audiometric assessment was, however, included in the next experiments.

This experiment confirmed the attention issue in PWS. Even though there were main effects in the hypothesis tested, there were no interactions throughout the levels between groups. This suggests that differences on dependent variables accuracies, RTs and DS between groups did not vary across levels. Could this be the case only in the auditory domain, or would this also be the case in the visual domain? Also, if only two load levels are included, one without distractors (low load) and another with all the distractors (high load), would we get an interaction between levels and groups on the dependent variables? To address these questions, a related paradigm was developed in a VR environment in Experiment 2 to test whether similar results would be achieved in PWADHD as well as in PWS in audio, visual, audio-visual domains and whether behavioural and physiological measures vary across conditions under low and high load.

2.6 Experiment 2

Fairnie et al. (2016) suggested that the load theory of attention dual tasks based on selective attention (focus on a target while ignoring distractions) can assess attentional limitations and lower performance is expected under high load. To date, the load theory of attention has not been assessed in PWS and PWADHD in either auditory or visual domains or both domains combined except that, in Experiment 1 the load theory of attention was explored in the auditory domain and then only in PWS. Using both visual and audio tasks would yield more information than using only one as suggested by Doyle et al. (2000). It is therefore necessary to investigate the performance of PWS and PWADHD (correct/incorrect responses, RTs) in this task paradigm in all modality conditions as well to understand whether groups differ in the domains and across load levels. Since the visual modality is tested, eye movement measures can be examined as well. Only gaze velocity and pupil diameter were investigated due to the limited amount of measures available from the eye tracker hardware. In previous studies, both measures have been assessed in PWADHD in which lower gaze velocities (Munoz et al., 2003) and lower pupil diameter (Fried et al., 2014; Munoz et al., 2003; Wainstein et al., 2017) have been linked to higher impulsive and poorer attention abilities in PWADHD (see Table 1.4). However, no studies have assessed these measures in PWS. A network model is used using these measures in PWS to reach to clear conclusions as to whether PWADHD and PWS share comorbid psychological measures. The load theory of attention paradigm was investigated in a VR environment in three modality domains (audio, visual, audio-visual) and behavioural and physiological measures were obtained and analyzed between the groups.

In Experiments 2a comparisons were made to determine whether there were differences in ADHD Self Report Scale (ASRS), Stuttering Severity Instrument (version 3; SSI-3), and Universal Non-Word Repetition (UNWR) between the groups to determine whether groups differed in attention, speech and WM abilities. In Experiment 2b, three presentation modalities were examined in VR environments to determine whether participant groups differed in their accuracy, RTs, DS, gaze velocity and pupil diameter.

The below predictions were made based on comorbid symptoms between PWS and PWADHD in a NM analysis. In Experiment 2a, UNWR scores should be lower if WM acts similarly to attention, whereas ASRS and SSI-3 scores should be higher in the stuttering and ADHD group compared to controls. The latter prediction was based on literature that suggests that ADHD is comorbid with stuttering (Ajdacic-Gross et al., 2018; Ajdacic-Gross et al., 2009;

Blood et al., 2003; Healey & Reid, 2003) and WM deficits (Rapport et al., 2001; Tillman et al., 2011). In Experiment 2b, controls should have better performance with higher accuracies in the primary task, shorter RTs in the primary task and higher DS in the secondary task compared to participants with attention problems and who stutter, as found when PWS and controls were compared in Experiment 1.

Based on the prediction that PWS and PWADHD share attentional problems in NM, the hypotheses in Experiment 2a were: H1: Groups should differ from each other on their ASRS scores. H2: Groups should differ from each other on their SSI-3 scores. H3: there should be a difference between the groups in the WM scores.

Considering that PWS and PWADHD are both predicted to have attentional issues in NM, the hypotheses for Experiment 2b for PWADHD and PWS compared to controls were as follows: H4: Accuracies should decrease under high load, and there should be differences between groups and across modality conditions. H5: RTs should increase under high load, and there should be differences between groups and across modality conditions. H6: DS should decrease under high load, and there should be differences between groups and across modality conditions. H7: There will be differences in gaze velocity under high load, and there should be differences between groups (to test whether results are consistent with those in Munoz et al., 2003 or to resolve discrepancies otherwise) and across modality conditions. H8: Pupil diameter should decrease under high load, and there should be differences between groups (similarly as is in Fried et al. (2014), Munoz et al. (2003) and Wainstein et al. (2017)) and across modality conditions.

2.7 Methods

2.7.1 Participants

Twenty-two controls (Mean age: 29.86, SD: 7.453, 13 Females and 9 Males), ten PWADHD (Mean age: 26.40, SD: 3.748, 2 Females and 8 Males) in which one was clinically diagnosed with ADHD, the rest were assigned to the group based on reporting attention and/or hyperactive symptoms as per DSM-5 and five PWS diagnosed with stuttering (Mean age: 38.25, SD: 17.443, 2 Females and 3 Males) were recruited from the UCL Sona system. One male participant was excluded from the analysis as he could not complete the experiment, therefore 4 PWS were included in the study. All participants had normal hearing (assessed using UCL Audiometer software) and normal or corrected vision (assessed by an online visual acuity test). UCL Research Ethics Committee approved the study (6252/002). Participants were paid £15 for their time, and transport costs were covered for participants who made a special journey. Information sheets and consent forms were given before the experiment, and participants could withdraw at any time. Power analysis showed that with a large effect size of 0.8, there is a 93% chance of detecting an actual effect in repeated measures ANOVA within-between interactions.

2.7.2 Design

For Experiment 2a, participants completed the ASRS questionnaire, read out paragraphs from the SSI-3 manual while they were video recorded and completed the online version of UNWR[3] while the experimenter scored the task. The online version was developed according to the original version[4] with the same audio files provided by the authors to facilitate the procedure. The between-participants factor was the participant group (controls vs PWS vs PWADHD). The dependent variables were: ASRS, SSI-3 and UNWR.

In Experiment 2b, a mixed design was used where the within-participant factors were levels (the two loads) and modality conditions (visual stimuli only, auditory stimuli only, visual and audio together). The between-participants factor was the participant group (controls vs PWS vs PWADHD). The dependent variables were: Accuracy and RT in the primary task, DS of the critical stimulus in the secondary task, gaze velocity and pupil diameter.

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[3] The online version of UNWR can be found here: https://fjordakazazi.github.io/WM/

[4] The original version of UNWR can be found here: http://fistproject.org/resources/

2.7.3 Materials

The experiment was programmed in C# and Unity. HTC Vive Pro[5] Virtual Reality headset was used with a Pupil Labs[6] add-on eye-tracker for VR. A calibration step was conducted to map the gaze coordinates from the pupil for measuring the participants' gaze. All stimuli (3D objects) and the environment (a field and a blue sky) were purchased from Unity Asset Store[7], and all sounds corresponding to all stimuli were downloaded from the 'Apple Loops' library of pre-recorded clips. Stimuli consisted of a dog, lion, chicken, rooster, crow, cow, duck, and a car. Visual stimuli were spatially separated and positioned randomly within a 90-degree angle of view. Interaural amplitudes and time differences manipulated the position of sounds across the 90-degree space. Participants were exposed to each stimulus for 250ms with 10ms fade-ins and fade-outs. The duration of stimuli in all conditions was adjusted to 250ms for audio and/or visual targets since visual targets required this exposure time. When audio-visual (AV) stimuli were presented, auditory (A) and visual (V) locale corresponded. Data were stored securely into CSV file in the computer. Accuracy, RT, DS and oculomotor measures were examined across load levels and conditions. Eye tracking data were cleaned by selecting only high confidence values following the tutorial provided by Pupil Labs' eye tracking company[8].

2.7.4 Measures

Adult ADHD Self-Report Scale Screener, (ASRS; Ustun et al., 2017)

At present, there is no specific tool available to diagnose ADHD. A formal diagnosis of ADHD is determined based on data gathered from clinical evaluations and classification schemes. The two main diagnostic classification systems of ADHD are the DSM-5 (Diagnostic and Statistical Manual of Mental Disorders) and the ICD-10 (International Classification of Mental and Behavioural Disorders). These systems can be applied independently or in combination with a

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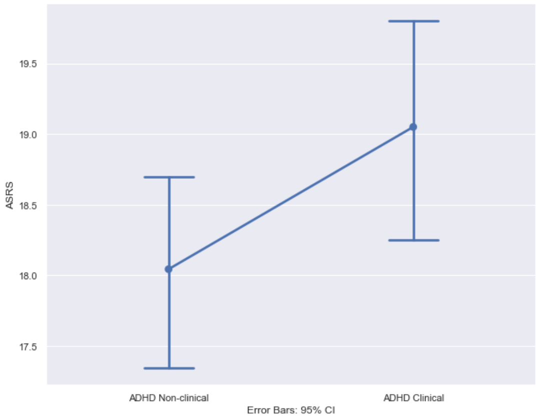
[5] HTC Vive Pro VR headset: https://www.vive.com/uk/product/vive-pro-full-kit/
[6] Pupil Labs eye tracker for HTC Vive Pro VR headset: https://pupil-labs.com/products/vr-ar/
[7] Unity Asset Store: https://assetstore.unity.com/
[8] Tutorial on data collection and filtering from pupil labs: https://docs.pupil-labs.com/core/software/pupil-player/

variety of assessment scales. The World Health Organization created the ASRS v1.1 symptom checklist, which has 18 questions based on the DSM-4 (Kessler et al., 2005). From the 18 questions, 6 that were the most accurate predictors of ADHD were included in the ASRS v1.1 screening scale. The ASRS v1.2 screening scale was an updated version of ASRS v1.1 in which 4 of the 6 questions were revised based on DSM-V instead of DSM-IV and 2 non-DSM (Ustun et al., 2017). ASRS (Ustun et al., 2017) was developed using a machine learning algorithm-based diagnosis on responses to six items for participants to complete using rules of optimal integer scoring. The scale exhibited a high cross-validated correlation with DSM-5. The assessment tool is short, easy to score and can correctly evaluate patients. Compared to the complete 18-item ASRS, the 6-item ASRS was reported to have higher sensitivity (91.4%), specificity, and classification accuracy, and a lower likelihood of misclassifying a typical adult with ADHD (Hines et al., 2012). Each item complied with the DSM-5 criteria (American Psychiatric Association, 2013). ASRS is not intended to provide a clinical ADHD diagnosis but rather to further evaluate ADHD in participants (Caci et al., 2014).

In most chapters there have been individuals with a clinical diagnosis of ADHD, individuals who have self-reportedly ADHD and those who report symptoms of ADHD. ASRS scores were utilized to assess symptoms of the controls, PWADHD and PWS as a dependent variable. To determine whether there is a significant difference between individuals with a clinical ADHD diagnosis (N = 20) and those with a non-clinical ADHD diagnosis (N = 23; participants indicated that they have inattentive and/or hyperactive symptoms and they scored high on the ASRS scale), ASRS scores were compared between the two groups (see Figure 2.3). No significant difference between the two groups was found as assessed by the parametric Independent Samples T-test t(41) = -1.864, p = 0.070 and the non-parametric Mann-Whitney U test (p = 0.070). The assumption for the equality of variances was met. Although the clinical group had on average higher ASRS scores, groups did not differ significantly from each other indicating that the non-clinical ADHD group can be reported as PWADHD.

Figure 2.3

A comparison between the ASRS scores of participants with a clinical ADHD diagnosis and those who reported symptoms of ADHD.



Stuttering Severity Instrument version 3, (SSI-3; Riley, 1994)

Riley's SSI-3 instrument was used to assess the severity of stuttering and other stuttered speech examinations. Participants were asked to read out loud two short paragraphs while they were video recorded, and three parameters were analysed: 1) frequency of stuttering; 2) duration of chosen stutters; 3) physical concomitants.

Universal Non-Word Repetition Test[9], (UNWR; Howell et al.'s 2016)

This test is used to assess WM. In UNWR, participants listen to different non-words and repeat them out loud. It has 4 sets ranging from two to five syllables with 12 non-words per set. There are two practice non-words for each set size. Participants must correctly pronounce the non-words to proceed to the next set. The points achieved on each set were then added together. An online version of the original UNWR that was used in this experiment[10].

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[9] The original version of UNWR can be found here: http://fistproject.org/resources/

[10] The online version of UNWR can be found here: https://fjordakazazi.github.io/WM/

2.7.5 Procedure

The procedure was similar to that in Experiment 1. Here the task was implemented in a VR environment in a laboratory at UCL, and visual and audio-visual conditions were included as well as the audio condition. Also, there were only two load levels in each condition (either no distractors or five distractors consisting of all the animals (see Table 2.4). The experimenter first completed the demographics information for the participant and then ran the application. Participants completed a calibration process to correctly determine gaze positions from the eye tracker[11]. Then participants were calibrated in the VR environment by focusing on a fixation point. After this step, participants read the instructions and completed four practice trials for each load level. In the main blocks, participants selected the appropriate icon displayed in the VR environment using the trigger button from the VR controller after the stimuli appeared. Task consisted of 20 trials for each level in each condition.

Table 2.4

Load levels and the number of targets and distractors showed for each level.

LOAD 1	**LOAD 4**
One Target	One target + Five Non-Targets

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[11] Calibration step was conducted based on Pupil Labs User Guide: https://docs.pupil-labs.com/core/

2.8 Results

2.8.1 Experiment 2a Results

Table 2.5

Descriptive Statistics, hypothesis, and results for ASRS, SSI-3, UNWR.

	Outliers	Shapiro-Wilks	One Way ANOVA	Kruskal Wallis	Hypothesis Met?
H1: Groups should differ from each other on their ASRS scores.	None	p = 0.014	p < 0.001	p < 0.001	**Accepted**
H2: Groups should differ from each other on their SSI-3 scores.	Some outliers were removed	p < 0.001	p < 0.001	p = 0.019	**Accepted**
H3: There should be a difference between the groups in the WM scores.	One outlier was removed	p = 0.009	p = 0.003	p = 0.002	**Accepted**

H1: Groups should differ from each other on their ASRS scores.

Although no outliers were detected, data was not normally distributed F (36) = 0.922, p = 0.014. Descriptive statistics (Table A2.2 in Appendix A) and Figure 2.4 showed that ASRS was highest in the PWADHD group, followed by PWS and controls. Similar to Experiment 1, parametric (One Way ANOVA) and non-parametric tests (Kruskal Wallis) were conducted. Groups differed significantly on ASRS scores on both parametric F(2, 33) =12.079, p < 0.001, and the non-parametric tests (p < 0.001, see Table 2.5). Therefore, H1, that there should be a difference between the groups in ASRS scores, was accepted. Specifically, the Tukey post-hoc test showed that the groups that differed significantly were Controls vs PWADHD (p < 0.001) and PWADHD vs PWS (p = 0.049).

H2: Groups should differ from each other on their SSI-3 scores.

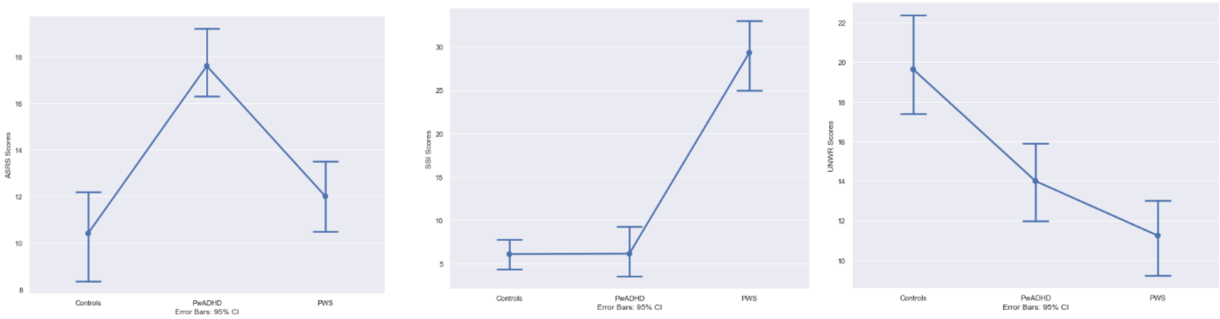
Descriptive statistics showed that SSI-3 was highest in the PWS group followed by PWADHD and controls (Figure 2.4 shows a visual representation of the results). Groups differed significantly on SSI scores (see Table 2.5 for more information). Therefore, H2 was accepted. Specifically, the Tukey post-hoc test showed that the groups that differed significantly were Controls vs PWS ($p < 0.001$).

H3: There should be a difference between the groups in the WM scores.

Descriptive statistics and Figure 2.4 showed that WM scores were the lowest (poorest) in PWS, followed by PWADHD. There was a significant difference on UNWR scores (see Table 2.5). Therefore, H3 was accepted. Tukey post-hoc test showed that the groups that differed significantly were Controls vs PWADHD ($p = 0.026$) and Controls vs PWS ($p = 0.015$).

Figure 2.4

Mean ASRS (left graph), SSI-3 (middle graph) and UNWR (right graph) scores obtained per controls (first x - axis in each graph), PWADHD (second x - axis in each graph) and PWS (third x - axis in each graph). Error bars represent ± 2 Standard Error [SE].



2.8.2 Experiment 2b Results

Table 2.6

Descriptive Statistics for accuracy, RT, DS, Gaze Velocity and Pupil Diameter.

	Outliers	**Shapiro-Wilks**	**One Way ANOVA**	**Kruskal Wallis**
H4: Accuracy	None	$p < 0.001$	$p = 0.033$	$p = 0.038$
H5: RT	Some outliers were removed	$p < 0.001$	$p = 0.852$	$p = 0.970$
H6: DS	None	$p < 0.001$	$p = 0.543$	$p = 0.629$
H7: Gaze Velocity	Some outliers were removed	$p < 0.001$	$p < 0.001$	$p < 0.001$
H8: Pupil Diameter	Some outliers were removed	$p = 0.006$	$p = 0.034$	$p = 0.039$

Table 2.7

Hypothesis and results for accuracy, RT, DS, Gaze Velocity, Pupil Diameter for all conditions under low and high load (levels 1 vs 4).

	Repeated Measures Anova					***Hypothesis Met?***
	Conditions	***Level* (1 vs 4)***	***Group****	***Condition****	***Level*Group* Conditions***	
H4: Accuracies should decrease under high load, and there should be differences between groups and across modality conditions.	**A1: A > C > S** **A2: S > A > C** **V1: A > S > C** **V2: A > S > C** **AV1: A > S > C** **AV2: A > C > S**	$p < 0.001$	$p = 0.159$	$p < 0.001$	$p = 0.045$	**Accepted**
H5: RTs should increase under high load, and there should be differences between groups and across modality conditions.	**A1: S > C > A** **A2: S > C > A** **V1: C > A > S** **V2: A > C > S** **AV1: S > C > A** **AV2: C > A > S**	$p = 0.009$	$p = 0.913$	$p = 0.449$	$p = 0.135$	**Partially Accepted**
H6: DS should decrease under high load, and there should be differences between groups and across modality conditions.	**A1: C > A > S** **A2: A > C > S** **V1: S > A > C** **V2: S > A > C** **AV1: C = S > A** **AV2: S > A > C**	$p = 0.047$	$p = 0.625$	$p < 0.001$	$p = 0.296$	**Partially Accepted**
H7: There will be differences in gaze velocity under high load, and there should be differences between groups and across modality conditions.	**A1: A > C > S** **A2: A > S > C** **V1: S > C > A** **V2: S > C > A** **AV1: S > C > A** **AV2: C > A > S**	$p < 0.001$	$p = 0.008$	$p < 0.001$	$p < 0.001$	**Accepted**
H8: Pupil diameter should decrease under high load, and there should be differences between groups and across modality conditions.	**A1: A > C > S** **A2: A > C > S** **V1: S > A > C** **V2: A > C > S** **AV1: A > C > S** **AV2: C > A > S**	$p = 0.157$	$p = 0.721$	$p = 0.686$	$p = 0.206$	**Partially Accepted**

Note. In the condition's column, A1 stands for Audio Low Load, A2 stands for Audio High Load, V1 stands for Visual Low Load, V2 stands for Visual High Load, AV1 stands for Audio-visual Low Load and AV2 stands for Audio-visual High Load. Under conditions, C stands for Controls, A stands for PWADHD, S stands for PWS.

H4: Accuracies should decrease under high load, and there should be differences between groups and across modality conditions.

Descriptive statistics (see Table A2.3 in Appendix A) and Figure 2.5 showed that overall, accuracy decreased as load-level increased for all groups in all conditions as expected. In the audio-only condition (Table 2.7), PWADHD, similar to controls, outperformed PWS in low load, but PWS performed better in high load than other groups. PWADHD outperformed PWS and controls in the visual condition in low load and high load. In the audio-visual condition, PWADHD performed better than controls and PWS at both load levels. It can be noted that under high load, in auditory modality (see Table 2.7) PWS have a better performance in accuracies, whereas for PWADHD this is true in visual and audio-visual modalities. For all tasks, data were checked for outliers using box-and-whisker plots (none found). Data were checked for normality, and non-parametric tests were used where necessary. Shapiro-Wilks showed that the accuracy measure was not normally distributed ($p < 0.001$). Parametric (One Way ANOVA) and non-parametric tests (Kruskal Wallis) were conducted. There was a significant difference in accuracy on both parametric $F(2,213) = 3.468$, $p = 0.033$, and the non-parametric tests ($p = 0.038$). See Table 2.6 for more information. Pairwise comparisons showed that groups that differed significantly were Controls and PWADHD ($p = 0.025$) regardless of the level and condition. A repeated-measures ANOVA was conducted to investigate the impact of groups, conditions, and load levels on accuracy. Sphericity was assumed for levels and level*conditions, and a Greenhouse-Geisser correction was applied for conditions. There was a significant main effect of levels, $F(1,33) = 53.463$, $p < 0.001$, $\eta p2 = 0.618$. There was not a significant main effect of groups $F(2, 33) = 1.945$, $p = 0.159$, $\eta p2 = 0.105$. There was a significant main effect of conditions $F(1.327, 43.785) = 11.858$, $p < 0.001$, $\eta p2 = 0.264$. These findings accept H4. There was a significant interaction of levels*conditions $F(2, 66) = 4.038$, $p = 0.022$, $\eta p2 = 0.109$ and a significant interaction of groups*levels*conditions $F(4,66) =$

2.582, p = 0.045, $\eta p2$ = 0.135 which suggests that accuracies did vary as a function of level, condition across groups (see Table 2.7 for more information).

H5: RTs should increase under high load, and there should be differences between groups and across modality conditions.

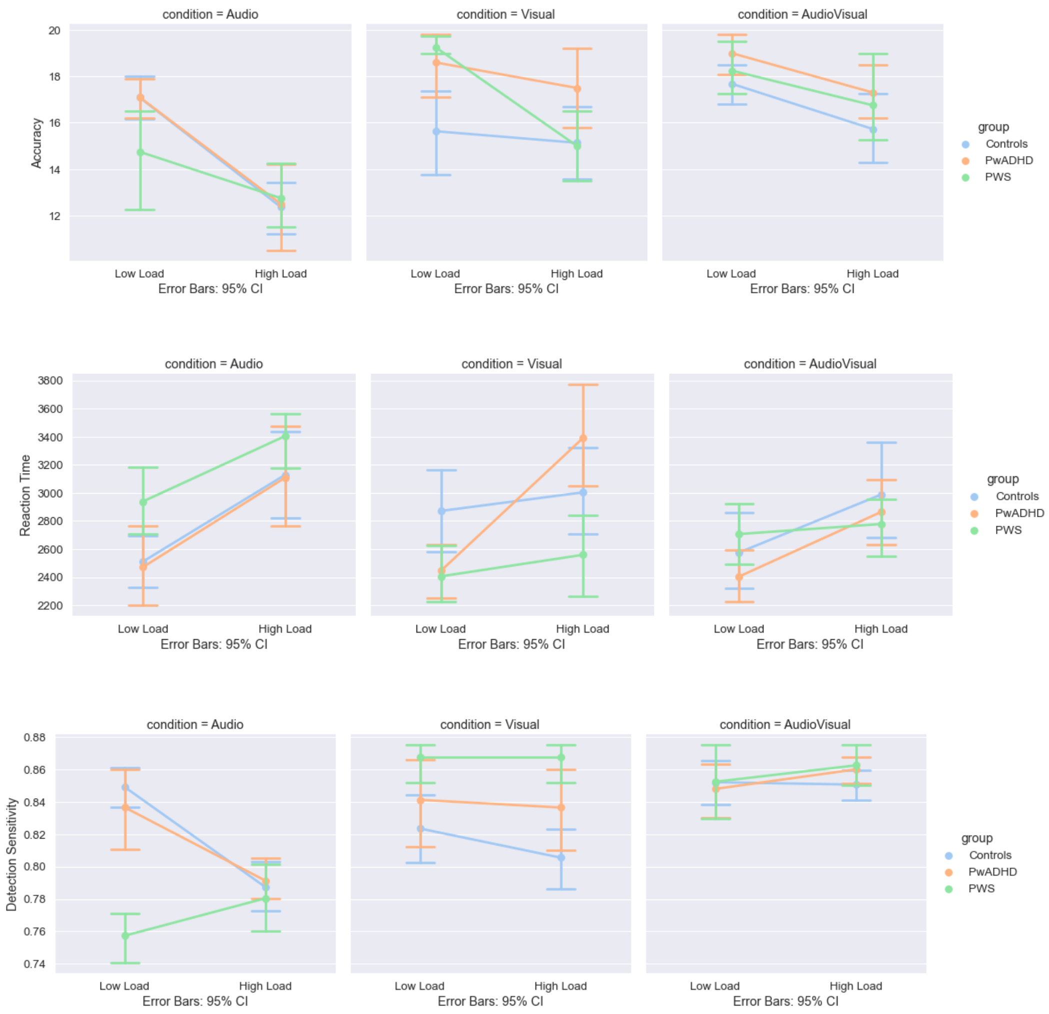
Descriptive statistics and Figure 2.5 showed that overall, RTs increased as load-level increased for all groups in all conditions as expected. In the audio-only condition, PWS had higher RT than controls and PWADHD in low load and high load. PWADHD and controls had higher RT compared to PWS in the visual condition under low and high load. In the audio-visual condition, PWS had longer RT than controls and PWADHD in low load levels, but in high load, PWADHD and controls had longer RTs (see Table 2.7 for more information). Under high Load, PWADHD performed better (lower RTs) in the audio modality whereas PWS performed better in visual and audio-visual domains (Table 2.7). There was no significant difference in RTs between groups (see Table 2.6). There was a significant main effect of levels (see Table 2.7). There was no significant main effect of groups. There was no significant main effect of conditions. These findings only partially support H5. There was no significant interaction of levels*conditions and there was no significant interaction of groups*levels*conditions which suggests that RTs were not impacted across groups by an interaction of levels and conditions.

H6: DS should decrease under high load, and there should be differences between groups and across modality conditions.

From Table 2.7, Figure 2.5 and descriptives, we can confirm that in audio condition, DS decreased for controls and PWADHD whilst it slightly increased for PWS under high load. In visual condition, DS decreased for all groups, while in audio-visual condition, DS decreased for controls and slightly increased for PWADHD and PWS under high load. Under high load, PWADHD performed better than PWS in audio, whereas PWS performed better than PWADHD in visual and audio-visual (Table 2.7). There was no significant difference in DS between groups (see Table 2.6). From Table 2.7, it shows that there was a significant main effect of levels but no significant main effect of groups. There was a significant main effect of conditions. These findings partially support H6. There was a significant interaction of levels*conditions but no significant interaction of groups*levels*conditions. This suggests that DS did not vary between groups from an interaction of levels and conditions.

Figure 2.5

Accuracies (top row). RTs (middle row) in the primary task and DS (bottom row) in the secondary task between controls (blue lines), PWADHD (orange lines) and PWS (green lines) at each load level (left x - axis in each graph – low load; right x - axis in each graph – high load) separated in columns for each condition (first column is audio, second column visual and third column shows scores in audio-visual). Error bars represent ± 2 Standard Error [SE].



H7: There will be differences in gaze velocity under high load, and there should be differences between groups and across modality conditions.

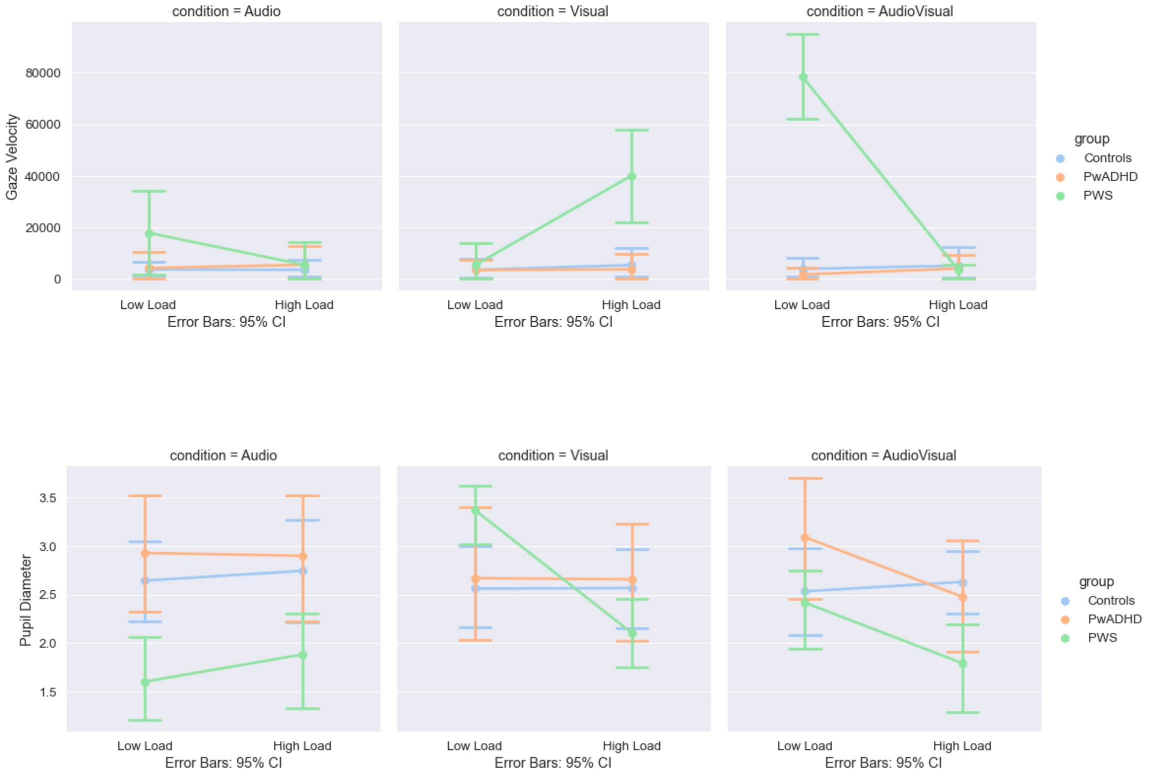
In audio condition gaze velocity increased in PWADHD and PWS in high load, but this was the opposite for controls. In the visual condition, in high load, gaze velocity increased for all groups under high load. In the audio-visual condition, gaze velocity increased for controls and PWADHD but this was opposite for PWS. See Table 2.7 and Table A2.4 in Appendix A for more information. It was observed that under high load, PWADHD had faster gaze velocities in audio and audio-visual conditions, whereas PWS had faster gaze velocities in the visual condition (more information is given in Table 2.7). From Table 2.6, we can conclude that there was a significant difference in gaze velocity between groups. Post-hoc tests showed that PWS differed significantly from Controls and PWADHD ($p < 0.001$, $p < 0.001$ respectively). Table 2.7 and Figure 2.6 shows that there was a significant main effect of levels, a significant main effect of groups and there was a significant main effect of conditions accepting H7. There was a significant interaction of levels*conditions and a significant interaction of groups*levels*conditions. Gaze velocity was impacted between groups as an interaction of level and condition.

H8: Pupil diameter should decrease under high load, and there should be differences between groups and across modality conditions.

Table 2.7 shows that in the audio condition, pupil diameter increased as load level increased for controls and PWS while this was the opposite for PWADHD. In the visual condition, pupil diameter decreased for PWADHD and PWS in high load while it stayed the same for controls. In audio-visual condition, pupil diameter increased for controls and decreased for PWADHD and PWS under high load. See descriptive statistics for more information. We can further conclude that under high load, pupil diameter decreased for PWADHD and PWS in visual and audio-visual conditions. In the audio condition, there was a significant difference in pupil diameter between groups between PWS and PWADHD (p = 0.026). From Table 2.7 and Figure 2.6, we can conclude that there was no significant main effect of levels, no significant main effect of groups and no significant main effect of conditions. These findings partially support H8. There was no significant interaction of levels*conditions and no significant interaction of groups*levels*conditions which suggests that pupil diameter did not vary between groups as a function of levels and conditions.

Figure 2.6

Gaze Velocity (top row) and pupil diameter (bottom row) between controls (blue lines), PWADHD (orange lines) and PWS (green lines) at each load level (low load shown in left x-axis; high load shown in right x-axis in all graphs) across each condition (left column – audio; middle column – visual; right column – audio-visual). Error bars represent ± 2 Standard Error [SE].



2.8.3 Experiment 2c Results

Network Models were conducted to look at the relationship between the significant performance measures (accuracy and gaze velocity) for the different groups to synthesize findings and compare them across groups. The results for the accuracies suggest that controls were similar to PWADHD but both groups differed from PWS (Figure 2.7). PWS were affected in audio whereas PWADHD in audio and audio-visual. The visual link was lost in PWADHD and cannot be determined (Figures 2.7, 2.8). With regards to gaze velocity, controls are similar to PWADHD but both groups differ from PWS (Figure 2.9). Gaze velocity was not affected in PWS in any modality whereas for PWADHD, gaze velocity was affected in visual and audio-visual domains (Figures 2.9, 2.10). Such results suggest that in the load theory attention tasks, accuracy in PWS are affected in the auditory domain whereas for PWADHD accuracy is affected in audio and audio-visual conditions in selective attention tasks. Gaze velocity is affected in PWADHD in visual and audio-visual whereas, for PWS, gaze velocity was not affected by any modality. For both accuracies and gaze velocity, PWS differed from other groups.

Figure 2.7

A Network Model visualised for each group (Controls, PWADHD, PWS) for accuracies, for three conditions. Top row shows NMs in low load for each condition separated by groups, bottom row shows NMs in high load in each condition across groups. ACL1A, ACL1V, ACL1AV stands for Accuracies Controls Level1 (Low load) Audio, Accuracies Controls Level1 (Low load) Visual, Accuracies Controls Level1 (Low load) Audio-visual respectively. This is the same for PWADHD and PWS with the difference only in the second letter in which A stands for PWADHD and S for PWS (e.g., AAL1A stands for Accuracies PWADHD Level2 (low load) Audio). NMs have an average layout across all networks representing them with the same layout structure (e.g., L1V is the first node for each group in top row and so on for each node).

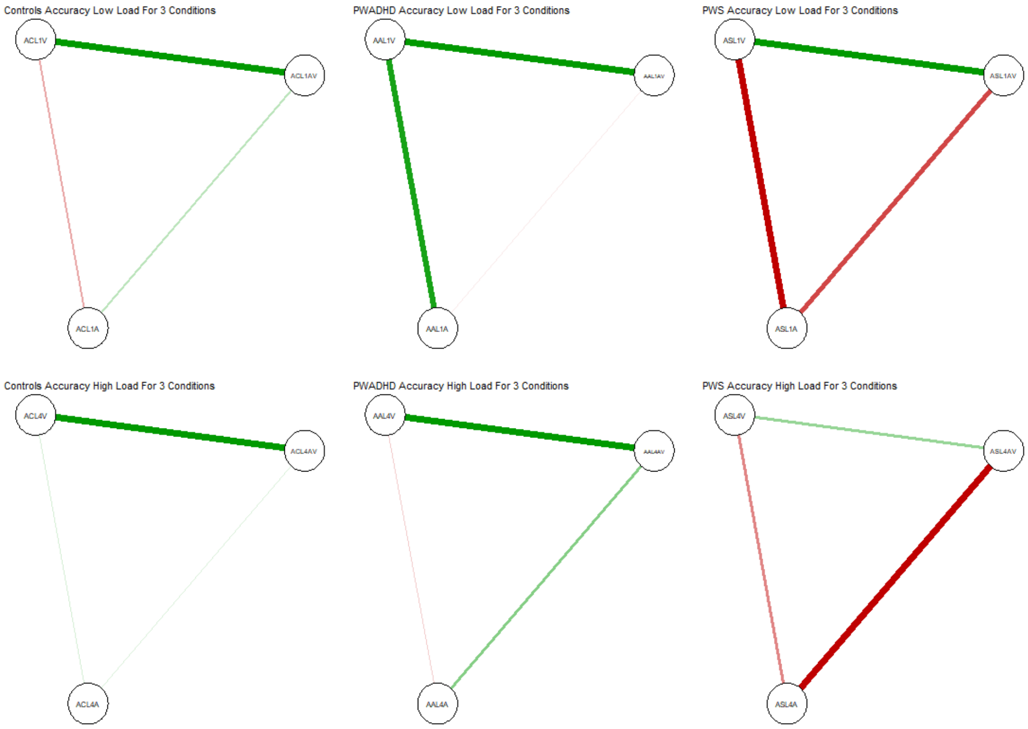


Figure 2.8

NMs for accuracies visualised for the three groups (Controls, PWADHD, PWS), for each condition. Top row shows NMs in low load for the three groups separated by condition, bottom row shows NMs in high load for the three groups across conditions. The first letter in the nodes is either C, A or S that stand for Controls, PWADHD and PWS respectively. The second letter stands for condition (A-Audio; V-Visual; AV-Audio-visual).

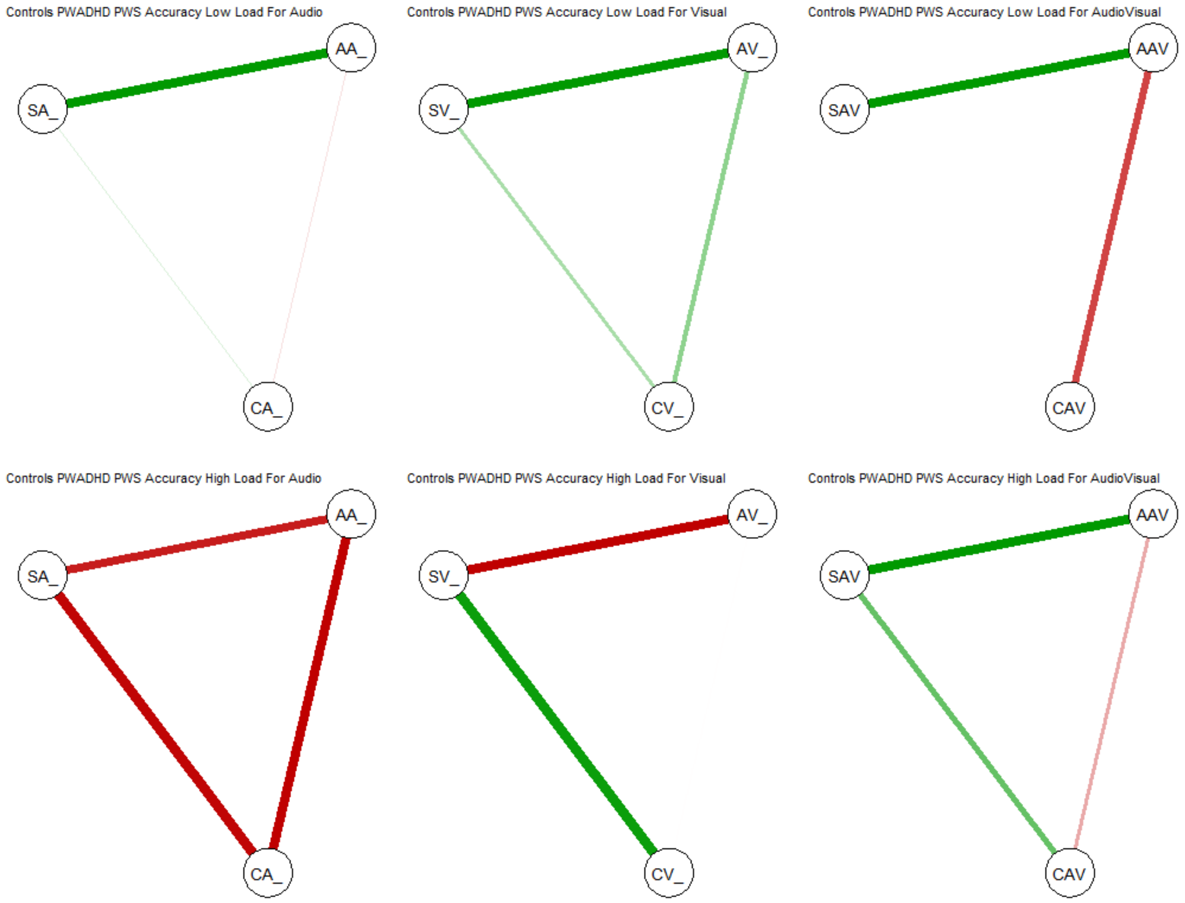


Figure 2.9

Gaze Velocity shown as NMs for Controls, PWADHD and PWS for the three conditions. Top row shows NMs in low load and bottom row shows NMs in high load. GVCL1A, GVCL1V, GVCL1AV stands for Gaze Velocity for Controls Level1 (Low load) Audio, Gaze Velocity Controls Level1 (Low load) Visual, Gaze Velocity Controls Level1 (Low load) Audio-visual respectively. This is the same for PWADHD and PWS with the difference only in the third letter in which A stands for PWADHD and S for PWS. Similar as in the NMs for Accuracy, NMs for Gaze Velocity have an average layout across all networks.

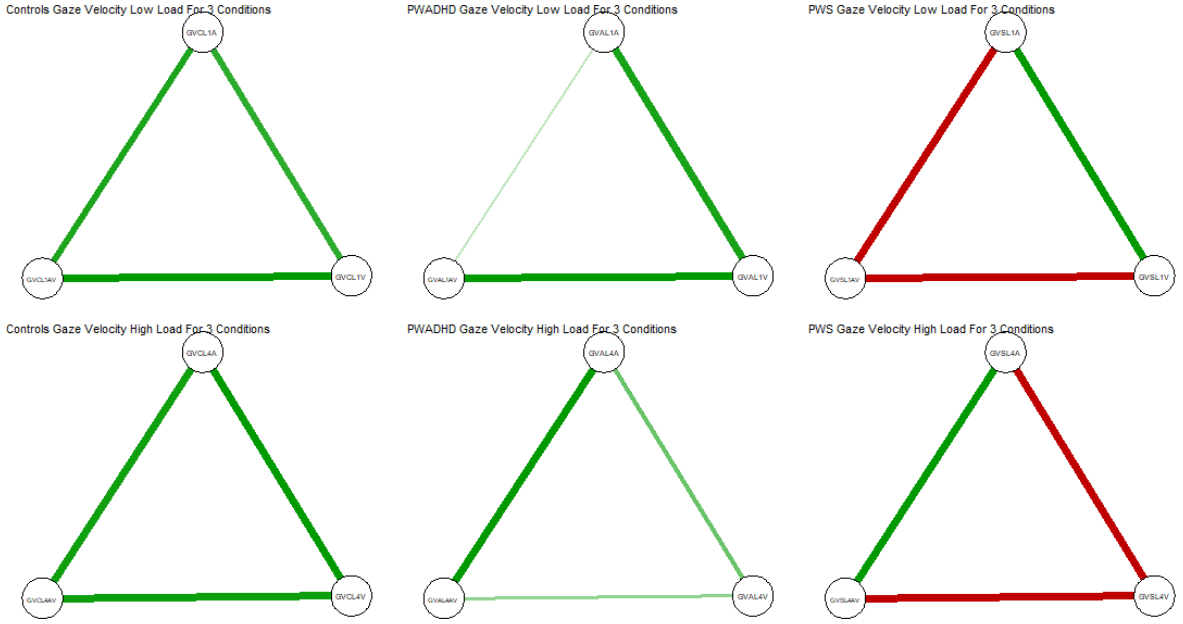
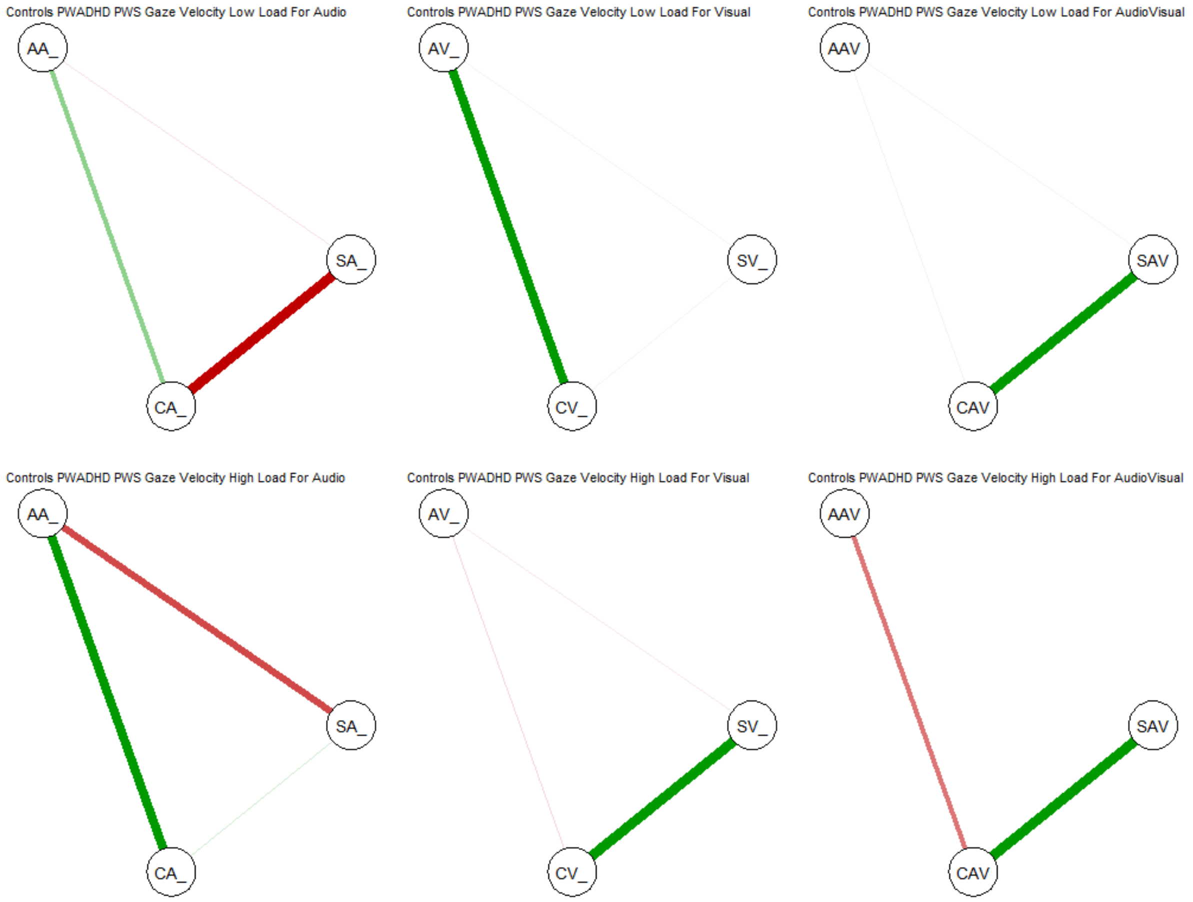


Figure 2.10

Gaze Velocity shown as NMs for Controls, PWADHD and PWS across three groups. Top row shows NMs in low load and bottom row shows NMs in high load. In the nodes, the first letter in nodes stand for the group (C – Controls; A-PWADHD; S-PWS), the second letter stands for the condition (A-Audio; V-Visual; AV-Audio-visual).



2.9 Discussion

In this experiment, the selective attention task investigated in Experiment 1 was explored in a VR environment in audio, visual and audio-visual conditions. Performance of controls, PWADHD and PWS, were compared on accuracy and RT (primary task) and DS (secondary task). Oculomotor measures, including gaze velocity and pupil diameter, were compared between groups and conditions in low and high load levels. Participants were also assessed on ASRS, SSI-3 and UNWR. With regards to ASRS, SSI-3 and UNWR measures, results suggested that groups differed significantly on ASRS scores with PWADHD having the highest scores, followed by PWS and controls. There was a significant difference between controls and PWADHD ($p < 0.001$) and between PWS with PWADHD ($p = 0.049$). SSI-3 was significantly highest in the PWS group, followed by PWADHD and controls. Pairwise comparisons suggested a significant difference between PWS and controls ($p < 0.001$). UNWR scores differed significantly, with controls having the highest scores followed by PWADHD and PWS. There was a significant difference between controls and PWADHD ($p = 0.026$) and controls and PWS ($p = 0.015$). To conclude, the results overall suggest that both controls and PWADHD differed from PWS. This contradicts the literature that both disorders have the same comorbid symptoms that distinguish them from typical controls. Further NM analysis will be conducted in chapter 8 to determine if claims about comorbidity between disorders are true.

With regards to performance on the task, for accuracies, there was a significant difference between groups and specifically controls and PWADHD differed ($p = 0.025$). Accuracies decreased as load level increased for all groups in all conditions. There was a main effect of levels and conditions suggesting that accuracies varied across levels and conditions. There was also an interaction effect of groups conditions and levels which suggests that group differences on the accuracies varied from levels and conditions. No group differences were observed in RTs although overall RTs increased in high load. There was a main effect of levels, no main effect of groups and no interaction effect was observed between groups, condition and levels suggesting that levels and conditions did not impact group differences on RT scores. DS decreased for all groups in high load and a main effect of levels and condition was observed. No interaction of groups levels and condition was reported suggesting that DS did not vary across groups, level, and condition. For gaze velocity, there were significant differences between groups across levels. Pairwise comparisons showed a significant difference between PWS and controls ($p < 0.001$), PWS and PWADHD ($p < 0.001$). Main effects were observed in level and condition. An interaction occurred between level condition and group suggesting that an interaction of the three independent variables impacted the gaze velocity. Gaze velocity varied in PWADHD and PWS in different conditions and levels but regardless of levels and conditions, gaze velocity was lowest in PWS followed by PWADHD and controls. Such results support the literature that suggests that gaze velocity in PWADHD is lower than controls (Munoz et al., 2003). There was a significant difference between groups in pupil diameter between PWS and PWADHD ($p = 0.026$), no main effects of level, group or condition were observed and no interaction of group level and condition suggesting that pupil diameter did not vary between groups across levels and conditions. Regardless of levels and conditions, pupil diameter was lowest in PWS, followed by controls and PWADHD. These results contradict with those from the literature which suggest that pupil diameter is lower in PWADHD compared to controls (Fried et al., 2014; Munoz et al., 2003; Wainstein et al., 2017).

The relationship between the significant performance measures (accuracy and gaze velocity) for the various groups was examined using network models in order to compare the results between the groups. The accuracy results indicate that controls and PWADHD are comparable, although both groups are different from PWS. PWADHD was impacted in both audio and audio-visual, whereas in PWS the audio domain alone was affected. Controls and PWADHD are comparable to one another in terms of gaze velocity, but neither group is comparable to PWS. For PWADHD, gaze velocity was affected in the visual and audio-visual domains while it was not impacted in any modality for PWS. Such results suggest that in the load theory attention tasks: 1- different domains are affected in PWS and PWADHD in selective attention tasks; 2- controls and PWADHD differ from PWS in accuracies and gaze velocity suggesting that PWS and PWADHD are not comorbid in these measures; 3- gaze velocity is affected in visual and audio-visual domains in PWADHD but in PWS no difference between domains were observed. 4- Gaze velocity is lower in PWADHD compared to controls; 5- Pupil diameter is higher in PWADHD compared to controls. 6- Overall, the results suggest that there are distinctive differences between controls, PWADHD vs PWS. Such findings limit claims about comorbidity between PWADHD and PWS.

Although, interesting findings were obtained in Experiment 2b, the study had some limitations. First the number of participants were not the same or similar in all groups. Controls outnumbered PWADHD and PWS. Second, the number of PWS was relatively lower compared to controls and PWADHD. Third, subtypes of ADHD (e.g., inattentiveness and impulsivity) could have been investigated by utilizing ASRS v1.1 (Kessler et al., 2005). This has 18 questions, nine which assess inattention and nine which assess hyperactivity. If this had been done, further conclusions would have been drawn about the impact that such subtypes have and whether gender plays a role in the symptoms investigated and subsequently in comorbidity between symptoms. Further investigations would have also been achieved if symptoms of anxiety had been taken into consideration to determine whether it affected both groups similarly and how the severity of stuttering affect anxiety. Lastly, there was a gender imbalance between groups. To understand whether gender imbalance affected the results, Experiment 3 was conducted. The next chapter explores this issue by analysing the data from a study with controls, PWADHD and PWS matched in number but not in gender and assesses if gender ratio impacts the results.

3. Chapter 3. Assessing Gender Imbalances

3.1 Introduction

An accurate clinical diagnosis is essential to verify any abnormal behaviours, thoughts, and/or sensations that patients may have and to guarantee good quality of life. Appropriate intervention(s) are required to control recognised disorders and are made easier by the diagnosis, allowing patients' lives to go on without hindrance or prejudice. However, gender bias can impact clinical diagnosis (Liu & DiPietro Mager, 2016). Such a propensity raises the questions whether, if gender differences are not taken into consideration during patient-testing and analysis, the diagnosis is credible if one gender is overrepresented in clinical conditions? As a result, research on the impact of gender differences on performance is necessary.

In PWADHD, the male to female ratio is around 3:1 in childhood (Biederman et al., 2002) and 1.6:1 in adults (Stibbe et al., 2020). For PWS the male-to-female ratio is around 2:1 in childhood and 5:1 in adulthood (Dworzynki et al., 2007). Whilst incidence of children with ADHD and with stuttering differ by gender in test samples, the relationship between genders in adults with ADHD and who stutter has not been widely researched and understood. Most of the studies investigated adults with ADHD and stuttering based only on cognitive differences. In this chapter gender differences in controls, PWADHD and PWS were examined in relation to symptoms of attention, stuttering, WM and cognitive performance. Specifically, are attention, stuttering, WM problems and cognitive abilities affected by gender imbalances?

Experiment 3 aimed at understanding the effect of gender on the performance of controls, PWADHD and PWS in a visual selective attention task under two load levels. Results are reported in two parts: In part a, participants were tested on three measures (ASRS, SSI-3, UNWR), and results are drawn about attention problems, speech, and WM performance without-testing for gender differences and then after testing for gender differences; In part b, results are reported on RTs between attention load levels in models with and without gender differences. Finally, LMM analysis was conducted to understand whether the gender imbalance affected all the measures. LMM models specify the relationship between independent and dependent variables (Magezi, 2015). In LMMs explanatory variables are classified as either "fixed " or "random " factors. Fixed factors are variables which the experimenter investigates. For example, the gender factor with two levels, would be a categorical fixed factor in research looking at the differences between males and females. In contrast, random factors, also known as "grouping variables", are random variables for example participants and groups. LMM is called mixed-effects because it includes both fixed-effects and random-effects. When analysing the data with LMM, a p-value of less than 0.05 indicates that the unknown term had a significant impact on the model fit. LMMgui[12] is a free Graphic User Interface, GUI developed by Magezi (2015) in R (R Core Team., 2016) that uses the lme4 package (Bates et al., 2015). Magezi (2015) explains in detail how to use the software to analyse the data. The following analyses have been conducted in R based on the literature (Bates et al., 2015; Magezi, 2015) and tutorials[13]. The lmer function in the lme4 package for R (Bates et al., 2015) calculates maximum likelihood or restricted maximum likelihood (REML) to estimate the parameters in the linear mixed-effects models. The lme4 package includes functions for fitting and analysing linear mixed models. The following syntax model is implemented in R:

Syntax model = lmer(target ~ fixed1 + fixed2+ (1|random1) + (1|random2), data=data)

3.2 Experiment 3

The literature suggests that more males than females have attention and stuttering problems for PWADHD and PWS. Whilst cognitive differences between PWS and PWADHD have been explored in previous studies, there is a need to assess gender imbalance to understand whether

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[12] The software can be found in: https://www.oa.uni-hamburg.de/datenbanken/lmmgui.html
[13] R tutorial for LMM can be found in: https://bodowinter.com/tutorial/bw_LME_tutorial2.pdf

results are affected by gender. Considering the gender imbalances across the three groups, in this study more male than female PWS and PWADHD were allowed for these groups than for controls, and it was necessary to test whether gender effects impacted the results.

The predictions for Experiment 3a were that UNWR scores should be lower and SSI-3 and ASRS should be higher in PWADHD and PWS compared to controls and gender imbalance should not affect ASRS, SSI-3 and UNWR scores. Formally, the hypotheses in Experiment 3a were: Groups should differ from each other on their ASRS scores (H1), on their SSI-3 scores (H2) and on their WM scores (H3). Assuming no effect of gender, the interactions between group and ASRS (H4), group and SSI-3 (H5) and group and UNWR (H6) should not be significant.

Experiment 3b tested whether there were differences between controls, PWADHD and PWS on RTs between the two levels (level 2 had a higher difficulty compared to level 1). It was predicted that RT in level two should be higher in all groups, with PWS and PWADHD having higher RTs compared to controls. It was also predicted that RTs should not be influenced by gender. Formally, the hypothesis was: H7: RT should increase at load level 2, there should be differences between groups but the interactions between group and gender should not be significant.

3.3 Methods

3.3.1 Participants

Eighteen controls (Mean age: 20.89, SD: 6.781, 16 Females and 2 Males), 16 clinically diagnosed PWADHD (Mean age: 24.00, SD: 4.017, 6 Females and 10 Males), 16 PWS (Mean age: 30.06, SD: 9.546, 4 Females and 12 Males) were recruited from the UCL Sona system. All participants had normal vision (assessed by an online visual acuity test) and normal hearing (assessed by the audiometric test). UCL Research Ethics Committee approved the study (6252/002). Participants were paid £5 or earned a 0.5 credit through SONA for their time. Information sheets and consent forms were given before the experiment, and participants could withdraw at any time. Power analysis showed that with an effect size of 0.8 in repeated measures ANOVA within-between interactions, there is a 91% chance of detecting an actual effect.

3.3.2 Design

Similar to Experiment 2a, in Experiment 3a participants completed the ASRS questionnaire, read out paragraphs from the SSI-3 manual and completed the UNWR. The between-participants factor was the participant group (controls, PWADHD and PWS). The dependent variables were ASRS, SSI-3 and UNWR.

In Experiment 3b, a mixed design was used where the within-participant factors was the two load levels. The between-participant factors were participant group and gender. The dependent variable was RT.

3.3.3 Materials

In 3b the experiment was programmed in C# and Unity and was converted into an online version using the WebGL add-on provided by Unity[14]. All stimuli (3D objects) and the environment were purchased from Unity Asset Store. The study was based on a game that-tested visuospatial working memory in a selective attention task. Stimuli consisted of boxes, obstacles and a gamified environment. Data were stored securely automatically into a CSV file once the participant completed each level. RT measures were obtained at the two levels.

3.3.4 Measures

1-Adult ADHD Self-Report Scale Screener, (ASRS; Ustun et al., 2017)

2-Stuttering Severity Instrument version 3, (SSI-3; Riley, 1994)

3-Universal Non-Word Repetition Test, (UNWR; Howell et al. 2016)

3.3.5 Procedure

Participants kept their cameras and microphones on during the experiment so that the experimenter could monitor them. The experiment was carried out individually via a Zoom

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[14] Application link: https://fjordakazazi.github.io/BNB_project/

video conference. Participants were given a URL link that led them to the experiment's access page at Gorilla (www.gorilla.sc). First, vision and hearing of the participants were assessed. The tasks (ASRS, SSI-3, UNWR, and the game) were then presented to participants in random order. Each participant underwent-testing for about 30 minutes. A demographics form was filled out by participants before the game began. After they submitted their user details, the participants could then start the application. The game included two levels varying in difficulty (L1 was easy, and L2 was difficult, see Table 3.1). Participants pushed boxes onto their assigned emplacements with the use of their keyboard keys to open gates. The goal was to manoeuvre the boxes appropriately to set them in their proper locations, open a gate, and pass the finish line as fast as possible. As a result, the task's total playing time was adequate to measure selective attention. If a level was not finished in time, participants were immediately advanced to the following level. Time taken to complete levels served as a performance indicator.

Table 3.1

Levels included in the task.

Level 1	**LOAD 2**
Low Difficulty (fewer obstacles to move the boxes in the appropriate places and open the gate)	Higher Difficulty (more obstacles such as walls, boxes that cannot be moved and sliding areas)

3.4 Results

3.4.1 Experiment 3a Results

Table 3.2

Descriptive Statistics, hypothesis, and results for ASRS, SSI-3, UNWR.

	Outliers	Shapiro-Wilks	One Way ANOVA	Kruskal Wallis	Hypothesis Met?
H1: Groups should differ from each other on their ASRS scores.	Some outliers were removed	p = 0.061	p < 0.001	NA	**Accepted**
H2: Groups should differ from each other on their SSI-3 scores.	Some outliers were removed	p < 0.001	p < 0.001	p < 0.001	**Accepted**
H3: There should be a difference between the groups on the WM scores.	None	p = 0.004	p < 0.001	p < 0.001	**Accepted**

H1: Groups should differ from each other on their ASRS scores.

After removing outliers, data was normally distributed F (48) = 0.955, p = 0.061. Descriptive statistics (Table B3.1 in Appendix B) showed that ASRS was highest in the PWADHD group, followed by PWS and controls. One Way ANOVA was conducted. Groups differed significantly on ASRS scores F(2, 47) =20.831, p < 0.001 test (see Table 3.2 and Figure 3.1 for more information). Therefore, H1, that there should be a difference between the groups in ASRS scores, was accepted. The Tukey post-hoc test showed that the groups that differed significantly were Controls vs PWADHD (p < 0.001), Controls vs PWS (p = 0.026) and PWADHD vs PWS (p = 0.046).

H2: Groups should differ from each other on their SSI-3 scores.

SSI was highest in the PWS group followed by PWADHD and controls as shown from descriptives. Groups differed significantly on SSI scores (see Table 3.2). Therefore, H2 was accepted. A Tukey post-hoc test showed that the groups that differed significantly were Controls vs PWADHD (p = 0.030), Controls vs PWS (p < 0.001) and PWADHD vs PWS (p = 0.016). See Figure 3.1 for further information.

H3: There should be a difference between the groups on the WM scores.

WM scores were the lowest (poorest) in PWS, followed by PWADHD and controls (see descriptive statistics and Figure 3.1). There was a significant difference in UNWR between groups (Table 3.2) accepting H3. Specifically, the Tukey post-hoc test showed that the groups that differed significantly were Controls vs PWADHD (p < 0.001), and Controls vs PWS (p < 0.001).

Figure 3.1

Mean ASRS (left graph), SSI-3 (middle graph), UNWR (right graph) scores per group. Controls are shown in the first x - axis, PWADHD are shown in second x - axis, PWS are presented in third x - axis values. Error bars represent ± 2 Standard Error [SE].

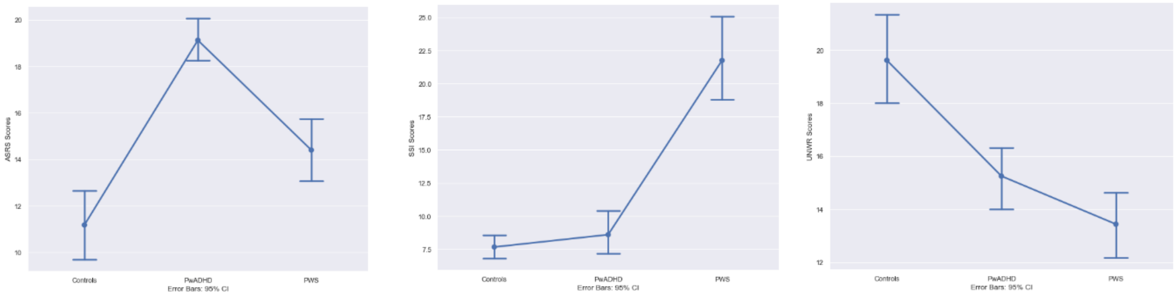


Table 3.3

*Descriptive Statistics, hypothesis, and results for group*gender effects on ASRS, SSI-3, UNWR.*

	Two Way ANOVA	**Hypothesis Met?**
H4: ASRS should not vary as a function of the group and gender.	$p < 0.590$	**Accepted**
H5: SSI-3 should not vary as a function of the group and gender.	$p < 0.823$	**Accepted**
H6: UNWR should not vary as a function of the group and gender.	$p = 0.586$	**Accepted**

H4: ASRS should not vary as a function of the group and gender.

A two-way ANOVA was conducted to investigate the influence of gender and group on the ASRS scores. There was not a statistically significant interaction between gender effect and group on ASRS scores ($F(2, 42) = 0.534$, $p = 0.590$, $\eta p2 = 0.025$) as shown in Table 3.3. Figure 3.2 provides a visual representation of these results. Hence H4 is accepted.

H5: SSI-3 should not vary as a function of the group and gender.

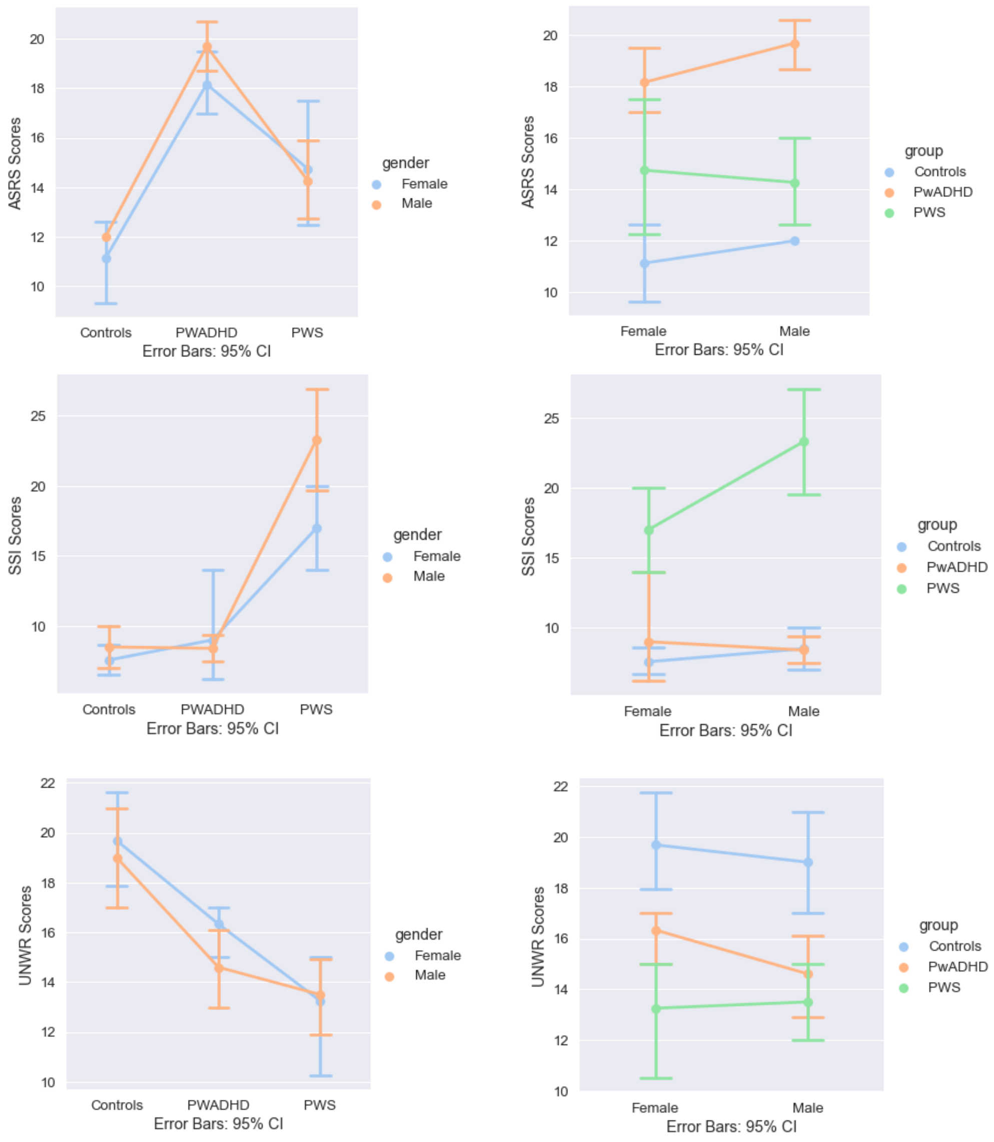
Results from Table 3.3 suggest that there was no significant interaction between gender effect and group on SSI scores (Figure 3.2). H5 was supported.

H6: UNWR should not vary as a function of the group and gender.

There was no significant interaction between gender effect and group on UNWR scores as shown in Table 3.3 and Figure 3.2 accepting H6.

Figure 3.2

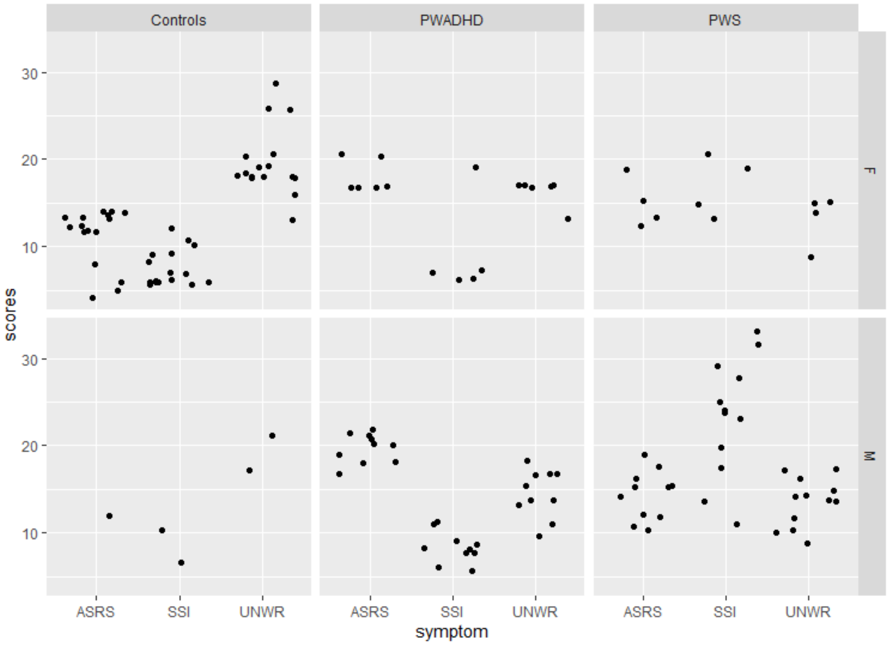
Mean ASRS (top row), SSI-3 (middle row) and UNWR (bottom row) scores between controls (blue lines), PWADHD (orange lines) and PWS (green lines) for each gender (left column) and between genders for each group (right column). Error bars represent ± 2 Standard Error [SE].



Using LMM analyses (see GGplot in Figure 3.3), two models were created. The first model looked at the effect that two fixed factors: 1-symptoms of ASRS, SSI-3, UNWR; 2- gender, and two random factors: 1-participant; 2-group had on the scores. The second model looked at the effect that one fixed factor: 1-symptom of ASRS, SSI-3, UNWR and two random factors 1-participant; 2-group had on the scores. The models were compared using ANOVA in R to determine whether removing the fixed factor gender would significantly impact the scores. The results showed that there were no significant differences between the likelihood of the two models (χ2(1) = 1.51, p=0.218). Thus, removing the fixed factor gender did not affect the scores.

Figure 3.3

Ggplot in R for ASRS, SSI-3 and UNWR for each group for males and females. On the right side of the plot, F stands for females (top row plots) and the last three blocks (bottom plots) are related to males. Each symptom is shown on the x - axis whereas the y - axis represents the scores for both genders.



3.4.2 Experiment 3b Results

Table 3.4

Descriptive Statistics, hypothesis, and results for RT.

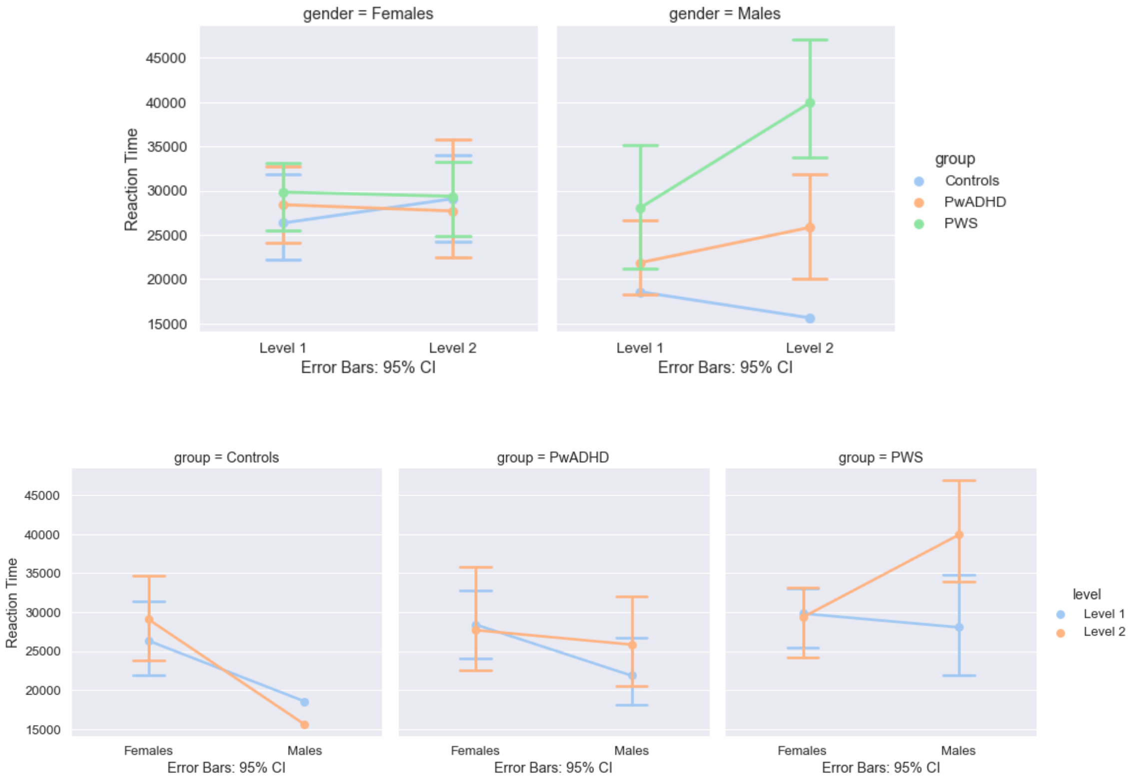
	Outliers	Shapiro-Wilks	One-Way ANOVA	Kruskal Wallis	Repeated Measures ANOVA	Hypothesis Met?
					Group*Gender	
H7: RT should increase at load level 2, there should be differences between groups but the interactions between group and gender should not be significant.	None sig. Some outliers were removed	p < 0.001	p = 0.014	p = 0.014	p = 0.122	**Accepted**

H7: RT should increase at load level 2, there should be differences between groups but the interactions between group and gender should not be significant.

Descriptive statistics (see Table B3.3 in Appendix B) show that overall, RTs increased under level 2 for all groups as predicted with PWS having the highest RT followed by controls and PWADHD. Post-hoc tests showed that PWS had significantly higher RTs under level 2 compared to PWADHD ($p = 0.024$). For all tasks, data were checked for outliers using box-and-whisker plots (outliers were not significant but any outliers were removed). Shapiro-Wilks showed that RT was not normally distributed ($p < 0.001$). Parametric (One Way ANOVA) and non-parametric tests (Kruskal Wallis) were conducted. There was a significant difference in RT on both parametric $F(2, 84) = 4.464$, $p = 0.014$, and the non-parametric tests ($p = 0.014$, see Table 3.4). A repeated-measures ANOVA (Table 3.4) was conducted to investigate the effect on genders and groups on RT between the two levels. There was no significant interaction of effect of groups*gender on RTs between levels F(2,35) = 2.239, p = 0.122, *ηp*2 = 0.133. Hence H7 was supported (see Figure 3.4).

Figure 3.4

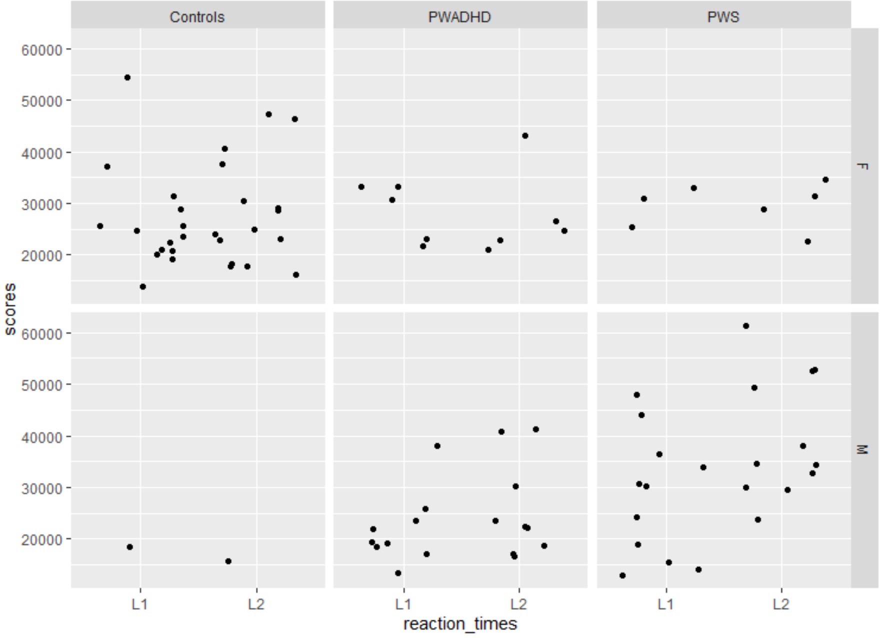
Line graphs with error bars show RTs between levels for each group (controls – blue lines; PWADHD – orange lines; PWS – green lines) separated by genders (first row) and RTs between genders for each level separated by group (second row). Error bars represent ± 2 Standard Error [SE].



No significant difference was observed between the models (1 fixed factor without gender vs 2 fixed factors with gender, χ2(1) = 0.0369, p=0.847). Hence gender did not affect reaction times. See Ggplot in Figure 3.5 for a visual representation of results from LMM.

Figure 3.5

RTs for each level (Level 1, Level 2 shown in x - axis as L1 and L2) in Ggplot for each group for males and females. Top row graphs are RTs for females and bottom graphs are scores for males. Y axis shows the RTs for both genders.



3.5 Discussion

Males are more prone to having attention (Biederman et al., 2002; Stibbe et al., 2020) and stuttering (Dworzynki et al., 2007) issues than females. However, assessing this gender difference has not been a focus of research. Most studies focus on differences in cognition between PWADHD and PWS compared to controls and do not compare genders (see Table 1.1 in introduction). Therefore, this study assessed gender bias in controls, PWADHD and PWS in attention, speech, WM measures and performance in a visual selective attention task.

Results suggest that there was a significant difference between the groups in ASRS, SSI-3 and UNWR scores. PWADHD had more attention problems as assessed by ASRS followed by PWS and controls. Similar to Chapter 2, ASRS did differ between PWADHD and PWS. Highest SSI-3 (stuttering problems) were reported in PWS followed by PWADHD and controls. PWADHD were significantly less fluent than controls (as well as being significantly more fluent than PWS). WM problems were observed in PWS (lowest UNWR scores) followed by PWADHD and controls. UNWR was significantly different between controls vs PWADHD and controls vs PWS. There was no such effect in UNWR as in SSI-3 between PWADHD and PWS.

Analyses were then conducted to understand if there was an interaction effect of gender and group on ASRS, SSI-3 and UNWR. No interactions were observed suggesting that gender differences did not affect the results between the groups on the measures. RTs increased at level 2 for all groups with PWS having the highest RT followed by controls and PWADHD and RTs did not vary differently by group and gender. Such results were also confirmed from the LMM (Magezi, 2015).

Overall, analysis suggest that gender imbalance did not affect the results on cognitive and behavioural measures for PWADHD and PWS. However, one limitation of this study was to assess whether gender imbalances affected the measures based on ADHD subtypes. Such analyses would have been possible by assessing participants on ASRS v1.1 (Kessler et al., 2005). ASRS v1.2 (Ustun et al., 2017), utilized in this study, only includes six questions to assess overall ADHD symptoms. Therefore, investigating gender imbalances based on subtypes was not possible. PWADHD differed significantly from PWS in the selective attention task on RTs in level 2 with PWS performing significantly worse than PWADHD. Such results raises the question if PWS are impaired in selective attention tasks whilst PWADHD are not. Hence Chapter 4 will assess in detail cognitive, behavioural and physiological measures in PWS, PWADHD and controls in a selective attention task.

4. Chapter 4. Behavioural and Physiological measures in a Visual Selective Attention Task

Chapter Summary

Selective attention tasks have been utilized in the literature for PWS and have successfully identified significant differences between groups with lower performance reported in PWS as compared to controls (Doneva et al., 2018). Studies into selective attention have yielded contradictory results about PWADHD's performance with one study (Douglas & Peters, 1979) suggesting no difference between groups whilst other studies (Carter et al., 1995; van der Meere & Sergeant, 1988) suggested a lower performance in PWADHD compared to controls. However, no study has compared both PWADHD and PWS to controls in tasks that measure selective attention. Furthermore, oculomotor and brain activity measures have not yet been investigated between groups in such tasks. It is therefore appropriate to investigate behavioural and physiological measures in a selective attention task to understand which measure distinguishes PWADHD and PWS from controls and whether selective attention tasks can be utilized to assess attention problems in PWS and/or PWADHD.

Results on cognitive measures (see Table 4.5) showed lower attention abilities and working memory abilities in PWADHD and PWS while disfluency was more evident in PWS. Lower performance in the task was observed for PWS and PWADHD compared to controls. With regards to oculomotor measures, impulsive behaviour was higher in PWADHD compared to other groups as assessed from higher number of saccades, saccade mean velocity and number of fixations although measures in PWADHD only differed significantly for number of fixations supporting previous findings (Vakil et al., 2016). Symptoms of impulsivity were not present for PWS. Inattentiveness was evident in PWS as shown by lower fixation durations (as seen in Lowe et al., 2012) suggesting that selective attention task correctly distinguished PWS from other groups, but this was not the case for PWADHD. PWS differed significantly from other groups in alpha activity showing higher levels of wakefulness supporting findings in Baird

(1996) while beta was significantly higher for PWADHD suggesting no attention impairments in this group in selective attention tasks as seen in some studies (Chabot & Serfontein, 1996; Clarke, 2002; Clarke et al., 2011; Loo et al., 2009). PWADHD also differed from other groups in theta and TBR activity with lower values suggesting that the task could not assess inattentiveness and impulsivity from EEG measures in this group in contrast to previous findings on theta (Bresnahan & Berry, 2002) and TBR (Loo & Makeig, 2012; Monastra et al., 2001; Snyder & Hall, 2006). PWS recorded higher theta activity and although the difference was not significant, the results show that there is a trend for inattentive behaviour in this group. NMs suggest that in behavioural data PWS differed from controls in fish consumed in the shark game that participants played whilst for PWADHD this was not the case. With regards to the total score achieved in the game, the architecture of NM did not differ between groups. NMs on eye movements showed a different pattern between groups suggesting that eye movements are affected differently whilst NMs in EEG data showed that the frontal cortex in both PWS and PWADHD is impaired. Comorbidity between groups in selective attention task is limited as shown by NMs and selective attention tasks can correctly assess impulsive behaviours in PWADHD while attention problems are assessed in PWS.

4.1 Introduction

The capacity to distinguish between stimuli is referred to as selective attention (Sohlberg & Mateer, 1987) which typically entails responding to a target stimulus in the presence of distractor stimuli. Selective attention tasks can be visual or auditory. Good cognitive control, otherwise known as a good executive function, is comprised of a set of skills or abilities to maintain attention, have good social skills and good performance in many aspects of life. Cognitive control includes different types of attention such as sustained, divided, selective attention and attentional switching. Selective attention is related to the ability to ignore irrelevant information while prioritizing important information. Therefore, it is clear why poor cognitive regulation impairs attentional performance. Impairment of attentional performance can be caused by a decreased executive capacity (McVay & Kane, 2012), factors linked to a decline in cognitive resources, including ageing (Maylor & Lavie, 1998), or an increase in the complexity of the task (such as cognitive load introduced by Lavie et al., 2004). Selective attention is part of the Executive Function (EF), and EF impairments are observed in the prefrontal cortex (Fuster, 2008). Such impairments cause impulsive/hyperactive and attention problems. Hence ADHD has been linked to impairments in the prefrontal cortex (Geurts et al., 2004). While studies show many areas of brain involved in speech (frontal, temporal and parietal lobes), frontal regions have also shown strong connections with speech development (Cieslak et al., 2015; Jäncke et al., 2004) and studies also have found attention impairments in PWS in attention tasks (Andreou & Trott, 2013; Blood et al., 2007; Bosshardt, 1999; Heitmann et al., 2004; Ratcliff-Baird, 2002). It is therefore appropriate to test whether EF is impaired in PWS in a selective attention task and whether the frontal cortex is an important region involved in speech.

In PWADHD, selective attention tasks have been studied, but the results have been contradictory. Early studies in the field, (e.g., Douglas & Peters, 1979), did not identify any evidence for such deficiencies in CWADHD. However, other research conducted in the 1980s support the theory that PWADHD show poor performance in selective attention tasks compared to controls. For instance, van der Meere and Sergeant (1988) compared 12 hyperactive children to 12 controls in a visual selective attention task. In one condition without distractors, CWADHD and controls had to identify whether the target letter was visible in one of the four corners of the screen (presented on half of the trials). In the second condition with distractors, only one area of the screen was important. Targets in this area demanded a response, but on some trials, the target showed up as a foil. When the latter happened, task performance decreased with CWADHD responding in a more inconsistent and erroneous manner than controls. Since then, research on ADHD has placed a strong emphasis on executive functions, particularly investigating inhibitory control. In a thorough review of the literature, Barkley et al. (1992) highlighted that ADHD children struggle with the Stroop task's incongruent condition, where the participants need to name the colour of the word inconsistent with its meaning and may require inhibition to complete the task successfully. They concluded that activities demanding reaction inhibition were most frequently linked to deficiencies in PWADHD. However, some tests showed inconsistent results possibly due to age differences and test version. Although response inhibition is typically used to explain performance on tests like Stroop, the exact nature of this impairment remains unknown. In Carter et al.'s (1995) study a Stroop task was utilised to investigate the performance of 19 controls and 19 CWADHD. No differences were found between the groups in congruent conditions, but higher RTs were observed in CWADHD in incongruent conditions. This shows that CWADHD have an impairment in the incongruent trials only and not general issues in completing the task. Since the results were not associated with an increase in errors in response to incongruent stimuli, it was argued by Carter et al. (1995) that this was not simply due to impulsive responses, but rather revealed a specific ADHD issue in evaluating relevant and non-relevant stimuli to respond correctly which is known as an impairment in selective attention (Bundesen & Habekost, 2014). A framework for evaluating visual selective attention is provided by visual search tasks. The promise of these tasks has not been completely recognized in ADHD, even though they have long been utilised to provide insight into the mechanism of selective attention (Wolfe, 1998). Typically, the tasks require identifying targets among distractor stimuli. Mason et al. (2003) compared 28 CWADHD with 28 controls in a visual selective search task in which participants responded to visually identifying a target (blue letter H) with a mouse click and ignored distractions in three conditions (1-single condition had a blue letter A distractor; 2-conjunction condition and 3-preview condition (had both green H and blue A distractors).

Results showed that CWADHD had slower RTs overall and made more errors in conjunction and preview conditions although groups did not differ significantly.

Traditionally, studies have primarily concentrated on the speech difficulties that the disorder causes and how they negatively impact stutterers' lives (PWS). Recently, it has been investigated whether stuttering is truly a unitary issue as traditionally believed, or if it might instead be linked to certain other issues that are not specifically related to stuttering (Maxfield et al., 2012). Typically, this is accomplished by contrasting the performance of PWS and people who do not stutter (PWNS) on a range of tests that evaluate various abilities, such as WM (Bosshardt, 2002), motor control (Sommer et al., 2002), attention (Felsenfeld et al., 2010), or comorbidity with other disorders such as ADHD (Alm & Risberg, 2007). To better understand the relationship between stuttering and poorer attentional skills it is important to assess PWS from an attentional perspective and to look into any connections between stuttering and executive function. In Doneva et al. (2018) the map search task (a sub test part of the test of everyday attention (TEA)), participants (50 controls vs 50 PWS in age range 19-77) looked for symbols on a coloured map of Philadelphia. The number of symbols they found (out of 80) in two minutes determined their score. In this study, participants completed two 1-minute sessions, termed Map Search 1 (MS1) and Map Search 2 (MS2). MS1 denotes the number of symbols participants detected in the first minute of the task, whereas MS2 denotes the overall score (the number of symbols individuals identified over the course of the two-minute task). Better performance was indicated by a higher score on this subtest. Controls had better performance than PWS in both MS1 and MS2. During the 1-minute test, the PWS group identified significantly fewer target symbols than healthy controls (MS1). Although in the first part of the task (MS1) there was a significant difference between the two groups, performance on both MS1 and MS2 was negatively correlated with the severity of stuttering in PWS. In the same study, in the telephone search task (sub test of TEA), in a simulated telephone directory, participants searched for key symbols while looking for plumbers, restaurants, or hotels. The final score is the estimated time per target and better performance is indicated by a lower score. There were no significant differences between groups. However, this might also be considered as a divided attention task since participants are simultaneously conducting two tasks. In another task of this study (in the elevator counting with distraction task), participants while pretending they are in an elevator, had to count the low tones they hear while ignoring any high tones. Better performance is indicated by a higher score. Although the results were not significant, researchers found an interesting trend of PWS having a lower performance compared to controls. A summary of the studies mentioned above is shown in Table 4.1 and includes methodology, findings and limitations.

Table 4.1

Summary of studies assessing PWADHD and PWS in selective attention tasks including methods, statistical approaches, findings, and limitations of the tasks.

Study	*Attention Task*	*Groups*	*Method*	*Statistical Approach*	*Findings*	*Task Limitations*
van der Meere & Sergeant, 1988	Selective Visual	12 CWADHD 12 controls	Identifying targets while ignoring distractors	Analysis of Covariance ANCOVA	CWADHD made more errors compared to controls.	In ANCOVA the design of experiment must be strong to meet the requirements of causality. The task is artificial and results might be due to a loss of interest in the task.
Barkley et al., 1992	Selective Visual	Meta analysis of past studies	Stroop task, where the colour of the word is inconsistent with its meaning	Review of studies	CWADHD show poorer performance in Stroop task with deficiencies in inhibiting responses.	There is a discrepancy of the results in some studies in the Stroop tests.
Carter et al., 1995	Selective Visual	19 CWADHD 19 controls	Stroop task, where the colour of the word is inconsistent with its meaning	One Way ANOVA	No differences were found between the groups in congruent conditions, but higher RTs were observed in CWADHD in incongruent conditions.	One Way ANOVA cannot be reliable if data is not normally distributed. Task is artificial and can cause fatigue effects.
Mason et al., 2003	Selective Visual	28 CWADHD 28 controls	Participants responded with a mouse click to targets and ignore distractions	One Way ANOVA	Children with ADHD were less accurate and had slower RTs, but groups did not differ significantly.	One Way ANOVA cannot be reliable if data is not normally distributed.

Study	*Attention Task*	*Groups*	*Method*	*Statistical Approach*	*Findings*	*Task Limitations*
Doneva et al., 2018	Selective Visual	50 AWS 50 controls	Participants looked for symbols within 2 minutes in a map search task.	Multivariate Analysis of Covariance MANCOVA	Groups differed significantly with controls obtaining a higher score.	MANCOVA is difficult to interpret however is appropriate for the study. The task however is short which can limit the findings.
Doneva et al., 2018	Selective Visual	50 AWS 50 controls	Participants searched for key symbols while looking for plumbers, restaurants, or hotels.	Multivariate Analysis of Covariance MANCOVA	No significant group difference was observed.	MANCOVA is difficult to interpret however is appropriate for the study. It can be argued that the task measures divided attention instead of selective.
Doneva et al., 2018	Selective Audio	50 AWS 50 controls	Participants had to count the low tones they heard while ignoring high tones.	Multivariate Analysis of Covariance MANCOVA	No significant group difference was observed although PWS had a trend of having a poorer performance compared to controls.	MANCOVA is appropriate although the task is simple and artificial which can affect the results.

4.2 Experiment 4

Studies report contradictory results for PWADHD due to utilizing different methodologies. However, most of the studies suggest impairments in PWS in selective attention tasks with a lower performance compared to controls (see Table 4.1). Taking into consideration that both PWADHD and PWS have attentional impairments as suggested by the literature (Alm & Risberg, 2007; Andreou & Trott, 2013; Arndt & Healey, 2001; Biederman et al., 1993; Blood et al., 2007; Bosshardt, 1999; Donaher & Richels, 2012; Druker et al., 2019; Engelhardt et al., 2010; Heitmann et al., 2004; Ratcliff-Baird, 2002; Riley & Riley, 1979; Riley & Riley, 2000; Jacobson et al., 2011; Tucha et al., 2005) and symptoms of both disorders are comorbid in NM the following hypothesis were tested: Groups should differ from each other on their ASRS (H1) SSI (H2) and WM (H3) scores. In a game where fish consumed was the score, the groups should differ on fish consumed (H4), and the total scores achieved in the game should differ between groups (H5). For eye movements measured in the game, there should be differences between groups in the number of saccades (as found in Munoz et al., 2003 for PWADHD and understand if the pattern will be similar to PWS) (H6) in saccade mean velocities (similarly as in Munoz et al. 2003 for PWADHD and test if PWS will have the same results, H7), number of fixations (and in which direction to support and resolve inconsistencies from Gould et al., 2001; Lowe et al., 2012; Pelczarski et al., 2018; Vakil et al., 2016, H8), and in fixation durations (to test which previous studies from Lowe et al., 2012; Pelczarski et al., 2018; Vakil et al., 2016 are replicated, H9). For EEG measures, groups should differ from each other in alpha activity (to understand findings from Baird, 1996; El-Sayed et al., 2002; Lazzaro et al., 1998; Loo et al., 2009; Ratcliff-Baird, 2002, H10), in beta activity (to test for PWADHD which finding from Bresnahan & Berry, 2002; Chabot & Serfontein, 1996; Clarke, 2002; Clarke et al., 2011; El-Sayed et al., 2002; Lazzaro et al., 1998; Loo et al., 2009 will be replicated and understand if PWS will have impairments similar to PWADHD, H11), in theta activity (to test if the direction will be similar as in Baird, 1996; Bresnahan & Berry, 2002; Ratcliff-Baird, 2002, H12), in:

TBR (as suggested in Loo & Makeig, 2012; Monastra et al., 2001; Sengupta et al., 2019; Snyder & Hall, 2006, H13).

4.3 Methods

4.3.1 Participants

Ten controls (Mean age: 21.40, SD: 1.350, 6 Females and 4 Males) were recruited through the UCL Sona participant pool. Eight PWADHD, three clinically diagnosed and the rest reported attention and/or hyperactive problems (Mean age: 28.38, SD: 11.173, 5 Females and 3 Males) volunteered through UCL Sona, advertisements on Facebook and from meet-up groups (e.g., London Adult ADHD Meet-Up group). Nine PWS (Mean age: 39.44, SD: 12.105, 5 Females and 4 Males) found the study from an advertisement on the British Stammering Association. Approval was obtained by UCL Research Ethics Committee (6252/002). Participants received £7.50 for participating in the study and a refund for travel expenses within the M25 area. All participants received an information sheet and a consent form to sign prior to conducting the study. Power analysis revealed that in one way ANOVA, with an effect size of 0.8, in 3 groups, there is an 86% chance of detecting an effect.

4.3.2 Design

Participants completed the ASRS questionnaire, read paragraphs from the SSI-3 manual and completed the UNWR task. After this step, participants conducted a visual selective attention game in VR in which scores obtained in the game, RTs, oculomotor and brain activity measures were obtained in real-time. The order of the tasks was counterbalanced and was determined by the ID of the users' (e.g., the first participants had ID '001', the second ID '002' and so on). If participants' ID was an odd number, the order of the tasks was ASRS, SSI-3, VR task, and UNWR. If the ID was an even number, the order was UNWR, VR task, ASRS, SSI-3. The dependent variables were behavioural and physiological measures whereas the between-participants factor was the participants' group.

4.3.3 Materials

A Google Pixel 2 smartphone was used to download the VR visual selective attention game Hungry Shark[15] from the Google Play Store. The google pixel 2 was chosen because it was one of the android smartphones required to work with the Looxid VR[16] headset. Looxid headset has a built in EEG and eye tracker to collect physiological data and a place to insert the smartphone. Through the smartphone, users can interact with applications either using the Looxid remote or from head movements depending on the VR application. The smartphone was placed into the Looxid VR headset, with the application running while the headset was wired to the MacBook laptop to enable the connection between the VR headset with the Looxid eye tracking and EEG plugin. The plugin (provided by Looxid company) was downloaded into the laptop before running the application. The game Hungry Shark was chosen because it offers accurate measurements of what can be inferred as visual selective attention (fish eaten, overall score, time taken), to focus on completing the game while avoiding predators allowing for thorough comparisons between groups. As a result, the game provided a spectrum of attentional measurements and a direct link between attention, eye movements and EEG.

4.3.4 Measures

1-Adult ADHD Self-Report Scale Screener, (ASRS; Ustun et al., 2017)

2-Stuttering Severity Instrument version 3, (SSI-3; Riley, 1994)

3-Universal Non-Word Repetition Test, (UNWR; Howell et al. 2016)

4.3.5 Procedure

Prior to signing the consent form, participants read an information sheet. The next step involved testing for hearing and vision. Depending on their participant ID, the participants either completed the ASRS, SSI-3, or UNWR. Next, instructions were given to the participants on how to play the Hungry Shark game after finishing whichever two questionnaires or tasks were

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[15] Hungry Shark Game: https://play.google.com/store/apps/details?id=com.ubisoft.vrhungryshark

[16] Looxid VR headset: https://looxidvr.looxidlabs.com/

assigned to them. Their mission was to consume as much prey as they could as a shark in the game while avoiding predators (bigger sharks), hunters (people bearing weapons), and shark-harming creatures (e.g., jellyfish). The survival and energy bars, which represented survival rate and hunger levels, were located at the top of the screen. The latter had an impact on the former. Once players understood the game, the headset was placed on (with the EEG electrodes properly aligned confirmed by the Looxid application). Participants received a controller that determined the shark's pace and the participant’s head motions controlled the motion of the shark. Participants started the game when they were ready because the experimenter was unable to view or control the VR screen. When the game started (indicated by in-game sound cues), the experimenter pressed a button in the Looxid VR application to start EEG and eye recordings. When the shark died, recordings were stopped by the experimenter. Participants were instructed to end the game if the task was not completed within a time limit of 10 minutes. After the task was finished, participants reported how much fish the shark ate overall as well as the overall score obtained in the game. Participants were only permitted to retake the trial once if they failed to report such information. The experimenter kept track of how long it took players to finish the game. Participants were not required to finish the game as soon as possible nor required to reach to a specific destination and therefore a lower RT to complete the game did not indicate a better performance.

4.4 Results

4.4.1 Experiment 4a Results

Table 4.2

Descriptive Statistics, hypothesis, and results for ASRS, SSI-3, UNWR.

	Outliers	**Shapiro-Wilks**	**One Way ANOVA**	**Kruskal Wallis**	**Hypothesis Met?**
H1: Groups should differ from each other on their ASRS scores.	None	p = 0.353	p < 0.001	NA	**Accepted**
H2: Groups should differ from each other on their SSI-3 scores.	None	p < 0.001	p < 0.001	p < 0.001	**Accepted**
H3: There should be a difference between the groups in the WM scores.	None	p = 0.014	p < 0.001	p < 0.001	**Accepted**

H1: Groups should differ from each other on their ASRS scores.

Data had no outliers and was normally distributed F (27) = 0.959, p = 0.353. Descriptive statistics (Table C4.1 in Appendix C) showed that PWADHD had highest ASRS followed by PWS and controls (see Figure 4.1). Groups differed significantly on ASRS scores on parametric test F(2, 24) =14.132, p < 0.001 as shown by ANOVA (Table 4.2). Therefore, H1, was supported. Tukey post-hoc test showed that Controls vs PWADHD (p < 0.001) and Controls vs PWS (p = 0.026) differed significantly.

H2: Groups should differ from each other on their SSI-3 scores.

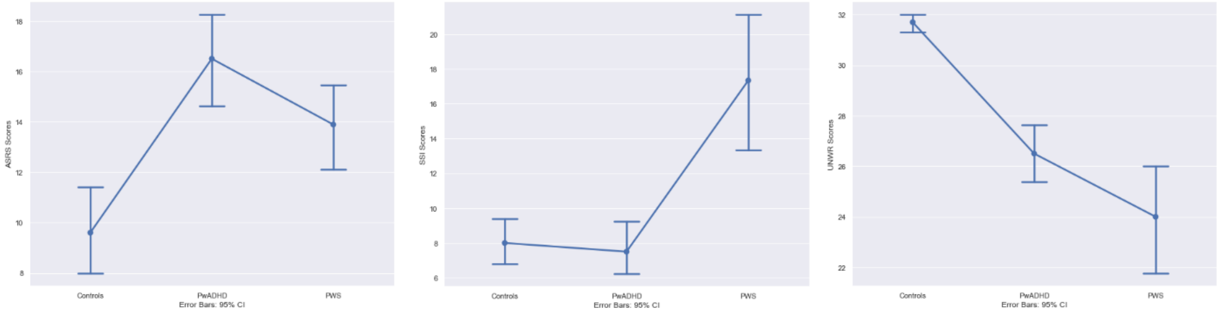
PWS had the highest SSI-3 followed by controls and PWADHD (see Figure 4.1). H2 was accepted as groups differed significantly on SSI-3 scores (see Table 4.2). Specifically, the Tukey post-hoc test showed that PWS differed significantly from Controls (p < 0.001), and PWADHD (p < 0.001).

H3: There should be a difference between the groups in the WM scores.

Controls had the highest WM scores followed by PWADHD and PWS as shown in Figure 4.1. Groups differed significantly and therefore H3 was accepted (see Table 4.2). Post-hoc test showed that Controls differed significantly from PWADHD ($p < 0.001$) and PWS ($p < 0.001$).

Figure 4.1

Mean ASRS (left graph), SSI-3 (middle graph), UNWR (right graph) scores per group. Controls shown in the first x axis, PWADHD in second x - axis and PWS in the third x - axis values in each graph. Error bars represent ± 2 Standard Error [SE].



4.4.2 Experiment 4b Results

Table 4.3

Descriptive Statistics, hypothesis, and results for scores achieved in the game.

	Outliers	Shapiro-Wilks	One Way ANOVA	Kruskal Wallis	Hypothesis Met?
H4: Groups should differ from each other in fish consumed in the game.	Some outliers were removed	$p = 0.010$	$p < 0.001$	$p < 0.001$	**Accepted**
H5: The total scores achieved in the game should differ between groups.	Some outliers were removed	$p = 0.015$	$p < 0.001$	$p < 0.001$	**Accepted**

H4: Groups should differ from each other in fish consumed in the game.

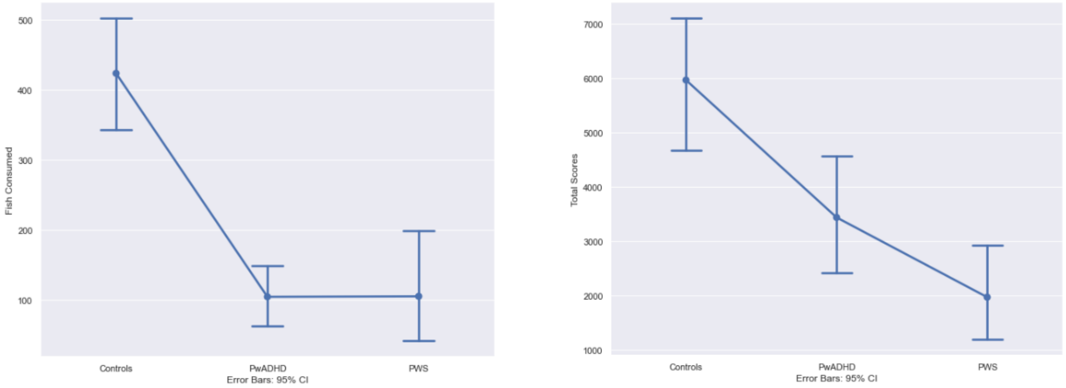
The highest number of fish consumed were recorded from controls whilst PWADHD and PWS had similar scores as shown by descriptive statistics (Table C4.2 in Appendix C) and Figure 4.2. PWS had slightly higher scores in fish consumed compared to PWADHD. H4 was supported as groups differed significantly (see Table 4.3). Post-hoc test showed that Controls differed significantly from PWADHD ($p < 0.001$) and PWS ($p < 0.001$).

H5: The total scores achieved in the game should differ between groups.

Controls had the highest scores followed by PWADHD and PWS (Figure 4.2). Groups differed significantly therefore H5 was accepted (see Table 4.3). Groups that differed significantly were Controls vs PWADHD ($p < 0.019$) and Controls vs PWS ($p < 0.001$).

Figure 4.2

Mean fish consumed (left graph) and the total score achieved in the game (right graph) per group. Controls are shown in the first x axis, PWADHD shown in second x - axis and PWS presented in the third x - axis in both graphs. Error bars represent ± 2 Standard Error [SE].



4.4.3 Experiment 4c Results

Table 4.4

Descriptive Statistics, hypothesis, and results for physiological measures.

	Outliers	**Shapiro-Wilks**	**One Way ANOVA**	**Kruskal Wallis**	**Hypothesis Met?**
H6: There should be differences between groups in the number of saccades.	Some outliers were removed	p = 0.673	p = 0.003	NA	**Accepted**
H7: Groups should differ from each other in saccade mean velocities.	Some outliers were removed	p = 0.649	p = 0.023	NA	**Accepted**
H8: Number of fixations should differ between groups.	Some outliers were removed	p = 0.632	p = 0.002	NA	**Accepted**
H9: Groups should differ from each other in fixation durations.	Some outliers were removed	p = 0.794	p = 0.009	NA	**Accepted**
H10: Groups should differ from each other in alpha activity.	Some outliers were removed	p = 0.123	p = 0.002	NA	**Accepted**
H11: There should be a difference between the groups in beta activity.	Some outliers were removed	p = 0.014	p = 0.006	p = 0.042	**Accepted**
H12: Groups should differ from each other in theta activity.	Some outliers were removed	p = 0.906	p < 0.001	NA	**Accepted**
H13: TBR should differ between groups.	Some outliers were removed	p = 0.347	p = 0.046	NA	**Accepted**

H6: There should be differences between groups in the number of saccades.

NOS were highest in PWADHD followed by controls and PWS (see Table C4.3 in Appendix C) and Figure 4.3. Groups differed significantly in NOS therefore H6 was supported (see Table

4.4). Post-hoc test showed that Controls differed significantly from PWS (p = 0.028) and PWADHD differed from PWS (p = 0.003).

H7: Groups should differ from each other in saccade mean velocities.

PWADHD were highest in SMV followed by controls and PWS (see Figure 4.3). Groups differed significantly in SMV (see Table 4.4) and H7 was accepted. Post-hoc test showed that PWS differed significantly from PWADHD (p = 0.022).

H8: Number of fixations should differ between groups.

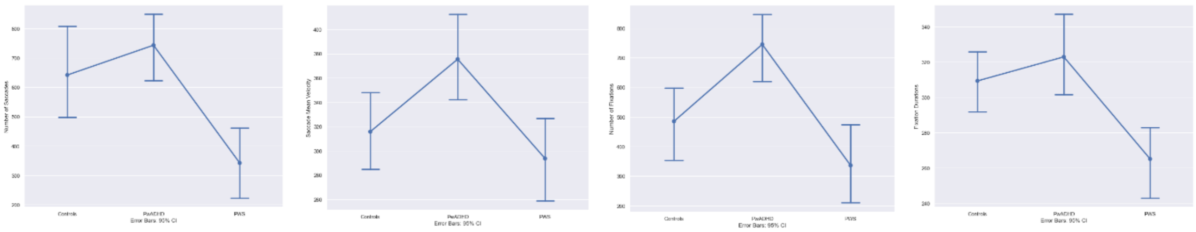
PWADHD had highest NOF followed by controls and PWS (see Figure 4.3). Groups differed significantly in NOF (see Table 4.4). Therefore, H8 was supported. Controls and PWADHD differed significantly (p = 0.030) and PWADHD differed significantly from PWS (p = 0.001).

H9: Groups should differ from each other in fixation durations.

FD were highest in PWADHD followed by controls and PWS as shown in Figure 4.3. Groups differed significantly in FD (see Table 4.4) and H9 was supported. Groups that differed significantly were Controls vs PWS (p = 0.050) and PWADHD vs PWS (p = 0.008).

Figure 4.3

Mean NOS (first graph), SMV (second graph), NOF (third graph) and FD (fourth graph) per group. Controls shown in the first x axis, PWADHD presented in second x - axis and PWS visualised in third x - axis in all graphs. Error bars represent ± 2 Standard Error [SE].



H10: Groups should differ from each other in alpha activity.

Alpha was highest in PWS followed by controls and PWADHD (see Table C4.3 in Appendix C, Figure 4.4). Groups differed significantly in alpha as shown in Table 4.4. Hence H10 is accepted. Groups that differed significantly were Controls vs PWS (p = 0.025) and PWADHD vs PWS (p = 0.001).

H11: There should be a difference between the groups in beta activity.

PWADHD recorded the highest beta values followed by PWS and controls (Figure 4.4). H11 was supported as groups differed significantly (see Table 4.4). Specifically significant differences were observed between Controls vs PWADHD (p = 0.007) and PWADHD vs PWS (p = 0.008).

H12: Groups should differ from each other in theta activity.

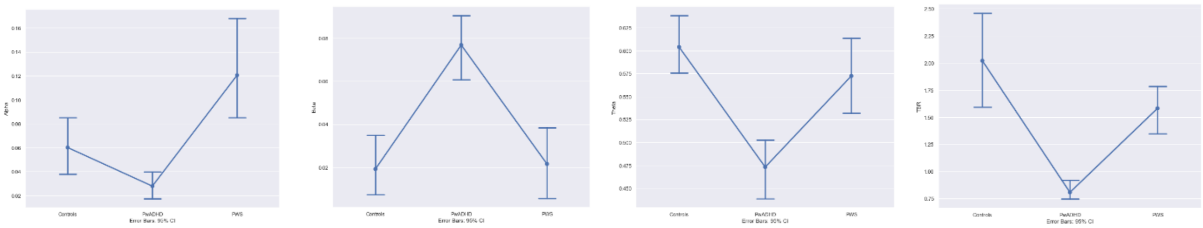
Controls recorded the highest theta followed by PWS and PWADHD as shown in Figure 4.4. Groups differed significantly (see Table 4.4). Hence H12 is supported. Post-hoc tests showed significant differences were observed between Controls and PWADHD (p < 0.001) and PWADHD vs PWS (p = 0.005).

H13: TBR should differ between groups.

TBR was the highest in Controls followed by PWS and PWADHD as shown in Figure 4.4. Groups differed significantly as shown in Table 4.4 and therefore H13 was accepted. Controls and PWADHD (p = 0.007) and PWADHD vs PWS (p = 0.001) differed significantly.

Figure 4.4

Mean Alpha, Beta, Theta, TBR activity per group presented from the first to the fourth graph respectively. In the x axis, controls are shown first followed by PWADHD and PWS. Error bars represent ± 2 Standard Error [SE].



4.4.4 Experiment 4d Results

To further understand whether PWADHD and PWS are comorbid in behavioural, eye tracking and EEG measures, NMs were conducted on significant results. All measures besides (theta/beta ratio) TBR were plotted in NM. TBR was not included in NM because the sample covariance matrix in TBR was not positive definite (as shown from output in R). The results for behavioural data suggest that controls differed from PWS but were similar to PWADHD in fish consumed while for the total score, groups showed no differences from each other (see Figure 4.5). NMs from eye tracking data showed that the NM architecture was different between groups (Figure 4.6). There were comorbidities in EEG measures between PWS and PWADHD for alpha, beta and theta values which differed from controls suggesting that in both PWS and PWADHD prefrontal cortex was impaired (see Figure 4.7).

Figure 4.5

NMs for fish consumed (left graph) and total score (right graph) in the task for Controls, PWADHD and PWS. The first letter in nodes stands for the group (C – Controls; A-PWADHD; S-PWS), FC stands for fish consumed, TS stands for total score.

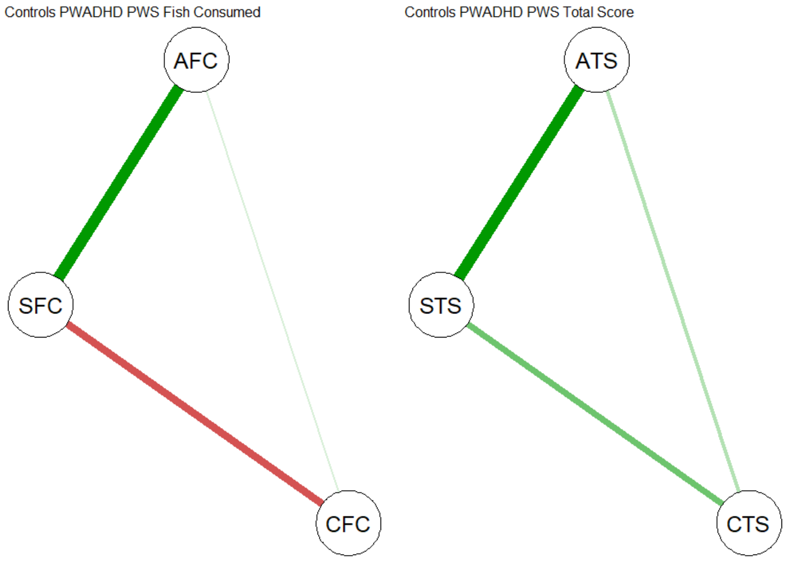


Figure 4.6

NMs for eye tracking measures for Controls, PWADHD and PWS. The first letter in nodes stands for the group (C – Controls; A-PWADHD; S-PWS), NOF, NOS, FD, SM stands for number of fixations, number of saccades, fixation durations, saccade mean velocity respectively.

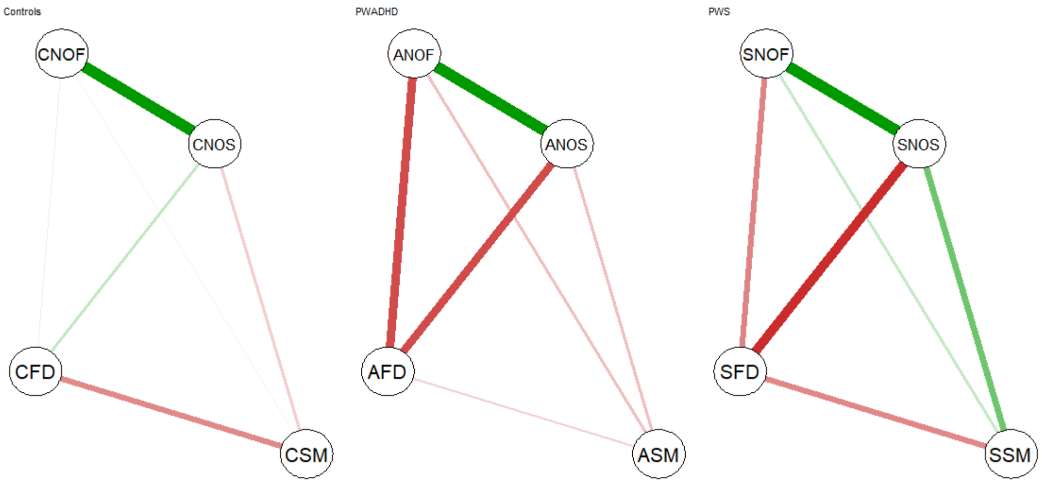
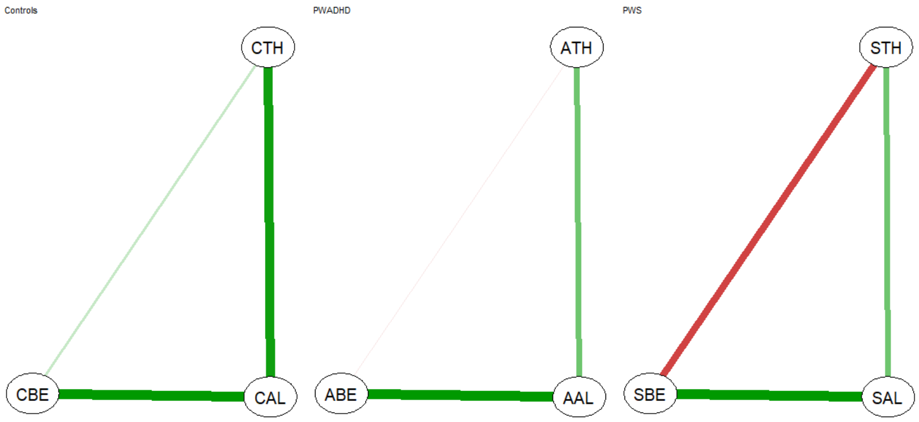


Figure 4.7

EEG data shown in NMs for Controls, PWADHD and PWS. The first letter in nodes stands for the group (C – Controls; A-PWADHD; S-PWS), TH, AL, BE stand for theta, alpha, beta respectively.



4.5 Discussion

The aim of the study was to understand whether EF which is related to frontal cortex (Fuster, 2008), is impaired in PWS similarly as in PWADHD (Geurts et al., 2004). For this purpose, PWADHD and PWS were compared to controls in a selective attention task which is part of the EF. Research suggests that PWS show impairments in selective attention tasks (Doneva et al., 2018) while for PWADHD results have been contradictory with some studies showing impairments (Carter et al., 1995; van der Meere & Sergeant, 1988) and others showing no significant differences between PWADHD and controls (Douglas & Peters, 1979; Mason et al., 2003). Hence it was necessary to test both groups in a task that measures selective attention and understand if groups are comorbid in cognitive, behavioural, and physiological measures.

Results from cognitive abilities suggested that both PWS and PWADHD have attention impairments as assessed by ASRS and differed significantly from controls ($p = 0.026$; $p < 0.001$) supporting the literature that attention problems are evident in both groups (Alm & Risberg, 2007; Andreou & Trott, 2013; Arndt & Healey, 2001; Biederman et al., 1993; Blood et al., 2007; Bosshardt, 1999; Donaher & Richels, 2012; Druker et al., 2019; Engelhardt et al., 2010; Heitmann et al., 2004; Ratcliff-Baird, 2002 Riley & Riley, 1979; Riley & Riley, 2000; Jacobson et al., 2011; Tucha et al., 2005). Stuttering symptoms on SSI-3 were observed in PWS and differed from other groups ($p < 0.001$) suggesting no comorbidity between PWS and PWADHD in symptoms of disfluency in this study in contrast to what other research suggests (Andreou & Trott, 2013; Biederman et al., 1993; Engelhardt et al., 2010; Jacobson et al., 2011; Tucha et al., 2005). Both PWADHD and PWS showed working memory problems and differed significantly from controls ($p < 0.001$; $p < 0.001$) confirming previous findings (Bakhtiar et al., 2007; Byrd et al., 2015; Hakim & Ratner, 2004; Martinussen et al., 2005). Task performance was significantly lower in PWS and PWADHD compared to controls in both fish consumed ($p < 0.001$; $p < 0.001$) and the total score ($p < 0.001$; $p < 0.019$) suggesting impairments in selective attention tasks in both PWS and PWADHD (Carter et al., 1995; Doneva et al., 2018;

van der Meere & Sergeant, 1988). However, data from the eye tracker suggested that the tasks correctly assessed hyperactivity symptoms in PWADHD as seen by a significantly higher NOF (p = 0.030) in this group supporting the literature (Vakil et al., 2016) and confirming that PWADHD have inabilities in supressing impulsive behaviour related to impairments in prefrontal cortex (Munoz et al. 2003). While impulsive symptoms shown by NOF were not present in PWS, (although the pattern was similar as in Lowe et al. (2012) with lowest NOF recorded in PWS), selective attention task distinguished this group from controls (p = 0.050; as seen in Pelczarski et al., 2018) and PWADHD (p = 0.008) in inattentive symptoms as observed from lower FD suggesting that PWS show impairments in attention in selective attention tasks. For PWADHD, FD (although not significant) were higher than other groups replicating findings in Vakil et al. (2016) suggesting that this group do not show inattentiveness in selective attention tasks. The direction of NOS in PWADHD was similar to that in Munoz et al., (2003) which suggested higher NOS associated with higher impulsivity in PWADHD, although the findings were not significant possibly due to the chosen attention task (Munoz et al's used sustained attention task). NOS was significantly lower in PWS compared to controls (p = 0.028) and PWADHD (p = 0.003) showing again a lower impulsivity. SMV, similar to NOS, were higher in PWADHD showing higher impulsive behaviours as in Munoz et al. (2003), but this measure in PWADHD was not significant from controls and differed significantly from PWS (p = 0.022) suggesting again that PWS do not have symptoms of hyperactivity.

PWS differed from controls (p = 0.025) and PWADHD (p = 0.001) with higher alpha activity replicating findings from Baird, (1996) suggesting that this group had higher levels of wakefulness in contrast with PWADHD who recorded the lowest values (although did not differ significantly from other groups the pattern was similar as in El-Sayed et al., 2002; Lazzaro et al., 1998). With regards to beta activity, PWADHD differed significantly from controls (p = 0.007) and PWS (p = 0.008) recording higher values (as in Chabot & Serfontein, 1996; Clarke, 2002; Clarke et al., 2011; Loo et al., 2009) suggesting that attention was significantly higher in PWADHD confirming again that PWADHD show no attention problems in selective attention tasks. Whilst beta was lower in PWS, values did not differ significantly. There was a positive trend for PWS to have higher theta values (as opposed to findings from Baird, (1996) and Ratcliff-Baird, (2002)) and although the findings were not significant, they suggest that PWS had higher inattentiveness. In contrast, PWADHD had significantly lower theta compared to controls (p < 0.001) and PWS (p = 0.005) contradicting previous findings (Loo & Makeig, 2012; Monastra et al., 2001; Snyder & Hall, 2006). It can be argued that theta activity differs across different types of attention tasks. Furthermore, higher theta values indicate higher inattentiveness and based on oculomotor measures, we would expect higher inattentiveness in PWS and higher attention in PWADHD in selective attention task from EEG data. Similarly, as in theta activity, TBR in PWADHD was significantly lower than controls (p = 0.007) and PWS (p = 0.001) in contrast to previous findings (Loo & Makeig, 2012; Monastra et al., 2001; Snyder & Hall, 2006) which suggest a higher TBR in PWADHD associated to higher impulsivity. For PWS, results in Sengupta et al. (2019) were not replicated although PWS did not differ significantly from other groups. Again, findings might differ in different attention task, although the result suggest that TBR might not be a good indicator to assess ADHD traits in PWADHD and PWS.

NMs from behavioural data suggested that only PWS differed from controls in fish consumed in the task while the architecture on the total score did not differ between groups. Eye pattern behaviour differed across groups while EEG data showed comorbidities between PWS and PWADHD suggesting that prefrontal cortex is impaired in both groups supporting the literature (Cieslak et al., 2015; Geurts et al., 2004; Jäncke et al., 2004). See Table 4.5 for a summary of all the results achieved in this experiment including comparisons with previous studies.

Overall, the results suggest that: 1- selective attention tasks can assess impulsive behaviours in PWADHD but this type of task can assess inattentive impairments only in PWS; 2- eye movement behaviour differs between PWS and PWADHD but both groups show impairments in the frontal cortex in EF abilities; 3- selective attention tasks are more appropriate to assess PWS than PWADHD as shown by NM and physiological measures confirming studies that suggest PWS show impairments in selective attention tasks (Doneva et al. 2018) while such tasks are not appropriate to distinguish PWADHD (Douglas & Peters, 1979; Mason et al., 2003). The study confirmed that selective attention tasks in EF are appropriate to assess attention problems in PWS but not in PWADHD. This raises the question, which type of attention task in EF can assess inattentiveness as well as hyperactivity in PWADHD? Furthermore, what pattern of results would we expect from behavioural, oculomotor and EEG measures in the attention task that correctly assesses ADHD traits in PWADHD? To answer these questions, behavioural (Chapter 5), eye (Chapter 6) and EEG (Chapter 7) measures were investigated between controls and PWADHD in 10 VR tasks which are based in real-life scenarios and include all types of attentions in EF.

Table 4.5

A summary of the results in experiment 4 in all measures between groups and conclusions on supported literature or inconsistencies.

	Groups	**Comparisons with the literature and comments**
	Controls vs PWADHD vs PWS	*Supported literature or inconsistencies*
Cognitive Measures		
ASRS scores	A > S > C*	Alm and Risberg (2007), Andreou and Trott (2013), Arndt and Healey (2001), Biederman et al. (1993), Blood et al. (2007), Bosshardt (1999), Donaher and Richels (2012), Druker et al. (2019), Engelhardt et al. (2010), Heitmann et al. (2004), Ratcliff-Baird (2002), Riley and Riley (1979), Riley and Riley (2000), Jacobson et al. (2011), Tucha et al. (2005).
SSI-3 scores	S* > C > A	No comorbidity between PWS and PWADHD in contrast to what research suggests (Andreou & Trott, 2013; Biederman et al., 1993; Engelhardt et al., 2010; Jacobson et al., 2011; Tucha et al., 2005)
UNWR scores	C* > A > S	Bakhtiar et al. (2007); Byrd et al. (2015); Hakim and Ratner (2004); Martinussen et al. (2005)
Behavioural Measures		
Fish consumed	C* > S > A	Significant difference between controls and PWADHD in selective attention tasks, supports findings from some studies (Carter et al., 1995; van der Meere & Sergeant, 1988). Significant differences between controls and PWS support findings from (Doneva et al., 2018).
Total score	C* > A > S	
Eye Measures		
Number of Saccades	A > C > S*	Findings in Munoz et al. (2003) which suggests C < A is supported for PWADHD although not significant possibly due to attention task (Munoz used sustained attention task). NOS is significantly lower in PWS showing a lower impulsivity. No comorbidity between A and S in impulsive behaviour.
Saccade Mean Velocities	A > C > S (A≠S)*	Munoz et al. (2003) is supported for PWADHD although not significant showing SMV in selective attention task is not a good indicator of impulsive behaviour in PWADHD. No comorbidity between A and S in impulsive behaviour.
Number of fixations	A* > C > S	Vakil et al. (2016) is supported for PWADHD showing impulsivity can be assessed by NOF in selective attention tasks. Lowe et al. (2012) is supported in PWS although not significant. No comorbidity between A and S in impulsive behaviour.
Fixation Durations	A > C > S*	For PWS, Pelczarski et al. (2018) is supported showing selective attention task can assess inattentiveness in this group. For PWADHD, although not significant, Vakil et al. (2016) is supported. Selective attention task cannot distinguish PWADHD in attention problems. No comorbidity between A and S in inattentiveness behaviour.

	Groups	Comparisons with the literature and comments
	Controls vs PWADHD vs PWS	*Supported literature or inconsistencies*
EEG Measures		
Alpha Activity	S* > C > A	Findings from Baird, (1996) are supported in PWS showing that this groups had higher levels of wakefulness. For PWADHD lower levels of wakefulness were observed supporting previous studies (El-Sayed et al., 2002; Lazzaro et al., 1998) although not significant. No comorbidity between A and S in alpha activity.
Beta Activity	A* > S > C	Previous findings in PWADHD (Chabot & Serfontein, 1996; Clarke, 2002; Clarke et al., 2011; Loo et al., 2009) are supported showing that attention was significantly higher in PWADHD confirming again that PWADHD show no attention problems in selective attention tasks. No comorbidity between A and S in beta activity.
Theta Activity	C > S > A*	For PWADHD, findings from Bresnahan and Berry, (2002) are not supported showing no inattentiveness in this group in tasks that measure selective attention. Although not significant previous results in PWS (Baird, 1996; Ratcliff-Baird, 2002) are not replicated. No comorbidity between A and S in theta activity.
Theta-Beta Ratio	C > S > A*	Previous findings in PWADHD are not supported (Loo & Makeig, 2012; Monastra et al., 2001; Snyder & Hall, 2006) suggesting that TBR is not a good indicator of ADHD in selective attention tasks. For PWS, results in Sengupta et al. (2019) are not replicated although PWS did not differ significantly from other groups. No comorbidity between A and S in TBR.
Network Models		
Behavioural Data FC	A = (C ≠ S)	PWS are impaired in selective attention tasks (Doneva et al., 2018) while PWADHD show no differences from controls (Douglas & Peters, 1979; Mason et al., 2003).
Behavioural Data TS	C = A = S	
Eye Data	C ≠ A ≠ S	The pattern of eye movements differs in all groups.
Brain Data	C ≠ (A = S)	Frontal cortex is impaired in PWS and PWADHD (Cieslak et al., 2015; Geurts et al., 2004; Jäncke et al., 2004).

Note. C stands for Controls, A for PWADHD and S represents PWS. The sign (*) shows that the group differed significantly from other groups. (A≠S)* shows that PWADHD differed significantly from PWS. A = (C ≠ S) means that Controls differed from PWS but both were similar to PWADHD. C ≠ (A = S) indicates that while PWADHD were similar to PWS, both groups differed from Controls. FC stands for Fish Consumed while TS represents Total Score.

5. Chapter 5. Real-life VR Scenarios in different attention tasks to assess attention problems.

Chapter Summary

EF is compromised by WM and subserves a set of skills that are part of our daily activities. EF impairments are seen in prefrontal cortex that cause inattentive and hyperactive deficits. Hence ADHD has been linked to impairments in the prefrontal cortex (Geurts et al., 2004). Different types of attention are part of EF including sustained, selective, divided and switched attention. It has been suggested that deficits in EF can distinguish PWADHD from typical controls (Boonstra et al., 2005; Re et al., 2015; Willcutt et al., 2005). However, studies report contradictory results with some studies suggesting poorer performance in PWADHD in a certain type of attention and other studies suggesting impairments with other types of attention (see Table 5.1). It can be argued that studies are limited in methodological aspects such as testing small numbers of participants and utilize tasks that are artificial and far from those in real-life where attention problems arise in daily activities. Furthermore, no study has tested PWADHD across all types of attention. Hence, to address these limitations, a comprehensive range of attention tasks were investigated in this chapter using controls and PWADHD in a VR environment that approximated real-life scenarios.

This chapter investigates cognitive measures assessed by ASRS, SSI and UNWR between PWADHD and controls. Then behavioural measures and questionnaires in 10 VR tasks compared between PWADHD and controls follows. The aim of this chapter is to: 1- understand if PWADHD differ from controls on cognitive measures; 2- determine which particular task in which domain correctly assesses ADHD traits as shown from t-tests and NMs (Are PWADHD impaired in all EF abilities or only in particular attention tasks?); 3- draw further conclusions from questionnaires on each task on their performance and VR technology. Chapter 6 focuses on exploring eye tracking measures in the tasks introduced in this chapter and specifically in tasks that show impairments in PWADHD as determined in this chapter.

Specifically, what are the eye measures that can correctly assess ADHD traits in impaired EF attention tasks? Conclusions are made based on t-tests and NMs. Whereas chapter 7 further investigates EEG measures in the 10 VR tasks and in particularly the tasks that assessed ADHD traits in PWADHD to assess the pattern of these measures from t-tests and NMs. Additionally, is frontal cortex impaired in PWADHD?

Cognitive measures showed higher attention problems, disfluency and working memory problems in PWADHD as assessed by ASRS, SSI, UNWR supporting previous studies (Andreou & Trott, 2013; Biederman et al., 1993; Engelhardt et al., 2010; Jacobson et al., 2011; Marchetta et al., 2008; Martinussen et al., 2005; Rapport, 2001; Tucha et al., 2005). Based on behavioural data, PWADHD were affected more in sustained attention tasks regardless of the domain assessed and in switched attention task only in the visual domain. The results supported the literature that PWADHD do not suffer in all EF abilities (Duff & Sulla, 2015; Lambek et al., 2010; Nigg et al., 2005). The two main tasks that best assess ADHD traits in sustained attention tasks were the pro saccade (task 4) and anti saccade (task 5) tasks first introduced in Hallett (1978) and tested in PWADHD later in Munoz et al. (2003). Both tasks are appropriate for assessing poorer performance in PWADHD who have lower accuracy and longer RTs. Task 9 that drew upon switched attention in the visual domain, correctly distinguished PWADHD from controls with lower accuracy and longer RT to complete the task. NMs from behavioural data showed a different architecture between groups in all sustained attention tasks and attentional switching task in the visual domain confirming previous findings. Finally, results from questionnaires showed that overall PWADHD were more distracted and had less confidence in completing the tasks compared to controls. Both groups strongly agreed that the tasks were interesting and that they felt present in VR.

5.1 Introduction

5.1.1 Executive Function in types of attention

Attention can be thought of as a part of executive control. As a result, the executive control system must choose the targets for attention and communicate them to the systems responsible for executing them. Executive control and WM are linked, as the ability to use previous information whilst also keeping a present goal in mind requires WM (Lindsay, 2021). Different types of attention are involved in part of our everyday life. The four main types of attention are: sustained, selective, divided, and alternating (switching) attention which are all part of the EF. Deficiencies in EF occur in PWADHD (Re et al., 2015; Willcutt et al., 2005;). According to Miyake and Friedman (2012), EF refers to a set of abilities that enable the creation, control, regulation, and execution of actions necessary to accomplish complicated goals, particularly actions that enable us to respond to new situations. It would be difficult to make judgments, follow the rules, control emotions, maintain healthy social interactions, or ensure knowledge acquisition if these skills are impaired. Additionally, EF can be seen as a component of the attentional regulation of WM which significantly impacts academic performance (McCloskey et al., 2009; Miranda et al., 2015). Several tasks in EF implemented by researchers to measure each type of attention are described below (Table 5.1). Studies show conflicting results for the same attention type tasks and no study has assessed all tasks in PWADHD. The discrepancy of the results in previous studies requires testing all EFs components in PWADHD. Furthermore, most of the tasks tend to be laboratory-based and employ artificial stimuli often in 2D. VR technology can be used to eliminate such limitations in creating tasks in a more controlled environment in which researchers can create real-life scenarios.

5.1.2 Sustained Attention

In its most basic form, attention can be defined as a sustained state of alertness or the ability to engage with one's surroundings. It interacts with wakefulness in this way. In psychology, vigilance refers to the ability to sustain attention (Lindsay, 2021). By giving individuals repetitive activities that demand a level of sustained attention, researchers have noticed extended intervals of poor performance in sleepy patients that correlate with changes in EEG signals (Makeig et al., 2000; Mai et al., 2019). Martel et al. (2014) assessed the Mackworth Clock task in 12 controls who focused their gaze on a pointer that moved clockwise and they responded as fast as possible in the event of a jump of the pointer. From the repeated measures ANOVA, the participants had lowered ability for detecting the stimuli, a characteristic of the sustained attention known as vigilance decrement. Results also showed an increase of alpha frequency as assessed by the EEG. Sustained attention tasks have also been investigated in PWADHD. Such tasks involve focusing on a target for a period of time. Loo et al. (2009) assessed differences in brain activity between 38 AWADHD and 42 controls in the Conners CPT (Conners, 2012) in a 14-minute sustained attention task. Participants pressed the space bar for any letter shown except for letter “X”. Results from the repeated measures ANOVA suggested a difference in frontal and parietal regions between controls and PWADHD with higher alpha and beta values observed in the ADHD group. In another study (Tucha et al., 2009) two sustained attention tasks were carried out by 38 AWADHD, 38 healthy adults, 52 CWADHD and 52 healthy children. In the first task, participants had to press a button when a visual stimulus showed on the computer screen. In the second task, a two-square structure was displayed in the middle of the computer screen. There was a total of 600 stimuli that contained changing pattern locations. When there was no change in the pattern, participants pressed a button. Compared to controls, results from Multivariate Analysis of Variance (MANOVA) showed that children and adults with ADHD performed significantly poorly on the tasks and their performance declined over time. However, those were only main group effects and there was no interaction of group and time. The authors concluded that there was no deficit in CWADHD and AWADHD in a sustained attention task. Munoz et al. (2003) compared 114 PWADHD to 180 controls (age range 6-59 years old) in a sustained attention task. Participants fixated a visual target in the screen which randomly changed its position from centre to left or right. The authors assessed the ability to maintain prolonged fixation. Results from ANOVA indicated that PWADHD had more intrusive saccades suggesting that PWADHD have impairments in inhibiting voluntary behaviour and controlling their fixation (impulsive behaviour), a phenomenon shown in frontal lobe region in PWADHD. In traditionally formatted tasks (TFT), participants must respond overtly to critical stimuli whilst ignoring frequently occurring stimuli (high No-Go low-Go). Such tasks have been utilised in assessing attention. In Carter et al. (2013) 56 controls withheld their response to digits 1-2 and 4-9 while pressing for number 3 in a TFT task. There was more right than left frontal hemisphere activation as assessed by functional near infrared spectroscopy (fNIRS). However, the study's use of healthy controls limits the ability to generalize its conclusions about ADHD. A TFT task was administered to 52 CWADHD and 55 controls (Swaab-Barneveld et al., 2000). 3, 4, and 5 dot patterns were presented randomly and in a counterbalanced order. When a 4-dot pattern (target low-go) was shown, children were asked to click the yes button; if the pattern was comprised of 3 or 5 dots, children had to click a no button (non-targets high no-go). CWADHD were less accurate, more impulsive, and with lower levels of vigilance as assessed from ANOVA. In Hwang et al. (2019) 31 controls and 49 CWADHD performed a TFT task. Children had to respond whenever they saw a spiderman image (shown 25% of the trials) and withhold the response whenever a green goblin was presented (shown in 75% of the trials). Results from repeated measures ANCOVA showed a positive correlation between ADHD symptom severity and error rates. Sustained attention to response tasks (SART) have also been utilized to assess attention. In these tasks, participants must ignore the infrequent stimuli while responding to the frequently occurring stimuli (high-Go low No-Go). High-frequency tasks, (HFT or SART) as opposed to low-frequency tasks (LFT or TFT) were presented as "purer" measurements of sustained attention (Robertson et al., 1997). It has been hypothesised that frequent motor reactions would promote mindlessness. However, in Carter et al. (2013) this was disputed. In their study, 56 controls responded to digits 1-2 and 4-9 whilst withholding presses for number 3. The findings implied that the SART, places a high level of response inhibition and the argument that the SART induces mindlessness does not appear to be supported. SART tasks have been very popular for assessing differences between controls and PWADHD. In the same study, Hwang et al. (2019) also investigated differences between 31 controls and 49 CWADHD in a SART task. Similar results were achieved as in TFT task, and a positive correlation was observed between ADHD symptom severity and error rates as assessed by analysis of covariance (ANCOVA). McAvinue et al. (2012) compared 25 CWADHD and 25 controls in a SART task. Children responded to stimuli containing digits from 1-2 and 4-9 and withheld their response to digit 3. CWADHD showed significant differences from controls with a higher number of errors and longer RTs as indicated by independent samples t-test.

Munoz et al. (2003) introduced another task that measures sustained attention. The control of voluntary responses and saccadic suppression has been linked to frontal brain and basal ganglia regions. As a result, the authors hypothesised that children and adults with attention problems could face difficulties with oculomotor activities that require the inhibition of reflexive or unwanted saccadic eye movements. They examined eye-movement performance in a pro-saccade task to explore this hypothesis. Participants (114 people with ADHD and 180 control participants, in age range 6-59 years old) looked from a fixation point position in the centre toward visual target positioned to the left or right of the screen in the pro-saccade task. Results from ANOVA showed that ADHD participants had longer RTs and exhibited more difficulty inhibiting reflexive pro saccades toward the eccentric target. The findings imply that ADHD patients have a reduced ability to voluntarily inhibit undesirable saccades and control fixation behaviour, which is consistent with a frontal-striatal pathophysiology. Munoz et al

(2003) also assessed attention problems in controls (N = 180) and PWADHD (N = 114) in an anti saccade task in which participants first fixated a central point on the computer screen and then looked in the opposite direction of the visual stimuli. For example, if the stimuli was presented in the left side, participants had to look to the right side and vice versa. Results suggested that there were differences between groups with longer RTs and difficulties in suppressing reflexive saccades in PWADHD as assessed by ANOVA.

Overall findings from sustained attention tasks suggest that PWADHD show impairments in this type of attention. This can be due to difficulties in maintaining attention for long periods of time in a specific task which is indeed what is observed in PWADHD. A meta-analysis study (Huang-Pollock et al., 2012) drew conclusions from 47 studies that compared children with ADHD to typical children in their CPT performance in sustained attention. Results showed a large group difference with children with ADHD having a lower performance compared to controls supporting previous findings that this groups shows impairments in sustained attention tasks. Studies who assessed deficits in PWADHD in sustained attention based on self-ratings (Downey et al. 1997; Epstein et al. 1998) showed that about 84 to 90% of PWADHD experienced impairments in this type of attention indicating that evaluating long-term task performance in sustained attention task is important and relevant. Conclusions that can be reached in assessing sustained attention in PWADHD can have clinical importance. Therefore, it was relevant to focus on this type of attention when assessing ADHD traits. Specifically, the type of sustained attention task that this chapter addresses the most is based on Munoz et al. (2003). The results from Munoz et al’s can be of high reliance since authors assessed 114 PWADHD and compared them to 180 controls in a broad but matched age range between groups.

5.1.3 Selective Attention

The ability to focus on components of a task that are relevant to a goal is known as selective/orienting attention (Pashler et al., 2001). The ‘cocktail party effect' is often used to explain selective attention; in a noisy or busy environment, we may easily select stimuli to focus on, such as someone saying our name (Moray, 1959). In general, the tasks used to assay this form of attention must be extremely difficult. In a change detection task, for example, the difference between two stimuli to be recognised is small. Task complexity can be achieved by giving the stimulus for a brief duration or with weak signal strength (Lindsay, 2021). Selective attention tasks can be visual or auditory, and usually involve responding to a target stimulus in the presence of distractor stimuli. The Flanker Task (White et al., 2011) requires participants to respond to a target, such as the middle arrow's direction, that has congruent or incongruent distractor stimuli around (e.g., > > > > > for congruent stimuli vs. < < > < < for incongruent stimuli). Participants pressed the key “/” if the arrow in the middle faced left and the key “z” if the arrow in the middle faced right. Accuracy and response times to indicate the direction of the target arrow were measured. In Cherry's (1953) classic Dichotic Listening task participants listened to two audio channels (the two ears) with headphones and repeated the words from one channel and then from the unattended channel. Successful shadowing of the attended channel and a lack of information about the semantic elements of the unattended channel suggested higher selective attentional capacity. This has recently been replicated by Thomsen et al. (2004) where functional magnetic resonance imaging (fMRI) was used, and by Ross et al. (2010) who modified the dichotic listening task in which participants identified changes in pitch and volume of one auditory channel. Lewis (1970) reported that semantically similar words in both the attended and unattended channels reduced shadowing of the attended channel during dichotic listening tests.

Selective attention can also be measured using visual search tasks to see what areas of a display participants focus on. Rinck et al. (2003) employed a visual search for words task to explore the selective attention of 32 individuals with general anxiety disorder (GAD), 29 patients with speech phobia, (SP, who tend to pay more attention to threat-related stimuli than controls) and 31 controls. Participants' RTs to discover various target words were assessed. Anxiety patients showed a distraction effect for anxiety-related phrases. Such tasks can be used to see where selective attention focuses naturally without being directed. However, visual search tasks may fail to distinguish between selective and focused attention, where focused attention refers to the ability to respond to a specific task or stimulus, whilst selective attention refers to the ability to discriminate between stimuli (Sohlberg & Mateer, 1987). Because there is no set ‘distractor' in visual search, what this task assesses may be questionable (Pashler et al., 2001). In Simons and Chabris' (1999) "invisible gorilla" experiment, participants watched a video of players passing a ball and had to count the number of passes made. A person dressed as a gorilla, appeared on screen about halfway through the approximately one-minute-long video. The participants' selective attention was measured by their ability to count the number of passes accurately and to detect the gorilla. Most participants failed to notice the gorilla, displaying a condition known as “change blindness”. Change in inattentional blindness (IB) is useful for demonstrating changes in selective attention in AWADHD. Grossman et al. (2015), for example, adapted the invisible gorilla experiment for ADHD college students (N=14) and compared them to controls (N = 18) average age 24. It was hypothesised that PWADHD would be better in counting the passes and identifying neglected distractions, such as "gorilla." They found that they demonstrated IB much less frequently than controls (i.e., almost always detected unattended changes, such as the gorilla showing little or no inattentional blindness) as assessed by t-test.

5.1.4 Divided Attention

Unlike sustained and selective attention, in divided attention participants must process many tasks simultaneously. WM has been related to divided attention both behaviourally and physiologically (Nikolin et al., 2019). Attention appears to have a significant role in memory encoding (Aly & Turk-Browne, 2017). It is best for information to be the focus of attention for it to be correctly encoded into memory. When participants are asked to memorise a list of words whilst also performing a secondary task that diverts their attention, their capacity to recall those words later is impaired (but their ability to recognize the words as familiar is unaffected; Gardiner & Parkin, 1990).

In the literature, a wide range of dual tasks has been used, most of which include several modalities such as auditory, visual, motor, or verbal tasks. Performance on divided attention tasks, is influenced by an individual's skill level, task difficulty, as well as task interference (such as the level of similarity between task modalities which decreases performance; Lopez et al., 2016). The capacity to accomplish both visual and auditory tasks was tested in some of the early divided attention experiments. In Mowbray (1952), controls were expected to monitor alphabetic/numerical sequences both acoustically and visually while also identifying several missing items. When participants were given both auditory and visual information, they tended to perform poorly. According to Treisman and Davies (2012), the difficulty of divided attention increases when both tasks are verbal in nature, even when they are in different modalities. For example, monitoring auditory and visual words, would be more challenging than monitoring auditory tones and visual words. Baddeley’s (1997) dual task consisted of a verbal and visual task that was originally designed to measure the divided attentional abilities of people with ‘dysexecutive syndrome,' a cognitive disability caused by frontal lobe injury. While doing the Wisconsin card sorting task (WCST; sorting cards into categories by unknown rules that change over time), participants conducted a verbal fluency task (creating as many words as possible beginning with a specific letter). The number of accurate words created and RTs to WCST trials were used to assess attentional ability. Those with dysexecutive syndrome performed badly in both tests, implying that they had weaker divided attentional abilities than controls. As part of the TEA (Doneva et al., 2018), PWS (N = 50) and controls (N = 50) conducted the telephone search while counting dual task decrement (DTD). Participants looked through the phone book while simultaneously counting tones played on a tape recorder. A DTD is calculated by subtracting the score on the Telephone Search subtest from a time per target score weighted for tone counting accuracy. A lower score suggests that there is less of a gap in performance across the tasks, implying a better performance. Results suggested a significant difference between PWS and PWNS with better performance achieved from PWNS. The test of attentional performance (TAP) is a task often used in clinical research of attentional abilities, including divided attention. This includes both visual and auditory tasks (monitoring a graphic display and responding when a square shape is displayed and responding when two auditory tones are the same). According to Lopez et al. (2016), the TAP has strong reliability and validity. However, Catale et al. (2009), used the TAP to assess the attentional abilities of children with mild traumatic brain injuries (MTBI) and found that while the MTBI group performed worse on the divided attention task than controls, this effect vanished when accuracy in simple tasks was considered. This implies that the findings were due to a difference in selective, rather than divided attention. Trail Making Tests (TMTs) are more classic divided attention, cognitive flexibility, and WM tasks (e.g., Bowie & Harvey, 2006). TMTs are frequently used in clinical settings to detect signs of brain injury. In part A, participants connected 25 numbers in sequence, and in part B, they did the same with both numbers and letters in order (i.e., 1, A, 2, B, 3...). Part A was focused on visual search and motor speed, whereas part B included higher-level cognitive abilities such as "mental flexibility." The difference in RTs to complete A and B determines the participants' capacity in divided attention. This is a simple and effective task that may be conducted with both children and adults. However, when comparing this task to attention switching tasks, it is unclear whether the TMT evaluates divided or alternating attention. There is no certainty that participants are dividing their attention between the two tasks at the same time, rather than simply alternating their attention between alphabetical and numerical tasks. It is suggested that PWADHD have difficulties performing dual tasks, even if they involve different modalities. Some empirical data suggest the existence of a deficiency in this area, but not all investigations have shown conclusive evidence of dual-task deficits in PWADHD (e.g., Adams & Snowling, 2001; Li et al., 2004). The popular WM architecture of Baddeley (2003) has also been employed more explicitly as a potentially helpful paradigm for individuals with attentional problems. According to Conway and Engle (1994), WM differences are noticeable in probing recall tasks that cause response competition. Problems on cognitive tests intended to measure central EF have been documented in PWADHD, supporting the literature (e.g., Barnettet al., 2001; Nigg et al., 2002). Additionally linked to ADHD are visuospatial WM impairments, according to some of these studies. It has also been argued that relationships between attention problems and WM components like the central executive and visuospatial processes are particularly distinctive. Swanson (1993), for instance, claims that individuals with a variety of developmental problems share issues at all levels of the WM paradigm. According to other researchers, there are no conclusive links between attention issues and visuospatial cognition (Sonuga-Barke et al., 2002).

In conclusion, research to date offers different evidence for distinct cognitive patterns of dual-task and visuospatial WM deficiencies in PWADHD. A study (Savage et al., 2006) compared 58 CWADHD to 68 controls. Measures for phonological, visuospatial, and attention task performance were assessed. The authors investigated if visual memory and dual-task performance in CWADHD were accurate indicators of cognitive impairment. In one task, participants counted the number of tones played at random intervals during the trial while spaceships were presented simultaneously. Participants also identified as many spaceships as they could. In a second dual task, participants kept track of the number of tones played while also identifying an animal name shown. Regression analyses showed that the visual memory dual tasks successfully predicted attention group membership.

5.1.5 Attentional Switching

When numerous competing jobs are done at the same time, a central controller is required to decide which to engage in and when. Executive control is responsible for combining sensory inputs with prior information to coordinate numerous systems for efficient task selection and execution, and this control is commonly associated with prefrontal cortex activity. The ability to alternately direct focus between several tasks is known as alternating/switching attention, and it appears to be stimulus-driven with top-down influences (Pashler et al., 2001). As with divided attention, alternating attention has a cost in terms of performance, which worsens as the stimulus set/modality between tasks gets similar. Better performance in alternating attention tasks, has frequently been associated with improved literacy skills, such as reading (e.g., Kershner & Graham, 1995; Commodari, 2017). Like divided attention tasks, alternating attention tasks, typically contain numerous tasks from different modalities. Alternating attention traditionally has included switching attention between perceptual inputs, numerical lists, and mental tasks (Garavan, 1998). Dichotic listening tasks can be used for alternating attention, also called ‘directed attention dichotic paradigm' (DAD). Participants in this task listen to two simultaneous channels and are required to focus on the right/left stream in one trial and the other stream in the next. Commodari (2017) investigated alternating attention in children (288 controls) using a "multiple barrage task". Participants were given modified cancellation tasks in which they had to search for and ‘cancel' targets. Children identified and cancelled letters in an array in one verbal activity, and they searched for a pair of patterned squares in another visual-spatial challenge. As the type of work changed between sets, the children had to shift their attentional focus. Accuracy and RTs in each task were used to assess alternate attention abilities. Both tasks had good test-retest reliability, internal consistency, and concurrent validity. However, this paradigm does not appear to have been replicated in adults. Using the same stimuli as Commodari (2017), the Visual Attention Battery was created to measure sustained, selective, divided, and alternating attention (Smith et al., 1998). Geometric patterns in two colour combinations were given to participants. To respond to each stimulus set, participants were required to switch their attention between colour and pattern in the alternating attention task. Originally, this was used to assess the attentional abilities of schizophrenic patients, revealing that they struggled to switch attention compared to controls. This activity is a simple technique to test all types of visual attention. In Garavan (1998), participants watched a sequence of right or left facing arrows and maintained mental counts of each before responding. According to Garavan, this requires switching attention between two concepts in WM. However, because participants must retain mental counts of both stimulus types at the same time, this task could be interpreted as a measure of divided attention. In the visual elevator timing score developed by Doneva et al. (2018), participants count up and down presented tones while they follow a series of visually presented “floors” in the elevator. For accurate responses, the final score is the average time it takes to switch (i.e., go up and down). Better performance is indicated by a lower time-per-switch score. In the elevator counting with reversal, the identical activity is provided to participants on audiotape at a fixed speed. A higher score implies better performance on this subtest. Although there were no significant differences between PWS and PWNS for either task, PWS performed worse than controls. Rather than employing two tasks as in dual tasks, some researchers use ‘switching attention' tasks using two concepts of the same modality in alternating attention.

Attentional switching in PWADHD has generally been assessed using the TMT. According to studies, the time it takes to complete the TMT part B can distinguish between individuals who have and do not have ADHD (Pennington & Ozonoff, 1996; Willcutt et al., 2005). The time taken and mistakes made during this task may be related to the impulsive behaviours that PWADHD make when faced with stimuli that require consecutive replies. PWADHD take longer and make more mistakes than healthy controls (Hale et al., 2009). However, it has been suggested that this test lacks sufficient predictive power to distinguish participants (Perugini et al., 2000). Elosúa et al., (2017) assessed 26 CWADHD (in which 20 were with a combined subtype whereas 6 had the inattentive subtype) and 29 typically developed (TD) children in the TMT task. There are two components to this test (A and B). Part A requires the participant to link as many numbers from one to twenty-five as fast as they can. In part B, participants link the letters A to L (ordered alphabetically) and alternate the letter with the numbers one to thirteen in ascending order such as: 1 -> A -> 2 -> B -> 3-> C. Results from t-test showed higher RTs in the ADHD group in Part B of TMT, but no difference was observed between groups in part A. Moreover, there was a significant difference between groups in the ratio of the RT to complete Part B with respect to Part A with higher RTs in PWADHD in part B compared to part A.

Research on cognitive training in PWADHD in attentional switching tasks in the visual domain shows clinical implications. White and Shah (2006) compared 16 adults with ADHD to 18 controls in two switched attention tasks. In the first task, a letter followed by two-digit numbers (e.g., “W10”) would show on the screen. Participants had to first indicate if the letter was a vowel or a consonant and then to indicate if the two-digit number was even or odd by pressing the designated buttons on the keyboard. In the second task, two figures (one smaller and one larger) would show on the screen. Participants had to first report the number of lines that made up the smaller figure then report the number of lines for the larger figure by pressing a number from the keyboard. Results showed that ADHD group was impaired in switched attention task. Further investigations were made when PWADHD were trained in this attention type utilizing the tasks. It was concluded that PWADHD showed significant improvements in switched attention. Results suggest that attentional switching particularly in the visual domain, can correctly assess ADHD traits and therefore it is relevant that besides sustained attention, a focus on this chapter would also be on switched attention.

5.1.6 Limitations of previous attention tasks and advantages of VR

To date sustained attention tasks implemented in past studies have the same limitation. They lack ecological validity and are highly artificial because they do not represent real-life scenarios and have little meaning for participants. Unlike many other tasks that require prolonged attention, such as playing a video game or driving a car, participants are likely to become fatigued rapidly, influencing the measurement of their sustained attentional ability and influence the significance of the results. There have been however efforts to address such limitations. Ko et al. (2017) integrated a sustained attention task into a real university lecture. Students (only controls) reported identifying randomly placed visual targets throughout the lecture using a phone app. However, students were also required to attend and pay attention to the lecture, and this may be considered a dual task rather than a sustained attention task. Furthermore, such settings can limit researchers in manipulating the scene, collecting more data such as eye movements, EEG, and behavioural data which would be more accessible in a more controlled setting. Cao et al. (2019) used a virtual reality driving simulator to create a sustained attention task. Participants (controls) sat in a real car while EEG recordings were collected, and the participant’s task was to stay in the centre lane on a virtual road. The car would ‘drift' out of the lane at random intervals throughout a 90-minute period, and participants' RT to correct this was assessed. This was a very naturalistic task, yet it was heavily reliant on the participant's driving expertise and muscle memory. Furthermore, it is not advisable to implement a moving scene in VR especially if that movement is not controlled by users as it can cause motion sickness. According to Clay et al. (2019), a discrepancy between visual and vestibular stimuli is the cause of motion sickness. In VR, eyes perceive the movement of the scene and the apparent movement of the player, even if the actual person is usually sitting still on a chair and this causes motion sickness. There are other ways to move in VR such as teleportation in VR in which users can go from point a to point b using a light beam from the VR controllers in the 3D environment, but this is not a realistic movement. A more realistic movement would be to use an omnidirectional treadmill, but this technology is not very well developed and is quite expensive. In conclusion, when implementing a scene in VR for assessing attention, motion sickness should be considered, and the best decision is to avoid the movement of the user inside the 3D environment. Alternatively, researchers should at least give users the option to make moves themselves in the VR environment using arrows in the controllers, but the speed of this movement should be slow, and the task should not include many movements and turns.

Similarly as in previous sustained attention tasks, the above selective tasks have the limitation of being artificial and not related to real-life scenarios. Furthermore, the tasks are in 2D and there are few many elements to make the task interesting for participants. To increase ecological validity, Olk et al. (2018) employed the Flanker paradigm in VR to assess attention and distraction with daily objects instead of simple letters in 22 controls. The participant's task was to look for a target among the distractions on a virtual kitchen. They had to press a button to indicate the targets (red soda can and red or white yogurt). Discriminability between the target and the distractor varied. In high discriminability targets and distractors conditions, stimuli had different colours. In low discriminability targets and distractors conditions, stimuli had the same colours. The displays were accompanied with a peripheral flanker item that was either congruent or incongruent with the target that had to be ignored. The authors concluded that when target–distractor discriminability was poor and flankers were incongruent, RT was slower. The findings were confirmed in a second experiment that they implemented in which stimuli were shown in 2D on a computer screen instead of VR. The authors obtained the same results as in VR, indicating that standard paradigms and manipulations may be successfully translated into immersive VR. Li et al. (2020) also developed a selective attention task in a VR application. Researchers compared the same task in VR and desktop PC platform to understand which platform was better for assessing attention abilities from behavioural and neural perspectives in 40 controls. The game started with a cue that showed the region and depth where a single ocean animal (either a "Target" or "Distractor" stimuli) would appear. On a trial-by-trial basis, both target and distractor stimuli were presented in a pseudorandomized form, with each colour (red, yellow, blue, and green) being randomly assigned. A cue with area and depth information was displayed on the screen for 300 milliseconds. The greater the region (and thus the deeper the depth), the more difficult it was to predict where stimuli would emerge. Participants pressed the colour-matched buttons on the controller if the stimuli was a target and did not release their thumb from the controller's home button if it was a distractor (any other fish). Findings suggested that the allocation of attentional resources in head mounted display (HMD) in VR may be superior to other methods of assessing these abilities, such as using a PC, laptop, tablet, or any computer with a 2D screen. However, attention decreased throughout the levels for both platforms showing a reduction in attentiveness as the levels progressed which might indicate that this specific task might not be suitable for training attention. A solution for this is to create VR scenarios that can replicate/mirror real-life scenarios. Also, tasks should include some level of interactivity and should not take very long. Otherwise participants will start to fatigue, and their level of attention will decrease.

Using a virtual reality driving simulator, Lengenfelder et al. (2002) evaluated the impact of divided attention on driving performance. Controls and patients with traumatic brain injuries were included in the study. While driving a simulated car on a winding road, they completed a verbal fluency task (e.g., produce as many words beginning with the letter F as possible) and a visual task (e.g., locate the number 9 in a sequence). Driving speed and the number of errors in verbal/visual tests were used to differentiate participants' attentional ability.

Results suggested that divided attention had the greatest impact on the number of errors in the secondary task, especially in the brain damaged group. Incorporation of driving simulation as in Lengenfelder et al.'s (2002) study, reflects an important everyday task but driving in VR can cause motion sickness and that can have an impact on the significance of the results. Furthermore Lopez et al. (2016) also emphasized that the participants' experience in each task should be considered. Stavrinos et al. (2011) implemented a VR scenario from the perspective of a pedestrian to understand the risks of pedestrian injuries caused by being distracted when using cell phones. Participants (108 controls in age range 17-41) used a phone to perform various tasks such as communicating in a phone call or conducting an arithmetic/spatial task while crossing a virtual street. Performance on phone tasks and attention to traffic/walking speed were used to assess divided attentional abilities. Unlike driving in Lengenfelder et al. (2002), participants were more likely to have equal experiences of being pedestrians. Rather than verbal counting activities, completing tasks on a phone more accurately represents a real activity, and hence appears to have greater ecological validity. Results suggested that cell phone conversations distracted pedestrians significantly.

Alternating attention tasks described above share the same issue of ecological validity and interactivity with the task. Penaloza et al. (2020) tested a cognitive training task involving Brain Machine Interface (BMI) in a virtual reality environment to improve the cognitive decline from aging in 30 controls. Researchers examined the level of accuracy and processing speed of the attention switching ability between this paradigm and the classic attention switching task cognitive training paradigm to assess the effectiveness of the BMI-VR paradigm. In the task a 2 by 2 grid with a combination of letters and numbers was shown. In the upper two positions, task A was shown (e.g., letter task; consonant vs. vowel assessment task) whereas Task B which is shown in the lower two positions of the grid represent the digit task: odd vs. even number task. Participants pressed the key with their left finger to respond to consonants or odd numbers, and their right finger to respond to vowels or even numbers. The BMI-VR scenario included tasks that resemble daily life such as getting a coffee or cooking. In this task users need to balance short-term attention switching tasks (like stove management) with longer-term planning goals like arranging the table and complete all food preparation before a deadline (before guests arrived). The user is prompted to imagine pouring coffee within the VR with BMI, which was achieved using EEG, and the trial begins after an auditory cue is played twice. Then the user is asked to imagine releasing the coffee pot and relaxing the arm for further 10 seconds after the bell sound has been played once. Finally, after 10 seconds, a bell sound is played to inform the user that the trial is over. According to preliminary trial results, the BMI-VR group was 3.96s faster than the group who conducted the task on the computer in terms of attention accuracy scores. Although the results were not statistically significant due to the high level of intraparticipant variability, preliminary data suggests that the proposed training technique has the potential to increase attention switching speed. In Liao et al. (2019) the goal of the study was to understand how VR-based cognitive training affected VR in older people with mild cognitive impairment (MCI). There were 6 tasks in total and the tasks related to attentional switching included taking the mass rapid transit (MRT) game, in which participants (34 elderly people) had to move to where station gates, ticket vending machines, and ATMs were positioned in the customary areas. Participants needed to be aware of their current position as well as the allocated stations to accomplish the task. They also needed to collect enough coins to purchase a ticket based on the fare table. In less than 3 minutes, participants had to walk virtually to a retailer shown on a map. If the participants did not get closer to the target store in 2 minutes, red directional marks appeared to direct them. In the kitchen chef game, a player was placed in a well-equipped kitchen with a variety of utensils at their disposal to produce a required food. After they completed a simple dinner, they moved on to a more sophisticated dish that required more materials and utensils to complete. In older persons with MCI, the 12-week VR-based cognitive training program resulted in significant improvements in executive function.

Table 5.1

Summary of studies assessing PWADHD in different attention tasks including methods, statistical approaches, findings, and limitations of the tasks.

Study	*Attention Task*	*Groups*	*Method*	*Statistical Approach*	*Findings*	*Task Limitations*
Loo et al. 2009	Sustained Visual	38 AWADHD 42 controls	Conners CPT, respond to any letter besides letter “X”	Repeated measures ANOVA	Higher alpha and beta values in PWADHD in frontal and parietal regions.	The task is highly artificial, and the results can be due to the simplicity of the task.
Tucha et al., 2009	Sustained Visual	38 AWADHD, 38 healthy adults; 52 CWADHD and 52 healthy children	Participants responded to visual target stimuli by pressing the space bar	Multivariate Analysis of Variance (MANOVA)	Main group effects of CWADHD and AWADHD performing poorly compared to controls. No interaction effect of group by performance over time was observed.	MANOVA cannot be reliable if data is not normally distributed. Task lacks ecological validity and have little meaning for participants.
Munoz et al., 2003	Sustained Visual	114 PWADHD 180 controls (in age range 6-59 years old)	Participants were instructed to fixate to a visual target	One Way ANOVA	PWADHD had more intrusive saccades and difficulties to control and maintain their fixation.	One Way ANOVA cannot be reliable if data is not normally distributed. Task is very artificial and has little meaning to participants.
Swaab-Barneveld et al., 2000	Sustained TFT Visual	52 CWADHD 55 controls	Participants pressed yes when target (4-dot pattern low-go) appeared and click no when non-targets (3,5 dots, high-no go) showed	One Way ANOVA	Children with ADHD were less accurate, more impulsive, and with lower levels of vigilance.	One Way ANOVA cannot be reliable if data is not normally distributed. Task is artificial and has little meaning to participants which can affect the results.

Study	*Attention Task*	*Groups*	*Method*	*Statistical Approach*	*Findings*	*Task Limitations*
Hwang et al., 2019	Sustained TFT Visual	49 CWADHD 31 controls	Children were asked to respond whenever they saw a spiderman image (target, low-go) and withhold a response when they saw a green goblin image (non-target, high-no go).	Repeated measures ANCOVA	Positive correlation between ADHD symptom severity and error rates.	ANCOVA is appropriate to control for errors, the task however is artificial and lacks ecological validity.
Hwang et al., 2019	Sustained SART Visual	49 CWADHD 31 controls	Children were asked to respond whenever they saw a spiderman image (target, high-go) and withhold a response when they saw a green goblin image (non-target, low-no go).	Repeated measures ANCOVA	Positive correlation between ADHD symptom severity and error rates.	ANCOVA is appropriate to control for errors, the task however is artificial and lacks ecological validity.
McAvinue et al., 2012	Sustained SART Visual	25 CWADHD 25 controls	Children responded to digits from 1-2 and 4-9 and were asked to hold their response to digit 3	Independent samples t-test	Significant differences were observed between groups with higher errors and RTs observed in CWADHD.	T-test is appropriate for this study, but the task lacks ecological validity and has little meaning to participants.
Munoz et al., 2003	Pro-saccade Sustained Visual	114 PWADHD 180 controls (in age range 6-59 years old)	Participants were instructed to look from a fixation point in the centre toward visual target positioned in the left or right of the screen	One Way ANOVA	PWADHD had longer RT and exhibited more difficulty inhibiting reflexive saccades	One Way ANOVA cannot be reliable if data is not normally distributed. Task is very artificial and has little meaning to participants.

Study	*Attention Task*	*Groups*	*Method*	*Statistical Approach*	*Findings*	*Task Limitations*
Munoz et al., 2003	Anti saccade Sustained Visual	114 PWADHD 180 controls (in age range 6-59 years old)	Participants first fixated in a central point in the computer screen and then looked at the opposite direction of the visual stimuli.	One Way ANOVA	There were differences between groups with higher reaction times and difficulties in suppressing reflexive saccades in PWADHD	One Way ANOVA cannot be reliable if data is not normally distributed. Task is very artificial and has little meaning to participants.
Grossman et al., 2015	Selective Visual (Invisible Gorilla)	14 AWADHD 18 controls	Participants were assessed in the ability in identifying neglected distractions, such as "gorilla."	Independent samples t-test	AWADHD almost always detected unattended changes, such as the gorilla showing little or no inattentional blindness	Independent t-tests are sensitive to small sample sizes and the task lacks ecological validity.
Savage et al., 2006	Divided Visual Audio	58 CWADHD 68 controls	1- Participants had to count the number of tones played and identify as many spaceships presented. 2-Participants had to count the number of tones an identify an animal name shown.	Regression analyses	The visual memory dual tasks successfully predicted attention group membership.	Task lacks ecological validity and has little meaning to participants.
Elosúa et al., 2017	Alternating Visual	26 CWADHD 29 controls	1- Participants must link as many numbers from one to twenty-five as fast as they can. 2- Participants must link the letters A to L alphabetically and alternate the letter with the numbers one to thirteen in ascending order such as: 1 -> A -> 2 -> B -> 3-> C.	Independent samples t-test	Higher RTs in ADHD group in Part B	Independent t-tests are sensitive to small sample sizes and the task lacks ecological validity.

Study	*Attention Task*	*Groups*	*Method*	*Statistical Approach*	*Findings*	*Task Limitations*
White & Shah (2006)	Alternating Visual	16 adults with ADHD 16 controls	Task 1-Indicate if letter is consonant, or vowel then indicate if number is odd or even; Task 2- Report how many lines have the smaller figure than report the number of lines on the larger figure.	Independent samples t-test	PWADHD showed impairments in switched attention and training in the tasks showed improvements.	The sample size is small which can affect the results and the tasks lack ecological validity.
Gevensleben et al., 2009	Neurofeedback (NF) Visual	102 CWADHD randomly assigned in two groups	(1-computerised attention skills training, AST; 2- NF training)	Parent and teacher ratings.	Improvements in the NF group were higher (lower theta, higher beta) than in the AST group.	Study is interesting however analysis based on ratings is not an appropriate way to investigate significant differences across groups.
Ochi et al., 2021	Neurofeedback (NF) Visual	3 AWADHD 14 controls	Participants had to keep their attention levels high to complete the task.	Independent samples t-test	There was a significant difference in users' level of attention with lower scores obtained in PWADHD.	Independent t-tests are sensitive to small sample sizes although the task is interesting.
Blandon et al., 2016	Neurofeedback (NF) Visual	7 CWADHD	Participants had to keep their attention levels high to complete the sustained attention tasks.	A Matlab toolbox was utilised for analysing EEG data	Improvement of attention in the second session of NF treatment as well as a higher resting state in the power of the alpha and beta bands.	The task is interesting but the study had the limitation of having a small number of participants.

5.2 Experiment 5

ADHD has been associated with impairments in the frontal cortex (Geurts et al., 2004), causing impulsive, hyperactive, and inattentive behaviours in the EF. It has been claimed that the EF performance is the factor that distinguishes PWADHD (Boonstra et al., 2005) from controls. EF includes different types of attention such as sustained, selective, divided and attentional switching. However, evidence suggests that PWADHD does not necessary show impairments in all these abilities (Duff and Sulla, 2015; Lambek et al., 2010; Nigg et al., 2005). It is therefore necessary to test PWADHD in all types of attention to understand which particular attention task is associated with ADHD. Previous studies have assessed PWADHD in different attention tasks, but the results are contradictory (see Table 5.1) possible due to differences in methodology and containing highly artificial stimuli that have little meaning to participants and can cause fatigue and a loss of interest in completing the task. To effectively assess which type of attention is impaired in ADHD, the task should represent scenarios that contain daily activities and have meaning to participants. As suggested by the literature (Hendrikse et al., 2019; Keshner, 2004; Schultheis & Rizzo, 2002) VR technology offers the ability to recreate real-life scenarios in a safe and controlled environment while efficiently obtaining behavioural and physiological data. It has been proven to be an effective and a more preferred method of conducting tasks (Li et al., 2020; Olk et al., 2018; Penaloza et al., 2020; Stavrinos et al., 2011). To date, no study has explored all types of attention in PWADHD in a VR technology and assessed behavioural measures.

This chapter aimed to understand which type of attention in EF is affected in PWADHD that distinguishes them from typical controls. Are PWADHD impaired in all EF abilities or only in particular attention tasks? Participants were first tested in ASRS, SSI-3 and UNWR in which cognitive factors of attention, WM and fluency were assessed and then they conducted 10 VR tasks based on real-life scenarios with different types of attention. The first five tasks drew upon sustained attention, the next two tasks measured selective and divided attention and the last three tasks measured switched attention in different domains. Practice trials were also included in tasks 2, 3, 4, 5, 7, 8 and 10. Other tasks did not require a practice trial. Before each task, participants read instructions and could ask questions to the experimenter. Cognitive, behavioural measures, and results from NMs and questionnaires were investigated.

Based on the prediction that attention, fluency and WM problems are evident in PWADHD the hypothesis were: Groups should differ from each other on their ASRS (H1), SSI-3 (H2) and UNWR (H3) scores. Based on the literature that PWADHD performs poorly in different attention tasks (Blandon et al., 2016; Elosúa et al., 2017; Gevensleben et al., 2009; Grossman et al., 2015; Hwang et al., 2019; Loo et al. 2009; McAvinue et al., 2012; Munoz et al., 2003; Ochi et al., 2021; Tucha et al., 2009; Savage et al., 2006; Swaab-Barneveld et al., 2000), it was hypothesised that a lower performance and higher RTs will be obtained in PWADHD as compared to controls. The hypothesis tested whether groups differed in time looked at the TV (H4), correct responses in TFT (H5), incorrect responses in TFT (H6), RTs in TFT (H7), correct responses in SART (H8), incorrect responses in SART (H9) RTs in SART (H10), correct responses in pro saccade task (H11), incorrect responses in pro saccade task (H12), RTs in pro saccade task (H13), correct direction looked in pro saccade task (H14), incorrect direction looked in pro saccade task (H15), correct responses in anti saccade task (H15), incorrect responses in anti saccade task (H17), RTs in anti saccade task (H18), correct direction looked in anti saccade task (H19), incorrect direction looked in anti saccade task (H20), in map pressed in task 7 (H21), time to complete the task 7 (H22), time to complete the task 8 (H23), the number of times the phone was pressed in task 9 (H24), time to complete the task 9, (H25), scores achieved in task 10 (H26), time to complete task 10 (H27).

5.3 Methods

5.3.1 Participants

Fourteen controls (Mean age: 21.79, SD: 2.190, 5 Females and 9 Males) and seventeen PWADHD (Mean age: 23.65, SD: 3.390, 7 Females and 10 Males) were recruited through UCL

SONA. All PWADHD self-reported to have symptoms of inattention and hyperactivity. UCL Research Ethics Committee (6252/002) approved the study. All participants received £15 for conducting the study plus travel expenses for those travelling within the M25 area. Prior to starting the experiment, participants received an information sheet and a consent form to sign. Based on the power analysis, with 31 participants in total, with a 0.8 effect size in an independent sample t-test, there is an 80% to detect an actual effect.

5.3.2 Design

Participants were first assessed if they had normal vision and hearing. Only if they successfully completed this step, they proceeded to the next steps. They completed ASRS, read two short paragraphs from the SSI-3 manual while they were video recorded and conducted the UNWR task while the experimenter wrote down the scores. The order of the three tasks were counterbalanced to remove order effects. If the participant's ID was an odd number the order of the tasks was ASRS, SSI-3, all 10 VR tasks, and UNWR. If the ID was an even number order was UNWR, VR tasks, ASRS, SSI-3. VR tasks were also counterbalanced. The first ten participants completed tasks from 1 to 10, the next ten participants completed tasks from 10 to 1. Before each task users read instructions and had the opportunity to ask questions to the experimenter. Practice trials were included only for tasks 2, 3, 4, 5, 7, 8, 10 and were conducted after participants read instructions. Tasks 1, 6 and 9 did not require a practice trial. All tasks had a mixed design where the within-participant factors were the tasks. The between-participants factor was the participant group (controls vs PWADHD). The dependent variables were behavioural measures.

5.3.3 Materials

Task 1

Task 1 was developed in C# programming language in Unity. All materials were obtained from Unity Asset Store. Materials included 3D models for a house environment such as a 3D house model, a sofa, table, TV, fireplace, kitchen and a bag of chips. A particle effect of the fire was added to the scene and placed into the fireplace in Unity. A video of a news reporter was added to the TV model and played once the task started. Two human avatars imported from DAZ3D[17] were placed on the left (a female) and on the right (a male) side of the user. Both avatars had animations attached to them. The female was animated to create eye contact with the TV and at certain points to look and talk to the user about the topic that the TV news reporter was talking about. The male avatar was animated to eat chips during the task and had a sound of eating chips attached to it. The kitchen area had kitchen sounds such as fridge buzzing, water boiling and dishwasher sounds. All sounds were imported from https://freesound.org/. Human avatar animations were created in DAZ3D, fireplace animation and TV video were created in Unity. HTC Vive Pro VR headset with pupil labs eye tracker and Looxid Link EEG mask[18] attached to it were connected to Alienware m15 Ryzen Edition R7 laptop. A calibration process of the headset and the eye tracker was included prior to starting the task so the users were placed correctly in the VR environment and the eye tracker correctly determined user's eyes positions.

Task 2

Unity was the platform in which the VR task was developed in C# programming language. Materials were imported into Unity from Unity Asset store. The main 3D model was a classroom setting in which human avatars around user were sitting in chairs and represented other students. Human avatars were imported from DAZ3D, and all were animated and had sounds attached including coughing, sneezing and writing. One human avatar represented a lecturer who was animated to talk about a specific lecture in front of the classroom while in a big screen (placed in front of the user) images of the lecture were shown. A 3D model of a paper plane was also included in the scene. In front of the user, was a 3D model of a book.

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[17] DAZ3D is a software to create human avatars: https://www.daz3d.com/

[18] Looxid Link EEG mask for HTC Vive Pro: https://looxidlink.looxidlabs.com/product/looxid-link-package-for-vive-pro/

Sounds were taken from https://freesound.org/. All human avatar animations were created in DAZ3D. Pupil Labs eye tracker and Looxid Link EEG mask were mounted to the HTC Vive Pro VR headset, which was connected to an Alienware m15 Ryzen Edition R7 laptop. Before beginning the task, the eye tracker underwent calibration to ensure that the eye tracker was able to accurately locate users' eyes.

Task 3

Similarly, to tasks 1 and 2, task 3 was built using the C# programming language on the Unity platform and materials were imported from the Unity Asset Store. All materials and the setting were the same as in task 2. Users were placed in the same VR classroom in front of the lecturer and the big screen. Other student avatars were placed around the user and had animations and sounds. In front of the user was the book. VR headset, EEG, and laptop were the same as in previous tasks. The calibration process was included before the task was initiated.

Task 4

Task 4 was built in Unity in C# programming language and all materials were downloaded from Unity Asset store. The 3D materials included a city environment with sound noises such as cars driving, people talking, 3D models of cars and buses and 3D models of buildings. 3D bird models were included in the scene flying with bird sounds. A 3D model of a plane flying was also included in the scene. Human avatars (created in DAZ3D) with animations of talking and walking were placed around the user. A user was placed in the middle of the scene. In front of the users was a park and in the middle of the park, a lamp was placed. A street was placed on each left and right side of the park (in front of the user). The technology and the calibration process in this task was the same as in previous tasks.

Task 5

The environment, the setup and all materials were replicated from task 4. The same street environment was built in C# programming language in Unity and all materials in task 4 were included in task 5. The technology was the same and the calibration step was included prior to starting this task.

Task 6

Task was created in C# programming language in Unity. Unity Asset store was utilized to import all materials including a 3D model environment for a bar with tables and chairs. A music sound for the bar was downloaded from https://freesound.org/ and all the lighting and scripting were set up in Unity to make the scenario similar to a real bar environment. Human avatars with talking, dancing, drinking and preparing drinks animations were created in DAZ3D. An alien 3D looking creature with a walking animation was imported from https://www.mixamo.com/. IBM Watson text to speech API was utilized in Unity and placed in 3 human avatars in front of the user. HTC Vive Pro with pupil labs eye tracking and Looxid Link EEG mask add on connected to Alienware m15 Ryzen Edition R7 laptop were the technology used to collect data from users' eyes and brain in the VR environment. The calibration process was conducted prior to starting the task for the eye tracker to correctly map users' eyes.

Task 7

Scripting and the development of this task were made in Unity in C# programming language. Materials were imported from Unity Asset store and included a 3D model of a city environment with buildings, cars, buses, streetlamps, streets, parks, traffic lights and a phone 3D model with ringtone and message sounds attached to it. A 3D model of birds flying in the sky were animated and had bird sounds attached. A city environment sound and all sounds were downloaded from https://freesound.org/ and included cars, city noises birds and phone sounds. Human avatars were included in the scene and had animations of talking and walking. Car movements were implemented with artificial intelligence (AI) in which the cars would only drive around the city when the traffic light was green for the cars and red for the users and when the user was not in the middle of the road. If the latter happened, a honking sound attached to the cars would play. The technology used was HTC Vive Pro linked to Alienware m15 Ryzen Edition R7 laptop with the pupil labs eye tracker and Looxid Link EEG attached to it. A calibration process was included prior to starting the task for the eye tracker to determine users' eyes.

Task 8

The environment was built in Unity in C# programming language. Materials such as a 3D model of a train station with trains and ticket machine were downloaded from Unity Asset store. The sounds (downloaded from https://freesound.org/) were placed in the scene and contained train environment sounds, train doors opening and closing sounds, and train announcement sounds. Human avatars (built in DAZ3D) contained talking and moving animations. IBM text to speech API was utilized for one human avatar to talk to the user. Technology used was Alienware m15 Ryzen Edition R7 laptop, HTC Vive Pro, pupil labs eye tracker and Looxid Link EEG mask. A calibration process was conducted prior to starting the task.

Task 9

An elevator scene was implemented and built in Unity in C# programming language. The 3D model included an elevator with buttons to press and go to different floors and a 3D model of a phone which were imported from Unity Asset store. An elevator music sound and elevator doors opening closing and moving sounds were downloaded from https://freesound.org/. Two human avatars with animations were created in DAZ3D. IBM text to speech API was utilized for the conversation that the two avatars would initiate upon starting the task. VR environment ran in Alienware m15 Ryzen Edition R7 laptop connected with HTC Vive Pro with pupil labs eye tracker and Looxid EEG mask attached to it. The calibration step was conducted before the task to map users' eyes.

Task 10

Task 10 was built in Unity in C# programming languages. All materials were imported from Unity asset store and included a 3D model of a chemistry lab, 3D chemistry equipment, 3D period table, a robot placed into a table. Particle effects with sounds for chemical reactions were developed in Unity. Alienware m15 Ryzen Edition R7 laptop connected to HTC Vive Pro with pupil labs eye tracker and Looxid Link EEG mask was utilized for this task. A calibration step was included prior to the task to determine users' eye positions.

5.3.4 Measures

1-Adult ADHD Self-Report Scale Screener, (ASRS; Ustun et al., 2017)

2-Stuttering Severity Instrument version 3, (SSI-3; Riley, 1994)

3-Universal Non-Word Repetition Test, (UNWR; Howell et al.'s 2016)

5.3.5 Procedure

Task 1

In this task users were placed in a sofa in front of the TV. In the left side of the user a woman sitting in a chair looked at the TV and at certain times would look and talk to the user. In the right side of the user, a man was placed in a sofa looking at the TV and eating chips. Once the task started, a TV news reporter started talking about a topic. The users' task was to focus on the TV, listen and pay attention to the topic that the TV news reporter was talking about and ignore distractions such as the two human avatars, fireplace, and kitchen sounds. In total this task was 2:40 minutes long. This task measured visual and auditory sustained attention.

Task 2

Participants were placed in the middle of the classroom in front of the lecturer and the big screen. At the start, the lecturer began talking about the lecture while images on the big screen changed based on the sentences that the lecturer was talking about. Around the user, other students (animated human avatars) were placed in the classroom with sounds attached. In the middle of the task, a paper plane flew and landed on the ground with a paper plane sound attached. In front of participants, a book was placed in which digits from 1 to 9 were presented randomly (25 times each). Each digit was shown 25 times and therefore in total 225 digits were presented. Digits were presented with a delay of 1.15 seconds and were shown for 1.15 seconds. The users' task was to press the button on the VR controller only when digit 3 was presented and ignore distractions. A practice trial was included before starting the task. This test is based on TFT and measures visual sustained attention. Overall, it lasted for 4 minutes and 25 seconds.

Task 3

The scene and the environment were the same as in task 2. Once the task started, the lecturer started to explain the lesson while images on the big screen changed. In the book in front of the users' digits from 1 to 9 were presented for 1.15 seconds in a random order (25 times each) with a delay of 1.15 seconds between each other. Users had to press the button of the controller for every digit besides digit 3 while ignoring distractions. In total, the task lasted for 4:25 and measured sustained visual attention. Participants conducted a practice trial prior to starting the actual task. This test is based on SART.

Task 4

Participants were positioned in front of a park in a city environment. In the left and right side of the park two roads were included. One car at a time would drive randomly in each road (in random colours). In total, 50 cars were presented (25 in the left, 25 in the right) in random order and colours. Each car showed for 1.15 second till it disappeared at the end of the road and the delay between the cars is 1.15 second. At a certain time, a plane (with a sound attached) flew across the scene. Users looked in the direction of the presented car and pressed the corresponding button of the VR controller depending on where the car was shown. If the car was presented on the left road, users had to look on the left road and press the left button of the controller and similarly for the right side. After the car disappeared, users looked at the lamp in the park in front of them. Practice was included prior to the task. The task was 3:20 minutes long and measured visual sustained attention. The scenario was based on Munoz et al. (2003) pro saccade task.

Task 5

Similar to task 4, participants were placed in front of the park. The task was based on the anti saccade task from Munoz et al. (2003). 50 cars in total drove one at a time on the left or right road, in a random counterbalanced order with random colours. Each car showed for 1.15 second and had a delay between each other for 1.15 seconds. Users had to look at the opposite direction of the car presented and press the opposite button of the VR controller. If the car was shown on the left side, users had to look at the right side and press the right button and similarly for the right side. When the car disappeared, they had to look at the lamp in front of them. The task lasted for 3:20 minutes and drew upon visual sustained attention. Users conducted a practice step before starting the task.

Task 6

Participants were placed in front of 3 human avatars sitting in a chair around a table in the bar environment. At the start of the task, bar music and animations of other human avatars such as drinking, talking, and dancing and preparing drinks from the bartender would play. The 3 human avatars included a woman placed on the left, a man placed in front and a woman placed on the right of the user. Once the task initiated, the 3 human characters in front of the user started a conversation and talked about a specific topic. Avatars had animations, blinks, mouth movements when started to talk and would make eye contact with users at certain times. In the middle of the task, a 3D alien creature would walk in the bar, stay for 3 seconds in front of the user and walk out the bar. The user’s task was to count how many times the word ‘capacity’ was mentioned in total from the human avatars. The task was 1:15 minutes long, it measured selective visual and auditory attention and was inspired from the famous invisible Gorilla task

(Simons & Chabris, 1999) and assessed PWADHD similarly as in Grossman et al. (2015) study.

Task 7

Users were placed in the beginning of a road. Once the first traffic light turned green for the users, only then they would cross the road. This was the same for all roads that they needed to cross. If in case users were in the middle of the road and the traffic light turned red for them, cars would honk. During this time, users received a missed call, a phone call and a text message that were shown in front of the user in the VR environment in a phone 3D model. Users task was to memorise a map shown in the beginning of a task and cross 5 roads to go to the destination as soon as possible following the same paths provided from the map. They also had to memorise who the missed call was from, answer the phone call and remember what the phone call was about. They also had to remember what was written in the text message and who sent the text message. The missed call, phone call and text message happened in the first, third and fifth road and they showed for 3 seconds before disappearing. Participants had the opportunity to open the map (shown in the phone) as many times as they needed and answer the phone call with a button of the VR controller. The movement in the environment was slow to avoid motion sickness and was made possible with a button press of the VR controller. The direction changed based on the head movement in VR. The task had a time limit of 10 minutes and on average the task took approximately 5 minutes to complete. In cases where the user did not reach to destination within 10 minutes, the task was terminated. Prior to the task, users completed a practice step. This was a dual task and measured visual, visuospatial and auditory WM, response strategy and motor impulsivity and was inspired by Stavrinos et al. (2011).

Task 8

At the start of this task, a human character placed in front of the user initiated a conversation while making eye contact. The avatar informed the user which train to take with what number and that there was a ticket machine nearby to check again for the train number and destination in case user forgot. The train ticket nearby had a button and could be pressed as many times as necessary from the user to play a sound and inform the user about the right train to catch. Once the avatar finished the conversation, started walking away and the user could control the movement pressing a button of the VR controller and direction by head movements. The movement in the scene was slow enough to avoid motion sickness. Every 2 seconds a train would arrive and wait for 10 seconds before departing. There was no limit on how many trains would arrive. Every train had a number and a destination text attached to it. There were 10 destinations in total and the users' task was to go to only one of those and catch the right train as soon as possible. The trains with their destination appeared in a random order. The task terminated within 10 minutes if the user did not catch the right train by then. A practice step was conducted by participants before the task. The task took approximately 5 minutes to complete and drew upon switched attention and measured auditory and visual memory and response strategy.

Task 9

The participant, female and male avatars were placed inside of an elevator. The elevator buttons were on the right side of the user, whereas on the left side the two human avatars were placed. When the task began, elevator music sounds started playing and the two avatars initiated a conversation between them. After 10 seconds, a phone would show for 3 seconds in front of the user which gave details about the right floor that the user had to go to. Participants could see the phone as many times as needed by pressing a button of the VR controller. The user's task was to go the right floor by pressing the right number that represented the floors in the elevator. The task had a time limit of 10 minutes but on average it took approximately 2 minutes to complete. If it was not completed within 10 minutes, this task would terminate. This was a switched attention task and assessed visual memory, response strategy and motor impulsivity. The task was inspired by Doneva et al. (2018) which assessed PWS in an elevator task.

Task 10

Participants were placed in a chemistry lab and in front of them a robot placed in a table, gave instructions to complete 3 chemistry experiments. After instructions for each chemistry experiment, participants interacted with chemistry equipment. Their task was to complete the experiments as fast as possible. Only if their attention was higher than a threshold of 40% (assessed by the EEG mask), they could interact with the equipment. They interacted with the equipment with the VR controller. Users also had the opportunity to interact with a periodic table in front of them by pressing a button of the VR controller. A practice trial was conducted prior to starting the task. The task had a time limit of 10 minutes and approximately took on average 3 minutes to complete. This task assessed switched attention with NF, visual memory, response strategy and motor impulsivity and was inspired from Ochi et al. (2021).

5.4 Results

5.4.1 Experiment 5a Results

Table 5.2

Descriptive Statistics, hypothesis, and results for ASRS, SSI-3, UNWR.

	Outliers	Shapiro-Wilks	Independent t-test	Mann-Whitney U	Hypothesis Met?
H1: Groups should differ from each other on their ASRS scores.	None	p = 0.081	p < 0.001	NA	**Accepted**
H2: Groups should differ from each other on their SSI-3 scores.	Four outliers were removed	p = 0.002	p < 0.001	p = 0.002	**Accepted**
H3: There should be a difference between the groups in the WM scores.	One outlier was removed	p = 0.733	p < 0.001	NA	**Accepted**

H1: Groups should differ from each other on their ASRS scores.

Box plots showed no outliers and data was normally distributed F(31) = 0.940, p = 0.081. Descriptive statistics (see Table D5.1 in Appendix D) showed that PWADHD had higher ASRS scores compared to controls (see Figure 5.1). Equality of variances was met (p = 0.102) and groups differed significantly on ASRS scores as shown by the independent t-test (Table 5.2), t(29) = -6.026, p < 0.001. Therefore, H1 was supported.

H2: Groups should differ from each other on their SSI-3 scores.

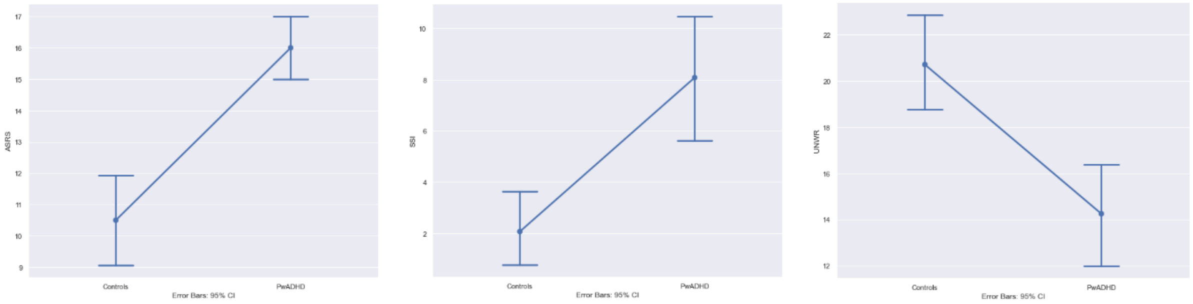
Descriptive statistics showed that PWADHD had higher SSI-3 scores than controls (see Figure 5.1 for a visualisation of the results). H2 was accepted because groups differed significantly (see Table 5.2).

H3: There should be a difference between the groups in the WM scores.

PWADHD had lower UNWR scores compared to controls as visualised by Figure 5.1. Groups differed significantly in the UNWR scores (see Table 5.2). H3 was supported.

Figure 5.1

Mean ASRS (left graph), SSI-3 (middle graph), UNWR (right graph) scores per group. Controls shown in the left of x - axis whereas PWADHD in the right of x - axis in each graph. Error bars represent ± 2 Standard Error [SE].



5.4.2 *Experiment 5b Results*

Table 5.3

Descriptive Statistics, hypothesis, and results for behavioural data.

	Outliers	Shapiro-Wilks	Independent t-test	Mann-Whitney U	Hypothesis Met?
H4: Groups should differ in time looked at the TV.	None	p = 0.311	p = 0.018	NA	**Accepted**
H5: Groups should differ from each other in their correct responses in TFT.	None	p < 0.001	p < 0.001	p < 0.001	**Accepted**
H6: Incorrect responses will be different between groups in TFT.	None	p < 0.001	p < 0.001	p < 0.001	**Accepted**
H7: RTs in PWADHD will differ from controls in TFT.	Some outliers were removed	p = 0.010	p = 0.014	p = 0.014	**Accepted**
H8: There will be differences between groups in correct responses in SART.	None	p < 0.001	p = 0.001	p = 0.001	**Accepted**
H9: Groups should differ from each other in their incorrect responses in SART.	None	p = 0.192	p = 0.005	NA	**Accepted**
H10: PWADHD should have higher RTs compared to controls in SART.	Two outliers were removed	p = 0.297	p = 0.002	NA	**Accepted**
H11: Groups should differ from each other in their correct responses in pro saccade task.	Some outliers were removed	p = 0.123	p = 0.010	NA	**Accepted**
H12: Incorrect responses will differ between groups in pro saccade task.	Some outliers were removed	p = 0.065	p < 0.001	NA	**Accepted**
H13: RTs should differ between groups in pro saccade task.	Some outliers were removed	p = 0.389	p = 0.023	NA	**Accepted**
H14: Groups should differ from each other in correct direction looked in pro saccade task.	Some outliers were removed	p = 0.430	p < 0.001	NA	**Accepted**
H15: There will be differences between groups in incorrect direction looked in pro saccade task.	None	p = 0.685	p < 0.001	NA	**Accepted**

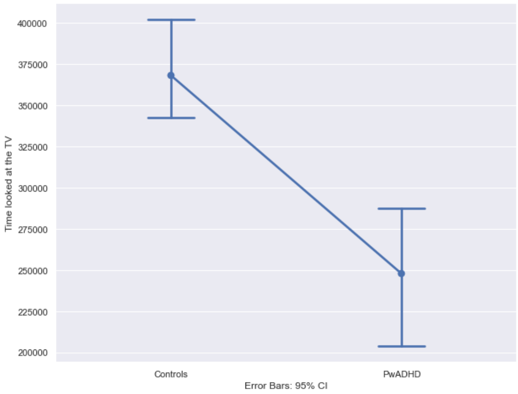
	Outliers	**Shapiro-Wilks**	**Independent t-test**	**Mann-Whitney U**	**Hypothesis Met?**
H16: Groups should differ from each other in their correct responses in anti saccade task.	Some outliers were removed	p = 0.112	p = 0.005	NA	**Accepted**
H17: Incorrect responses will differ between groups in anti saccade task.	Some outliers were removed	p = 0.034	p < 0.001	p < 0.001	**Accepted**
H18: RTs should differ between groups in anti saccade task.	Some outliers were removed	p = 0.082	p = 0.045	NA	**Accepted**
H19: Groups should differ from each other in correct direction looked in anti saccade task.	Some outliers were removed	p = 0.660	p < 0.001	NA	**Accepted**
H20: There will be differences between groups in incorrect direction looked in anti saccade task.	Some outliers were removed	p = 0.039	p = 0.011	p = 0.016	**Accepted**
H21: Groups should differ from each other in map pressed (task 7).	None	p = 0.493	p < 0.001	NA	**Accepted**
H22: Time to complete the task will differ between groups (task 7).	One outlier was removed	p = 0.006	p = 0.008	p = 0.001	**Accepted**
H23: Groups will differ in time to complete the task in the auditory and visual domains (task 8).	Some outliers were removed.	p = 0.415	p = 0.012	NA	**Accepted**
H24: Groups will differ in the number of times the phone was pressed in the visual domain (task 9).	Two outliers were removed.	p = 0.282	p < 0.001	NA	**Accepted**
H25: Groups will differ in time to complete the task in the visual domain (task 9).	Some outliers were removed.	p = 0.029	p < 0.001	p < 0.001	**Accepted**
H26: Groups will differ in the scores achieved in the task in the visual domain (task 10).	None	p < 0.001	p = 0.001	p = 0.004	**Accepted**
H27: Groups will differ in time to complete the task in the visual domain (task 10).	Two outliers were removed.	p = 0.034	p < 0.001	p = 0.005	**Accepted**

H4: Groups should differ in time looked at the TV.

Box plots showed no outliers, but some data was not recorded from the eye tracker. Data was normally distributed F(16) = 0.937, p = 0.311. Descriptive statistics (Table D5.2 in Appendix D) and Figure 5.2 showed that PWADHD had lower values in the amount of time they looked at the TV compared to controls. Assumption of equality of variances was met and groups differed significantly from each other t(14) = 3.629, p = 0.003 (see Table 5.3). Therefore, H4 was accepted.

Figure 5.2

Mean Time looked at the TV in controls and PWADHD. Error bars represent ± 2 Standard Error [SE].



H5: Groups should differ from each other in their correct responses in TFT.

Box plots didn't identify any outliers and data was not normally distributed (F(31) = 0.809, p < 0.001). Assumption of equality of means was not met (p = 0.001). Descriptive statistics and Figure 5.3 showed that PWADHD had significantly less correct responses compared to controls as assessed from the independent samples t-test shown in Table 5.3, t(19) = 4.972, p < 0.001 and Mann Whitney-U non-parametric test (p < 0.001). H5 is supported.

H6: Incorrect responses will be different between groups in TFT.

Descriptive statistics and Figure 5.3 show that PWADHD had significantly more incorrect responses than controls (see Table 5.3). Hence H6 was accepted.

H7: RTs in PWADHD will differ from controls in TFT.

Groups differed significantly in their reaction times (see Table 5.3) with PWADHD having higher values as shown in Figure 5.3. H7 was supported.

H8: There will be differences between groups in correct responses in SART.

Box plots showed no outliers and data was not normally distributed F(29) = 0.772, $p < 0.001$. Equality of variances was not met and the independent samples t-test ($t(19) = 3.742$, $p = 0.001$) and the non-parametric test ($p = 0.001$) showed significant differences between the groups (see Table 5.3) with PWADHD having less correct responses to controls. See descriptive statistics and Figure 5.3 for more information. H8 was supported.

H9: Groups should differ from each other in their incorrect responses in SART.

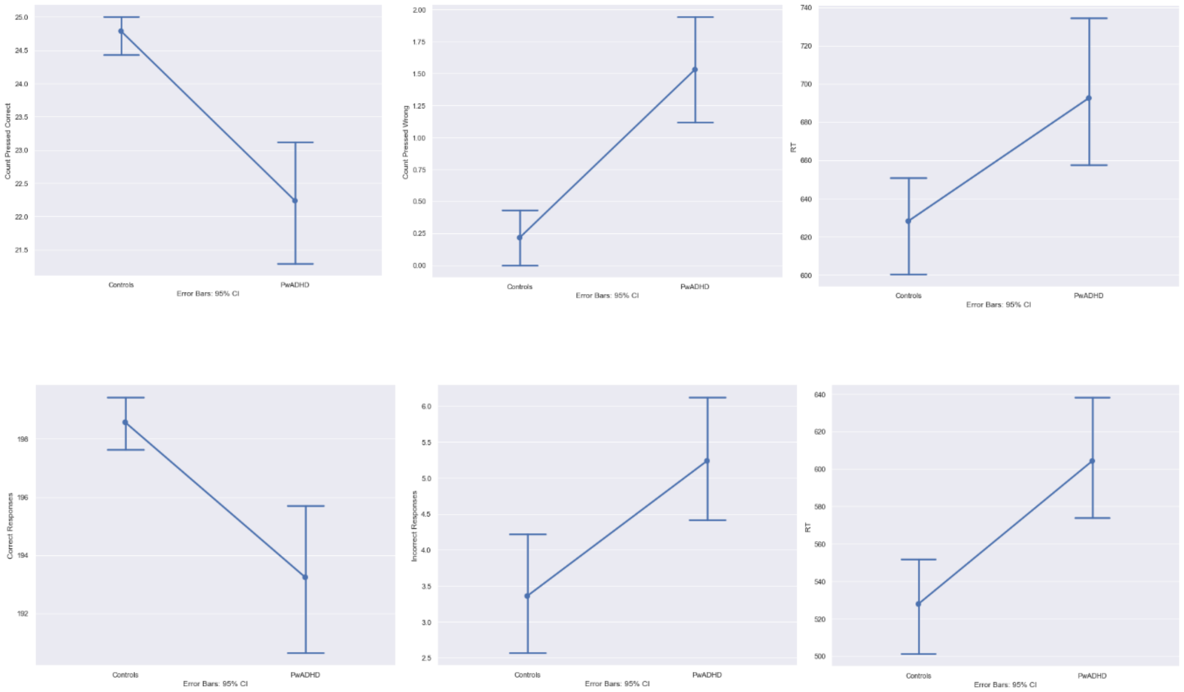
PWADHD had significantly more incorrect responses (see Table 5.3) accepting H9. Figure 5.3 shows a visualization of the results.

H10: PWADHD should have higher RTs compared to controls in SART.

H10 was accepted since groups differed significantly (see Table 5.3). From descriptive statistics and Figure 5.3 we can conclude that PWADHD had higher RTs.

Figure 5.3

Top row represents mean scores in TFT (task 2), bottom row shows mean scores of SART (task 3). Controls are in the left of x - axis, PWADHD shown in the right of x - axis in each graph. First graph in both rows shows mean correct responses, second graph in both rows shows mean incorrect responses and the last graph in both rows shows mean RTs. Error bars represent ± 2 Standard Error [SE].



H11: Groups should differ from each other in their correct responses in pro saccade task.

Some outliers were removed and data was normally distributed F(12) = 0.891, p = 0.123. Assumption for the equality of variances was met and groups differed significantly (see Table 5.3) as tested from independent samples t-test t(24) = 2.788, p = 0.010. PWADHD had less correct responses compared to controls as shown in Figure 5.4 and descriptive statistics. Hence, H11 was supported.

H12: Incorrect responses will differ between groups in pro saccade task.

More incorrect responses were made from PWADHD and groups differed significantly (see Table 5.3) accepting H12. See Figure 5.4 for more information.

H13: RTs should differ between groups in pro saccade task.

Groups differed significantly (see Table 5.3) accepting H13 with higher RT recorded from PWADHD (see Figure 5.4).

H14: Groups should differ from each other in correct direction looked in pro saccade task.

PWADHD looked less times in the correct direction (see Figure 5.4) and groups differed significantly (see Table 5.3). H14 was supported.

H15: There will be differences between groups in incorrect direction looked in pro saccade task.

H15 was accepted as groups differed significantly in the incorrect direction looked (see Table 5.3) with PWADHD having higher values (see Figure 5.4 and descriptives).

H16: Groups should differ from each other in their correct responses in anti saccade task.

Some outliers were removed and data was normally distributed (F(12) = 0.888, p = 0.112) Assumption for equality of variances is assumed and groups differed significantly in their correct responses (t(24) = 3.113, p = 0.005; see Table 5.3) accepting H16 with lower scores achieved in PWADHD (see Figure 5.4 and descriptive statistics).

H17: Incorrect responses will differ between groups in anti saccade task.

PWADHD scored significantly higher in incorrect responses (see Table 5.3, Figure 5.4 and descriptives). Hence H17 was accepted.

H18: RTs should differ between groups in anti saccade task.

Groups differed significantly in RTs (see Table 5.3) with PWADHD having higher values. See Figure 5.4 for more information. H18 was supported.

H19: Groups should differ from each other in correct direction looked in anti saccade task.

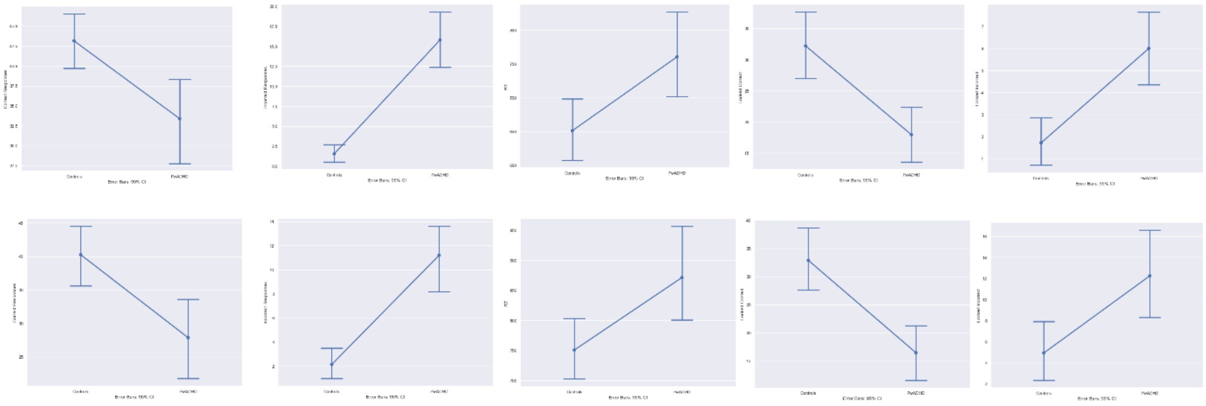
PWADHD had significantly lower scores in looking at the right direction of the car (see Table 5.3) accepting H19. See Figure 5.4 and descriptive statistics for more information.

H20: There will be differences between groups in incorrect direction looked in anti saccade task.

H20 was supported because groups differed significantly in looking at the wrong direction of the car (see Table 5.3) with PWADHD recoding higher values (see Figure 5.4).

Figure 5.4

Mean responses between controls (left x - axis in each graph) and PWADHD (right x - axis in each graph) in pro saccade task (top row) and anti saccade task (bottom row). From first to fifth graph in both rows represent mean scores on correct responses, incorrect responses, RTs, correct direction looked, and incorrect direction looked respectively. Error bars represent ± 2 Standard Error [SE].



H21: Groups should differ from each other in map pressed (task 7).

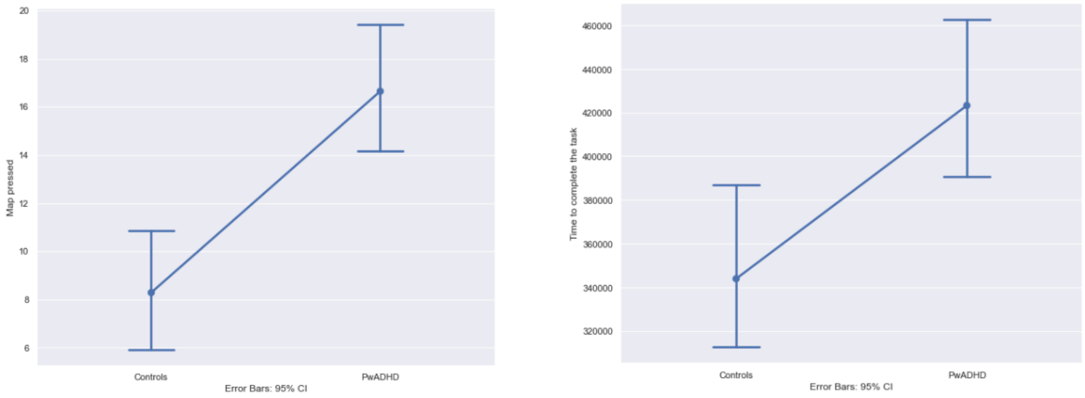
Box plots did not detect outliers and data was normally distributed F(30) = 0.968, p = 0.493. Groups differed significantly on the number of map pressed (see Table 5.3) t(29) = -4.233, p < 0.001 as assessed by independent samples t-test. Therefore, H21 was supported. Figure 5.5 show that PWADHD pressed the map more times compared to controls.

H22: Time to complete the task will differ between groups (task 7).

Groups differed significantly from each other (see Table 5.3) on the time to complete the task accepting H22 and PWADHD recorded higher values (see Figure 5.5).

Figure 5.5

The number of times the map was pressed (left graph) and time to complete the task (right graph) between groups. Error bars represent ± 2 Standard Error [SE].

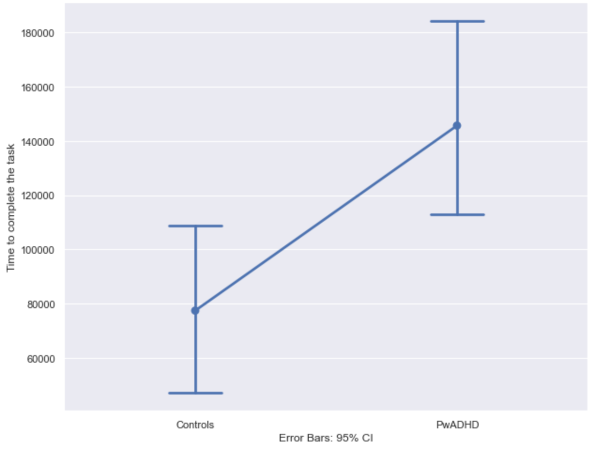


H23: Groups will differ in time to complete the task in the auditory and visual domains (task 8).

Some outliers were removed, and data was normally distributed (F(22) = 0.954, p = 0.415). Assumption for equality of variances was met. Groups differed significantly as assessed by independent samples t-test t(20) = -2.749, p = 0.012 (see Table 5.3). Descriptive statistics and Figure 5.6 show that PWADHD took more time to complete the task. H23 was supported.

Figure 5.6

Time to complete the task per group. Error bars represent ± 2 Standard Error [SE].



H24: Groups will differ in the number of times the phone was pressed in the visual domain (task 9).

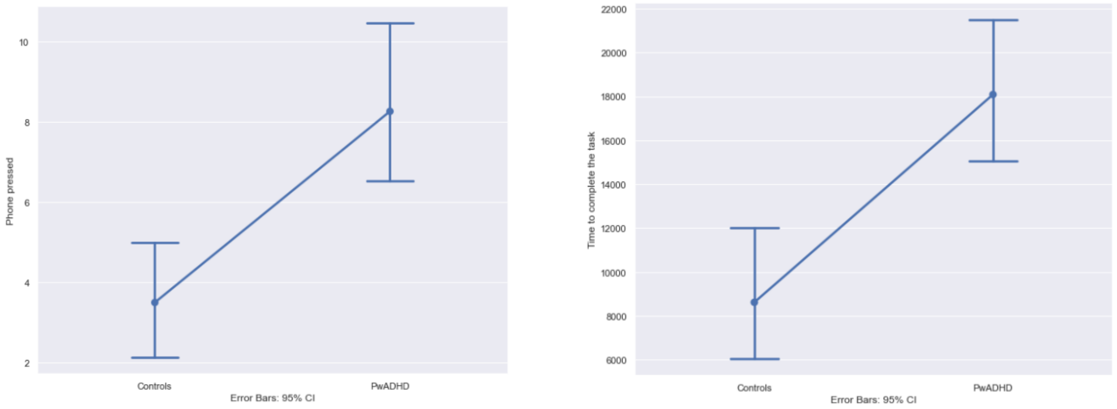
Two outliers were removed, and data was normally distributed F(21) = 0.946 , p = 0.282. Assumption for equality of variances was met and groups differed significantly as shown by the independent samples t-test t(27) = -3.712, p < 0.001 (see Table 5.3). Figure 5.7 show that the number of pressing the phone was higher in PWADHD. H24 was supported.

H25: Groups will differ in time to complete the task in the visual domain (task 9).

Groups differed significantly in the time to complete the task (see Table 5.3) accepting H25 with higher values recorded in PWADHD as shown in Figure 5.7.

Figure 5.7

Number of times the phone was pressed (left graph) and time to complete the task (right graph) in controls and PWADHD. Error bars represent ± 2 Standard Error [SE].



H26: Groups will differ in the scores achieved in the task in the visual domain (task 10).

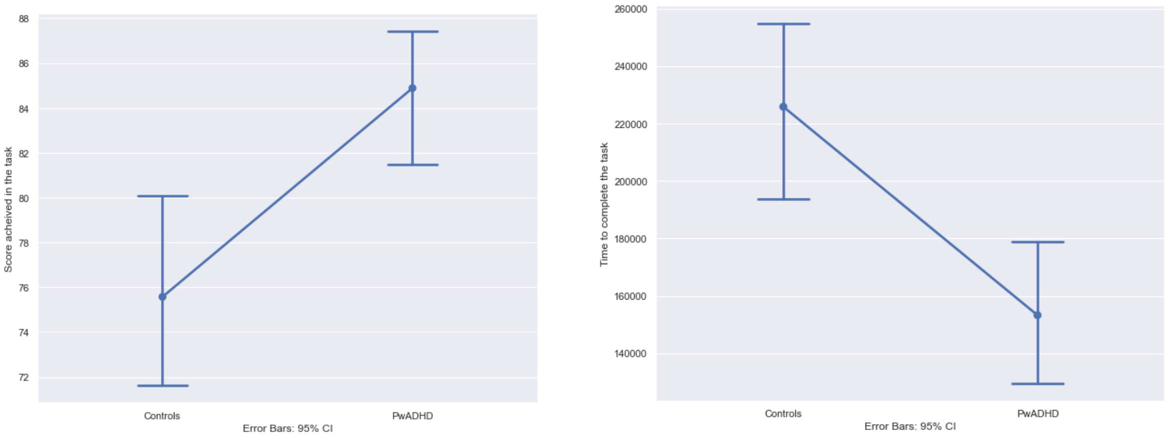
Box plots showed no outliers and data was not normally distributed F(31) = 0.749, p < 0.001. Assumption for equality of variances was met and groups differed significantly as assessed by independent samples t-test t(29) = -3.516, p = 0.001 and non-parametric test p = 0.004 (see Table 5.3). PWADHD recorded higher scores as shown in Figure 5.8. H26 was supported.

H27: Groups will differ in time to complete the task in the visual domain (task 10).

PWADHD had significantly a lower time to complete the task compared to controls (see Table 5.3) accepting H27. See Figure 5.8 and descriptive statistics for more information.

Figure 5.8

Mean scores achieved in the task (left graph) and mean time to complete the task (right graph) in controls and PWADHD. Error bars represent ± 2 Standard Error [SE].



5.4.3 *Experiment 5c Results*

NMs on behavioural measures were conducted to understand in which particular attention task PWADHD differed from controls. Results showed that NMs architecture in behavioural data differed in all sustained attention tasks (tasks 1, 2, 3, 4 and 5) suggesting impairments in this type of EF ability in PWADHD. There was a difference also between groups in task that measured switched attention (task 9). Although there were three tasks that measured attentional switching (task 8, 9 and 10), task 9 was based purely on visual stimuli whilst task 8 and 10 included both audio and visual. NMs architecture on behavioural data on tasks 8 and 10 showed no difference between groups suggesting that only in the visual domain of switched attention tasks we would expect impairments in PWADHD. Task 10 also included NF and interactions with stimuli making the task possibly more interesting for both groups and more difficult to assess differences between groups. By including NF in the task can also suggest that NF reinforces healthy brain functioning by providing positive feedback when attention is higher making it possibly a successful way for treatment of ADHD. From the results we would expect PWADHD to perform worse than controls in sustained attention and attentional switching tasks and therefore training in such tasks would enhance attention in PWADHD.

Figure 5.9

Results from behavioural data visualised in NMs for sustained attention tasks (from task 2 to task 5) for controls (top row) and PWADHD (bottom row). The first two NMs in both rows are related to task 2 TFT and task 3 SART. For controls in task 2 and 3 nodes with names CCT, ICT, RTC, CCS, ICS, RTC stand for correct responses controls TFT, incorrect responses controls TFT, reaction time controls TFT, correct responses controls SART, incorrect responses controls SART, reaction times controls SART. For PWADHD, for task 2 and 3 nodes with names CAT, IAT, RTA, CAS, IAS, RTA stand for correct responses PWADHD TFT, incorrect responses PWADHD TFT, reaction times PWADHD TFT, correct responses PWADHD SART, incorrect responses PWADHD SART, reaction times PWADHD SART. The following two NMs in both groups represent behavioural data for task 4 and 5. For controls, nodes CCP, ICP, RTC, CDC, IDC (task 4) stand for correct controls press pro saccade task, incorrect control press pro saccade task, reaction time controls pro saccade task, correct direction controls pro saccade task, incorrect direction controls pro saccade task. For task 5 the same variable names were used but the A letter in nodes represent anti saccade task. For PWADHD the only difference is in letter A instead of C in some nodes which represents the word PWADHD instead of controls.

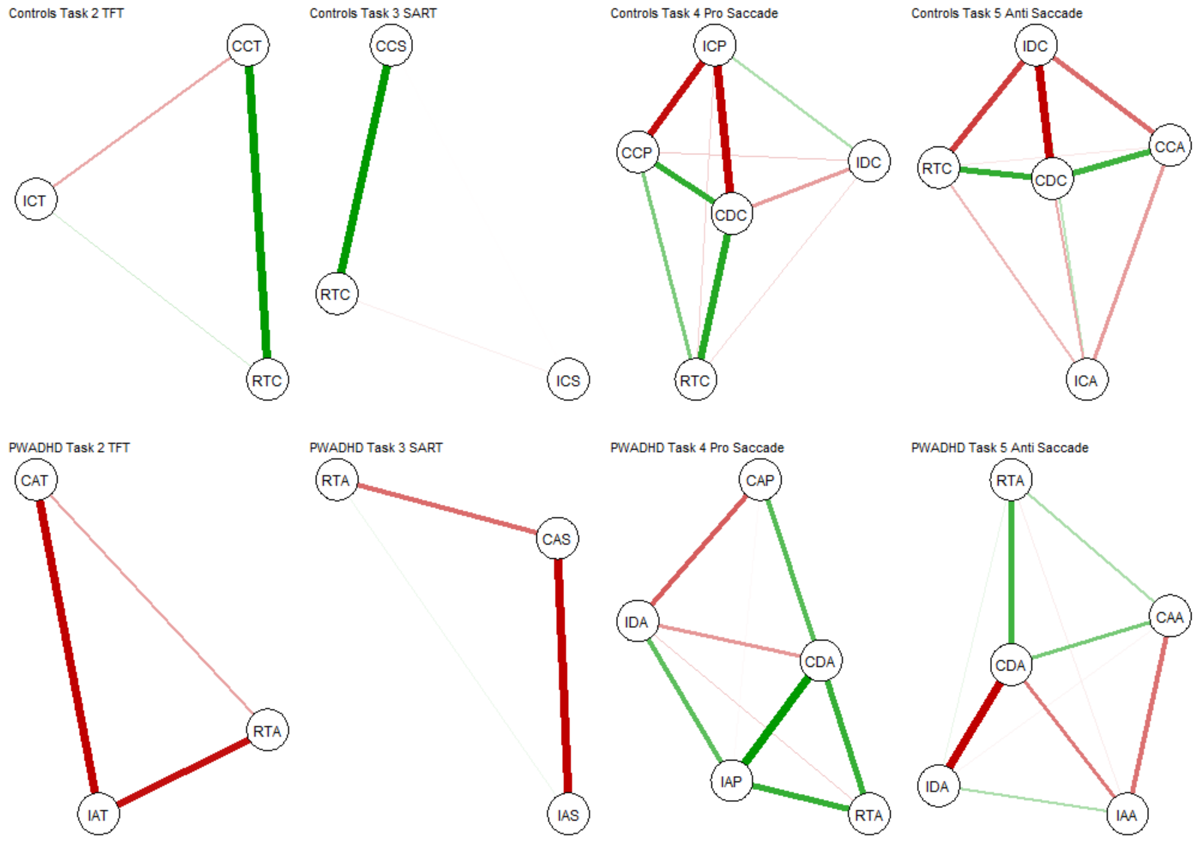


Figure 5.10

Results from behavioural data visualised in NMs for divided attention task (task 7) for controls (left NM) and PWADHD (right NM). MPC, RTC nodes for controls stand for map pressed controls, reaction time controls. MPA, RTA for PWADHD stand for map pressed PWADHD, reaction time PWADHD.

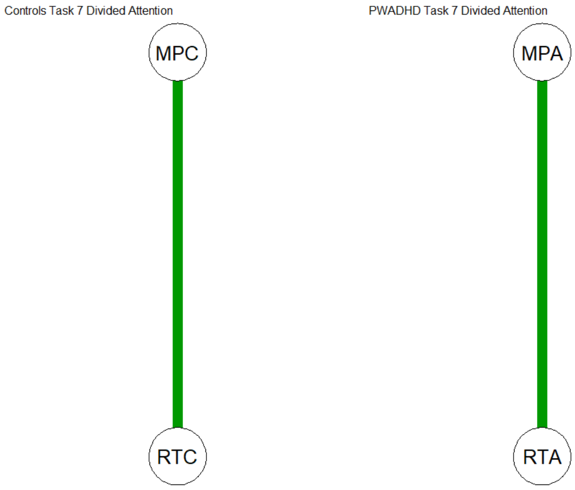


Figure 5.11

Results from behavioural data visualised in NMs for switched attention tasks (from task 9 to 10) for controls (top row) and PWADHD (bottom row). PPC, RTC, TSC, RTC for left and right NM for controls stand for phone pressed controls, reaction time controls, total score controls, reaction time controls. For PWADHD the only difference in nodes of left and right NM (bottom row) is the letter A which stands for PWADHD.

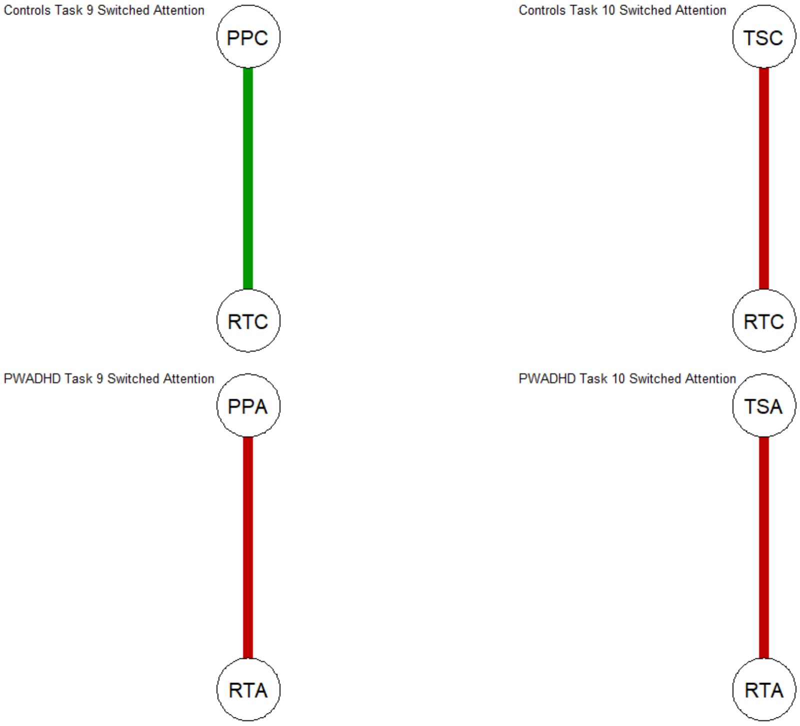
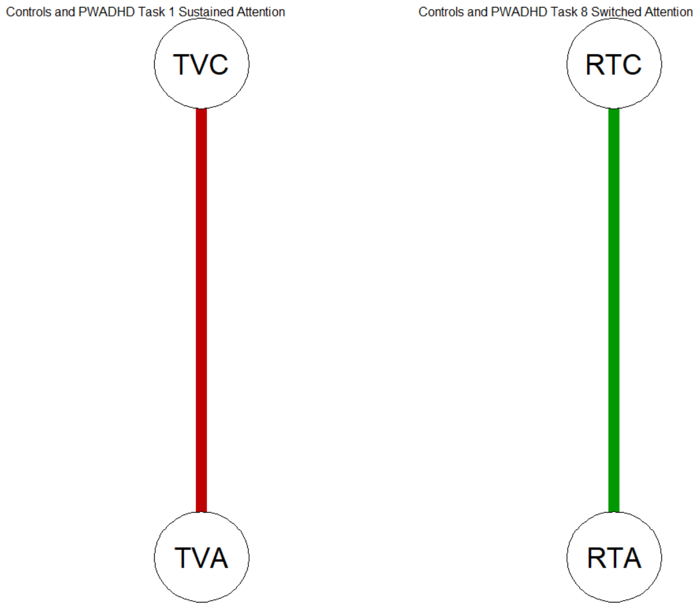


Figure 5.12

Additionally, since tasks 1 (sustained attention) and 8 (switched attention) had only one variable in each group in both tasks, NMs were plotted with controls to understand if correlation between PWADHD with controls is positive or negative. Task 1 is plotted on the left and task 8 is plotted on the right (for controls and PWADHD). TVC in left NM stands for TV time Looked for Controls and TVA stands for TV Time Looked for PWADHD. RTC stands for Reaction Time to complete the task for Controls and RTA stands for Reaction Time to Complete the task for PWADHD (right NM).



5.4.4 Experiment 5d Results

Table 5.4

Percentage or the responses from controls (C) and PWADHD (A) in tasks 1,6,7,8,9,10. The questions included in this table were asked with regards to the task and required from participants to choose an option. The other questions (not included in this table) were asked with regards to how distracted participants were during the task, confidence in correctly completing the task and how they found the VR experience. Those questions required from the user to choose an option from strongly agree to strongly disagree.

	Group	
Question	**C**	**A**
Task 1: How much plastic have we recycled?	28%	35%
Task 1: How many marine species have been affected by plastic?	35%	47%
Task 6: How many times the word capacity was mentioned?	57%	64%
Task 6: If you noticed that odd creature that walked for a moment in and out of the bar, what did it look like?	7%	17%
Task 7: The missed call was from:	92%	82%
Task 7: The call from Julie was about:	85%	94%
Task 8: Where were you supposed to go but you couldn't make it?	50%	82%
Task 8: Where was the human avatar going?	42%	41%
Task 9: How many floors did the building have?	21%	23%
Task 10: What happens to aluminium if we add it into a beaker with bromine?	64%	76%
Task 10: What was the second liquid that the user had to pour into the plate in experiment 3?	57%	52%

Note. For all questions, the percentage shows how many of participants got it right in each group.

Task 1

Q2: How many marine species have been affected by plastic?

Q3: I think I did very well in completing this task.

Q4: I think I didn't do very well in completing this task.

Q5: The task was interesting and was similar to a scenario that can happen in our day-to-day life.

Q6: I felt present and involved in VR.

Results from the Likert scale plot (Figure D5.1a in Appendix D) in question 1 show that PWADHD had more correct answers (35%) than controls (28%), but they were more unsure on how to answer this question (29%) compared to controls (21%). In the second question, PWADHD had more correct answers (47%) compared to controls (35%) and were less unsure (17%) than controls (42%) about the right answer. Results (see Figure D5.1b in Appendix D) showed that on both 3 and 4 questions, controls were more confident in the task compared to PWADHD. 21% of controls strongly agreed on question 3 while no answer in PWADHD was strongly agree. 28% of controls strongly disagreed in question 4 while no PWADHD strongly disagreed to this question. 21% of controls and 35% of PWADHD answered with strongly agree in both 5 and 6 questions (see Figure D5.1c in Appendix D).

Task 2

Q1: Pressing the button for the wrong number affected my next responses.

Q2: The lecturer and other students were distracting me during this task.

Q3: I think I didn't do very well in completing this task.

Q4: I think I did very well in completing this task.

Q5: I felt present and involved in VR.

Q6: The task was interesting and was similar to a scenario that can happen in our day-to-day life.

Overall, 35% of participants in both groups strongly disagreed in the first question while 11% of PWADHD strongly agreed in the second question (Figure D5.2a in Appendix D). No participant from controls strongly agreed in question 2. Results from question 3 showed that PWADHD were more confident than controls with 41% of PWADHD strongly disagreeing while the value was 35% for controls. More controls (42%) strongly agreed than PWADHD (41%) in question 4 (see Figure D5.2b in Appendix D for more information). 21% of the controls and 29% of PWADHD strongly agreed that they felt present in the VR while 7% of controls and 23% of PWADHD strongly agreed in question 6 (see Figure D5.2c in Appendix D).

Task 3

Q1: Pressing the button for the wrong number affected my next responses.

Q2: The lecturer and other students were distracting me during this task.

Q3: I think I did very well in completing this task.

Q4: I think I didn't do very well in completing this task.

Q5: The task was interesting and was similar to a scenario that can happen in our day-to-day life.

Q6: I felt present and involved in VR.

Overall, 21% of controls and 17% of PWADHD strongly disagreed to question 1. In the second question, 5% of PWADHD strongly agreed while no controls strongly agreed (see Figure D5.3a in Appendix D). 35% of the controls agreed whilst 11% of PWADHD strongly agreed to question 3. 14% of controls and 11% of PWADHD strongly disagreed to question 4 (see Figure D5.3b in Appendix D). 50% of controls agreed while 17% of PWADHD strongly agreed to question 5. In question 6, 7% of controls and 23% of PWADHD strongly agreed (see Figure D5.3c in Appendix D for more information).

Task 4

Q1: Pressing the button for the wrong car direction affected my next responses.

Q2: It was difficult to look and click in the direction of the car.

Q3: I think I didn't do very well in completing this task.

Q4: I think I did very well in completing this task.

Q5: I felt present and involved in VR.

Q6: The task was interesting and was similar to a scenario that can happen in our day-to-day life.

Responses indicated that 35% of controls and PWADHD strongly disagreed with the first question while 7% of controls and no PWADHD strongly agreed in question 2 (see Figure

D5.4a in Appendix D). 35% of controls and no PWADHD strongly agreed that they thought they did well in completing this task while 35% of controls and 23% PWADHD strongly disagreed to question 3 (Figure D5.4b in Appendix D). 14% of controls and 11% of PWADHD strongly agreed that they felt present in VR while 7% of the controls and 11% of PWADHD strongly agreed that the task was interesting and similar to a real-life scenario (see Figure D5.4c in Appendix D).

Task 5

Q1: Pressing the button for the wrong car direction affected my next responses.

Q2: It was difficult to look and click in the opposite direction of the car.

Q3: I think I did very well in completing this task.

Q4: I think I didn't do very well in completing this task.

Q5: The task was interesting and was similar to a scenario that can happen in our day-to-day life.

Q6: I felt present and involved in VR.

14% of controls strongly disagreed that their responses were affected in previous incorrect button presses while 35% of PWADHD strongly disagreed. No controls strongly agreed on question two whilst 11% of PWADHD strongly agreed (see Figure D5.5a in Appendix D for more information). Controls were less confident (14%) compared to PWADHD (23%) in correctly completing the task (strongly agreed) and in question 4 less controls (21%) than PWADHD (23%) strongly disagreed (Figure D5.5b in Appendix D). No controls and PWADHD strongly agreed in question 5 but 52% of PWADHD compared to 7% of controls agreed. PWADHD (5%) and no controls strongly agreed that they felt present in VR while 70% of PWADHD and 57% of controls agreed (see Figure D5.5c in Appendix D).

Task 6

Q1: How many times the word capacity was mentioned?

Q2: If you noticed that odd creature that walked for a moment in and out of the bar, what did it look like?

Q3: I think I didn't do very well in completing this task.

Q4: I think I did very well in completing this task.

Q5: I felt present and involved in VR.

Q6: The task was interesting and was similar to a scenario that can happen in our day-to-day life.

Surprisingly more PWADHD than controls answered correctly in both questions (Figure D5.6a in Appendix D). Specifically, 64% of the PWADHD compared to 57% of the controls answered correctly in the first question and 17% of PWADHD compared to 7% of the controls correctly indicated the odd creature in the task. PWADHD had a higher confidence in completing the task compared to controls with 11% of PWADHD strongly disagreeing to question 3 compared to 7% of controls and 17% of PWADHD compared to 7% of controls strongly agreeing to question 4 (see Figure D5.6b in Appendix D). More controls (21%) than PWADHD (17%) strongly agreed that they felt present in VR and more PWADHD (35%) than controls (14%) strongly agreed to question 6 as shown in Figure D5.6c in Appendix D.

Task 7

Q1: The missed call was from:

Q2: The call from Julie was about:

Q3: I think I did very well in completing this task.

Q4: I think I didn't do very well in completing this task.

Q5: The task was interesting and was similar to a scenario that can happen in our day-to-day life.

Q6: I felt present and involved in VR.

More controls (92%) than PWADHD (82%) responded correctly to the first question while more PWADHD (94%) than controls (85%) were correct in the second question. See Figure D5.7a in Appendix D for more information. PWADHD (23%) were more confident than controls in completing the task correctly compared to 14% controls by strongly agreeing to question 3. In question 4, more PWADHD (23%) than controls (14%) strongly disagreed as shown in Figure D5.7b in Appendix D. More PWADHD than controls strongly agreed to both 5 and 6 questions. The values were 35% to 21% in question 5 and 29% compared to 28% in question 6 (see Figure D5.7c in Appendix D).

Task 8

Q1: Where were you supposed to go but you couldn't make it?

Q2: Where was the human avatar going?

Q3: I think I didn't do very well in completing this task.

Q4: I think I did very well in completing this task.

Q5: I felt present and involved in VR.

Q6: The task was interesting and was similar to a scenario that can happen in our day-to-day life.

Surprisingly more PWADHD (82%) than controls (50%) answered correctly to the first question while more controls (42%) than PWADHD (41%) were correct in the second question (see Figure D5.8a in Appendix D). PWADHD were more confident than controls in completing the task as shown in Figure D5.8b in Appendix D. Specifically, 5% of PWADHD strongly disagreed and 47% of PWADHD disagreed in the fifth question while 50% of the controls only disagreed. 11% of PWADHD strongly agreed and 47% of PWADHD agreed in the last question while only 42% of controls agreed. In question 5, 14% of controls and 17% of

PWADHD strongly agreed while 21% of controls and 35% of PWADHD strongly agreed to question 6 (Figure D5.8c in Appendix D).

Task 9

Q1: How many floors did the building have?

Q2: The other human avatars were distracting me to focus on the task.

Q3: I think I did very well in completing this task.

Q4: I think I didn't do very well in completing this task.

Q5: The task was interesting and was similar to a scenario that can happen in our day-to-day life.

Q6: I felt present and involved in VR.

23% of PWADHD compared to 21% of the controls answered correctly in the first question. More people with ADHD strongly agreed compared to controls that the human avatars were distracting. See Figure D5.9a in Appendix D for more information. As shown in Figure D5.9b in Appendix D, more PWADHD (11%) than controls (7%) were more confident in completing correctly the task. Almost all participants agreed and strongly agreed that the task was interesting and that they felt present in VR. 11% and 23% of PWADHD strongly agreed in question 5 while 14% and 21% of controls strongly agreed in question 6. See Figure D5.9c in Appendix D for more information.

Task 10

Q1: What happens to aluminium if we add it into a beaker with bromine?

Q2: What was the second liquid that the user had to pour into the plate in experiment 3?

Q3: I think I didn't do very well in completing this task.

Q4: I think I did very well in completing this task.

Q5: I felt present and involved in VR.

Q6: The task was interesting and was similar to a scenario that can happen in our day-to-day life.

Figure D5.10a in Appendix D shows that more PWADHD (76%) than controls (64%) were correct in the first question while more controls (57%) than PWADHD (52%) were correct in the second question. More PWADHD than controls were confident in correctly completing the task as shown in Figure D5.10b in Appendix D. Specifically 11% of PWADHD compared to 7% to controls strongly disagreed to question 3 and strongly agreed to question 4. More PWADHD (29%) than controls (21%) strongly agreed that they felt present in VR and the task was interesting (see Figure D5.10c in Appendix D).

5.5 Discussion

Research suggests that PWADHD have impairments in EF located in the frontal cortex. While studies suggest that PWADHD do not necessarily show impairments in all abilities of EF, no study has investigated this claim fully. Hence, in this experiment, 10 VR tasks that drew upon different attention types were conducted on controls and PWADHD with the aim to understand if there are impairments in EF in PWADHD to investigate if the claim that PWADHD do not suffer in all EF abilities is true. All the tasks included VR scenarios that replicated real-life activities with the aim of assessing attention in participants in meaningful scenarios while decreasing the effect of becoming fatigued in the task and lose interest. An extensive investigation was made on the cognitive abilities and behavioral performance in the task. NMs on behavioural measures were conducted to understand in which specific attention type in EF, PWADHD differed from controls.

Cognitive factors including attention, stuttering and WM were predicted to be impaired in PWADHD based on the research that claims that PWADHD have symptoms of inattention, stuttering and WM issues (Andreou & Trott, 2013; Biederman et al., 1993; Engelhardt et al., 2010; Jacobson et al., 2011; Marchetta et al., 2008; Martinussen et al., 2005; Rapport, 2001; Tucha et al., 2005). Experiment successfully detected attention, fluency and WM problems in PWADHD as assessed from ASRS, SSI-3 and UNWR. The three measures were significantly different between groups with PWADHD scoring higher in attention ($p < 0.001$) and stuttering ($p < 0.001$) problems and lower in WM abilities ($p < 0.001$). With regards to the performance on the tasks, it was predicted that PWADHD would differ from controls. Specifically, in sustained attention tasks PWADHD would have a lower performance compared to controls (Hwang et al., 2019; McAvinue et al., 2012; Swaab-Barneveld et al., 2000; Tucha et al., 2009) with higher RTs and lower accuracy. Participants differed significantly in their performance in task 1 visual and auditory attention in their time looked at the TV ($p = 0.018$) with PWADHD recording lower times compared to controls. This suggests higher impulsive behaviour and a lower ability to maintain their visual attention on the TV. PWADHD differed significantly in task 2 TFT and task 3 SART that drew upon visual sustained attention. In TFT, PWADHD had lower correct responses ($p < 0.001$), higher incorrect responses ($p < 0.001$) and higher RTs ($p = 0.014$). Such results are in line with previous research (Hwang et al., 2019; Swaab-Barneveld et al., 2000) suggesting poorer performance in PWADHD in TFT tasks. Similar as in TFT, PWADHD had lower accuracy (lower correct ($p = 0.001$), higher incorrect ($p = 0.005$) responses) and higher RTs ($p = 0.002$) replicating previous findings (Hwang et al., 2019; McAvinue et al., 2012). The results showed that TFT and SART sustained attention tasks can successfully distinguish PWADHD from controls. Task 4 and 5 replicated Munoz et al. (2003) pro saccade and anti saccade task. There were significant differences between groups in both tasks (as seen in Munoz et al., 2003). In task 4 and 5 PWADHD compared to controls had fewer correct responses ($p = 0.010$, $p = 0.005$), more incorrect responses ($p < 0.001$, $p < 0.001$), longer RTs ($p = 0.023$, $p = 0.045$), looked less in the correct direction ($p < 0.001$, $p < 0.001$) and looked more in the incorrect direction ($p < 0.001$, $p = 0.011$). Such results suggest that pro saccade and anti saccade sustained attention tasks can distinguish PWADHD from controls from behavioural data. Groups differed significantly in divided attention task replicating findings from Savage et al. (2006) with higher presses of the map ($p < 0.001$) and a higher time to complete the task ($p = 0.008$) in PWADHD. Findings suggest that the WM ability to remember the map and the destination in the divided attention task was lower in PWADHD and behavioural data in divided attention tasks can distinguish PWADHD from controls as seen in Savage et al. (2006). Similarly, as in Elosúa et al. (2017), PWADHD performed poorly in attentional switching tasks with longer RTs to complete the task ($p = 0.012$) in auditory and visual domains in task 8. In the elevator task 9 which drew upon visual switching attention a higher number of phone pressed ($p < 0.001$) and time to complete the task ($p < 0.001$) was observed in PWADHD. Doneva et al. (2018) reached a similar conclusion in PWS in the attentional switching elevator task with auditory stimuli suggesting that both PWADHD and PWS performed poorly in the switched attentional tasks but in different domains. Interestingly in task 10 that measured visual switching attention with NF PWADHD had better performance with higher scores ($p = 0.001$) and a lower RT to complete task ($p < 0.001$) compared to controls. However, the task successfully distinguished PWADHD from controls as seen in Ochi et al. (2021) NF task. The results from attentional switching tasks suggest that these types of tasks can distinguish PWADHD from controls while showing impairments in WM abilities and attention (task 8 and 9). The task that included NF (task 10) additionally suggests that a VR scenario with NF can increase attention abilities in PWADHD as the task is more appealing and reinforces healthy brain functioning by providing positive feedback when attention is higher. Furthermore, task 10 included interactions with stimuli, possibly making the task more interesting for participants.

Results from questionnaires on sustained attention tasks showed that PWADHD were more correct than controls for the first two questions in task 1. Such results suggest that PWADHD had better performance in the audio domain and hearing what the topic was about while visually they did not maintain focus on the TV (as seen from the time looked at the TV above). More PWADHD than controls were distracted in tasks 2 and 3. It was more difficult for PWADHD to press the correct button and look in the right direction in task 5 compared to task 4. With regards to the confidence in correctly completing sustained attention tasks, overall, controls showed a higher confidence. For all the tasks, both groups strongly agreed that the task was interesting and that they felt present in VR. Results from the questionnaire in selective attention task showed that PWADHD were more correct than controls in question 1 and more PWADHD than controls noticed the odd creature replicating the findings from Grossman et al. (2015) in the famous invisible gorilla experiment. The results suggest that PWADHD performed better than controls in selective attention task and showed little inattentional blindness confirming that in selective attention tasks, PWADHD show no impairments. PWADHD were more confident in correctly completing the task than controls and more PWADHD than controls found the task interesting and felt present in VR although both groups strongly agreed with these statements. In divided attention task (task 7), controls were more correct in the question asked in visual domain while PWADHD were more correct in the question related to audio stimuli suggesting that PWADHD have more impairments in visual than audio domain in dual tasks. Controls were more confident in correctly completing the task and both groups strongly agreed that the task was interesting and that they felt present in VR. With regards to tasks that measures switched attention (tasks 8, 9, 10), overall PWADHD had more correct responses in questions related to the tasks suggesting that PWADHD show no impairments in attentional switching based on results from questionnaire. Although more PWADHD than controls felt distracted in task 9. More PWADHD than controls were confident in correctly completing the tasks and both groups strongly agreed that they felt present in VR and the task was interesting although PWADHD slightly agreed more to these statements.

Findings from behavioural data and questionnaires show a poorer performance in PWADHD in all sustained attention tasks with difficulties to maintain visual attention in the task, lower accuracies, and higher RTs in the visual domain while better responses from the questionnaire in task 1 were obtained by PWADHD in the auditory domain. Responses from the questionnaire in selective attention task show no impairments and little attentional blindness in PWADHD compared to controls suggesting that PWADHD performed better in this type of attention task. Data from the task and from questionnaire on divided attention task differed between groups with PWADHD showing higher impulsivity and working memory problems with higher RTs to reach to the destination compared to controls specifically in visual domain (as shown from questionnaire data). Data from the tasks that drew upon switched attention show contradictive results with PWADHD performing worse than controls in tasks

8, 9 while performing better than controls in task 10. Similar findings were achieved from the questionnaire. However, in task 9, only in visual domain PWADHD performed worse than controls in the task but not in responses from the questionnaire suggesting that tasks based only on visual domain can better assess ADHD traits. However attentional switching tasks might not give clear findings.

NMs showed clear insights that behavioural data from all sustained attention tasks differed between groups while other tasks showed similar NM architecture between controls and PWADHD (see Figure 5.9 and Figure 5.12). There was a difference however between controls and PWADHD in task 9 (switched attention task, Figure 5.11) suggesting that in attentional switching with only visual stimuli, PWADHD show impairments. Based on the results from NM, it can be concluded that the claim that PWADHD does not show impairments in all abilities of EF (Duff and Sulla, 2015; Lambek et al., 2010; Nigg et al., 2005) is supported and the type of the attention task that can correctly assess ADHD traits are based on sustained attention and switched attention particularly in the visual domain.

To conclude, results show that: 1- PWADHD do not suffer in all EF abilities (Duff and Sulla, 2015; Lambek et al., 2010; Nigg et al., 2005) but instead tasks that measure sustained attention and switched attention particularly in the visual domain can correctly assess inattention and impulsive behaviours in PWADHD as observed from results in NM. 2- Pro saccade, anti saccade and elevator tasks (tasks 4, 5 and 9) that measure sustained and switched attention in the visual domain better assess symptoms of ADHD as shown from NM.

One point to discuss is whether the amount of VR tasks utilized on this study caused participants to feel fatigued or lose interest on the tasks. Such factors can be a confound on the data and impact the results. In particular, ADHD group would have found the 10 VR tasks more tiring compared to other groups. However, in total the whole study took approximately 1 hour and a half which is a time commonly seen in studies that achieve relevant results. Studies that take less than 30 minutes are not appropriate to reach to clear conclusions. Furthermore, as observed from limitations on several studies particularly in ADHD, it is not advisable to assess PWADHD in short studies because PWADHD show impairments in their ability to focus on a task for longer periods of time. Hence it is important to assess this group in tasks that require them to pay attention for longer durations. Also, a careful consideration was taken when designing the tasks to mitigate the effects of feeling fatigued and lose interest on the tasks while simultaneously recording data. Each task included several animations, and the timing was set accordingly to the aim of the task based on the literature while allowing appropriate data to be recorded. Lastly, tasks were counterbalanced to avoid confounding factors that would impact the results. Findings from NMs help us understand which particular measure on which task can differentiate groups and can correctly determine differences and similarities between groups. NMs have excellent visualizations that distinct them from traditional statistical methods making such techniques more effective to assess which measures are impaired. It is therefore feasible to utilize NMs in experiments to draw better conclusions. Hence, NMs were conducted in chapter 8 to assess whether symptoms of attention, stuttering and WM are comorbid between PWADHD and PWS as commonly suggested by the literature.

Table 5.5

A summary of the results in Experiment 5 in all measures between groups in all tasks and conclusions on supported literature or inconsistencies.

	Groups	**Comparisons with the literature and comments**
	Controls vs PWADHD	*Supported literature or inconsistencies*
Cognitive Measures		
ASRS scores	C < A*	Previous studies that assessed disfluency in PWADHD (Andreou & Trott, 2013; Biederman et al., 1993; Engelhardt et al., 2010; Jacobson et al., 2011; Tucha et al., 2005) are supported. WM deficits are present in PWADHD supporting the literature (Marchetta et al., 2008; Martinussen et al., 2005; Rapport, 2001).
SSI scores	C < A*	
UNWR scores	C > A*	
Behavioural Measures		
Task 1 Sustained AV	C > A*	Literature on sustained attention tasks is supported (Hwang et al., 2019; McAvinue et al., 2012; Munoz et al. 2003; Swaab-Barneveld et al., 2000; Tucha et al., 2009) suggesting a lower performance in PWADHD compared to controls with higher RTs and lower accuracies. Results on sustained attention tasks suggests that this type of EF is impaired in PWADHD. Findings in Savage et al., (2006) were replicated in divided attention tasks suggesting that the working memory ability to remember the map and the destination was lower in PWADHD. Results in switched attention tasks were similar as in Elosúa et al. (2017), with higher RTs to complete the tasks 8 and 9, and lower accuracies in PWADHD in task 9. In task 10 PWADHD had a better performance than controls not replicating the findings in Elosúa et al. (2017) possibly because the task included interacting with stimuli and neurofeedback which reinforces healthy brain functioning by providing positive feedback making the task more interesting.
Task 2 Sustained V	C > A*	
	C < A*	
	C < A*	
Task 3 Sustained V	C > A*	
	C < A*	
	C < A*	
Task 4 Sustained V	C > A*	
	C < A*	
	C < A*	
	C > A*	
	C < A*	
Task 5 Sustained V	C > A*	
	C < A*	
	C < A*	
	C > A*	
	C < A*	
Task 7 Divided AV-WM	C < A*	
	C < A*	
Task 8 Switched AV	C < A*	
Task 9 Switched V	C < A*	
	C < A*	
Task 10 Switched AV-NF	C < A*	
	C > A*	

	Groups	**Comparisons with the literature and comments**
	Controls vs PWADHD	*Supported literature or inconsistencies*
Eye Measures Number of Saccades		
Task 1 Sustained AV	C < A	Findings from Munoz et al. (2003) that suggests that number of saccades are higher in PWADHD due to an inability to supress impulsive behaviour are replicated in tasks 1 (although not significant), 4, 5 and 7. Tasks 4 and 5 included the Munoz et al. (2003) study in a VR environment with a real-life scenario and the same conclusions are reached. Other tasks show that they cannot assess impulsivity in PWADHD based on the number of saccades.
Task 2 Sustained V	C > A	
Task 3 Sustained V	C > A*	
Task 4 Sustained V	C < A*	
Task 5 Sustained V	C < A*	
Task 6 Selective AV	C > A*	
Task 7 Divided AV-WM	C < A*	
Task 8 Switched AV	C > A*	
Task 9 Switched V	C > A*	
Task 10 Switched AV-NF	C > A*	
Eye Measures Saccade Mean Velocities		
Task 1 Sustained AV	C > A	Similarly, as in Munoz et al. (2003) all tasks except for task 9 replicate the findings that saccade man velocity is lower in PWADHD (although in task 1 the difference was not significant). The difference in task 9 compared to other tasks suggests that this measure does not have the same direction for PWADHD in all types of attention in EF. Task 9 correctly assessed impulsivity in PWADHD from saccade man velocity.
Task 2 Sustained V	C > A*	
Task 3 Sustained V	C > A*	
Task 4 Sustained V	C > A*	
Task 5 Sustained V	C > A*	
Task 6 Selective AV	C > A*	
Task 7 Divided AV-WM	C > A*	
Task 8 Switched AV	C > A*	
Task 9 Switched V	C < A*	
Task 10 Switched AV-NF	C > A*	
Eye Measures Number of Fixations		
Task 1 Sustained AV	C > A*	Gould et al. (2001) findings are supported in tasks 1, 2, 3, 7, 8, 9 and 10 suggesting lower number of fixations in PWADHD. Whereas findings in Vakil et al., (2016) are replicated in tasks 4, 5 and 6 showing a higher number of fixations in PWADHD. Findings suggest that this measure has a different direction for different types of attention tasks and also for the same type of attention task. A higher number of fixations suggests higher impulsive behaviours showing that tasks 4, 5 and 6 correctly assessed impulsivity in PWADHD.
Task 2 Sustained V	C > A*	
Task 3 Sustained V	C > A*	
Task 4 Sustained V	C < A*	
Task 5 Sustained V	C < A*	
Task 6 Selective AV	C < A*	
Task 7 Divided AV-WM	C > A*	
Task 8 Switched AV	C > A*	
Task 9 Switched V	C > A*	
Task 10 Switched AV-NF	C > A*	

	Groups	**Comparisons with the literature and comments**
	Controls vs PWADHD	*Supported literature or inconsistencies*
Eye Measures Fixation Durations		
Task 1 Sustained AV	C > A*	Tasks 1, 2, 3, 4, 5, 7, 8 ,9 and 10 replicate findings from Karatekin and Asarnow, (1999) showing lower fixation durations in PWADHD. Task 6 support findings from Vakil et al. (2016) showing higher fixation duration in PWADHD. Results suggest that almost every study correctly assessed inattentiveness in PWADHD (lower fixation durations) whilst study 6 show higher attention in PWADHD suggesting that selective attention cannot assess inattentiveness and is not impaired in PWADHD.
Task 2 Sustained V	C > A*	
Task 3 Sustained V	C > A*	
Task 4 Sustained V	C > A*	
Task 5 Sustained V	C > A*	
Task 6 Selective AV	C < A*	
Task 7 Divided AV-WM	C > A*	
Task 8 Switched AV	C > A*	
Task 9 Switched V	C > A*	
Task 10 Switched AV-NF	C > A*	
Eye Measures Number of Blinks		
Task 1 Sustained AV	C < A	Fried et al's (2014) findings were replicated in tasks 1 (although not significant), 2, 3 (although not significant), 4, 5, 7, 9 and 10. Since the number of blinks are negatively connected with wakefulness (Tanaka, 1999) and a higher number of blinks has been observed in PWADHD (Fried et al., 2014), tasks 1, 2, 3, 4, 5, 7, 9 and 10 correctly assessed lower levels of wakefulness in PWADHD. In tasks 6 and 8 it can be suggested that PWADHD had higher levels of wakefulness possibly finding the task easier to conduct making it more interesting for them.
Task 2 Sustained V	C < A*	
Task 3 Sustained V	C < A	
Task 4 Sustained V	C < A*	
Task 5 Sustained V	C < A*	
Task 6 Selective AV	C > A*	
Task 7 Divided AV-WM	C < A*	
Task 8 Switched AV	C > A*	
Task 9 Switched V	C < A*	
Task 10 Switched AV-NF	C < A*	
Eye Measures Pupil Diameter		
Task 1 Sustained AV	C < A*	Tasks that replicated previous studies (Fried et al., 2014; Munoz et al., 2003; Wainstein et al., 2017) were 6, 8, 9 and 10 suggesting a lower pupil diameter in PWADHD. Whilst tasks 1, 2 (although not significant), 3, 4, 5, and 7 show higher pupil diameter in PWADHD in contrast with previous studies. This suggests that pupil diameter differs for different types of attention tasks. Participants may have found the task engaging, causing their pupils to dilate, or pupil diameter may be associated with impulsive behaviour rather than inattentiveness (as literature suggests), although this can again vary in different attention tasks. Pupil diameter also changes based on the light. In VR light is controlled and the same for all participants. Additionally, a higher PD was positively correlated with number of saccades and number of fixations in task 4 and task 5 suggesting that PD is linked positively to impulsive behaviour instead of inattentiveness. This suggests that a higher impulsivity in PWADHD was correctly assessed in tasks 1, 2, 3, 4, 5 and 7.
Task 2 Sustained V	C < A	
Task 3 Sustained V	C < A*	
Task 4 Sustained V	C < A*	
Task 5 Sustained V	C < A*	
Task 6 Selective AV	C > A*	
Task 7 Divided AV-WM	C < A*	
Task 8 Switched AV	C > A*	
Task 9 Switched V	C > A*	
Task 10 Switched AV-NF	C > A*	

	Groups	Comparisons with the literature and comments
	Controls vs PWADHD	*Supported literature or inconsistencies*
EEG Measures Alpha Activity		
Task 1 Sustained AV	C > A*	Tasks 1, 2, and 6 supported findings in El-Sayed et al. (2002) and Lazzaro et al. (1998) suggesting lower alpha values associated with lower wakefulness in PWADHD whereas tasks 3, 4, 5, 7, 8, 9 and 10 replicated findings in Loo et al. (2009) that PWADHD have higher wakefulness shown by a higher alpha activity. Results suggest that for different attention tasks, a different alpha activity is observed. Furthermore, a different alpha activity is observed in tasks that measure the same attention type.
Task 2 Sustained V	C > A*	
Task 3 Sustained V	C < A*	
Task 4 Sustained V	C < A*	
Task 5 Sustained V	C < A*	
Task 6 Selective AV	C > A*	
Task 7 Divided AV-WM	C < A*	
Task 8 Switched AV	C < A*	
Task 9 Switched V	C < A*	
Task 10 Switched AV-NF	C < A*	
EEG Measures Beta Activity		
Task 1 Sustained AV	C < A*	While tasks 4 and 6 confirmed previous findings from El-Sayed et al. (2002) and Lazzaro et al. (1998) suggesting lower beta values in PWADHD associated with lower attention, a higher attention shown with higher beta activity was observed in tasks 1, 2, 3, 5, 7, 8, 9, 10 supporting other studies (Chabot & Serfontein, 1996; Clarke, 2002; Loo et al., 2009). The results suggest that beta differs in different tasks and might not be a good indicator to assess ADHD traits.
Task 2 Sustained V	C < A*	
Task 3 Sustained V	C < A*	
Task 4 Sustained V	C > A*	
Task 5 Sustained V	C < A*	
Task 6 Selective AV	C > A*	
Task 7 Divided AV-WM	C < A*	
Task 8 Switched AV	C < A*	
Task 9 Switched V	C < A*	
Task 10 Switched AV-NF	C < A*	
EEG Measures Theta Activity		
Task 1 Sustained AV	C > A*	Only tasks 7, 9 and 10 showed higher inattentiveness with higher theta activity in PWADHD similar as in Bresnahan and Berry, (2002). Theta was lower in PWADHD in the other tasks. The results suggest that this measure differs across attention tasks.
Task 2 Sustained V	C > A*	
Task 3 Sustained V	C > A*	
Task 4 Sustained V	C > A*	
Task 5 Sustained V	C > A*	
Task 6 Selective AV	C > A*	
Task 7 Divided AV-WM	C < A*	
Task 8 Switched AV	C > A*	
Task 9 Switched V	C < A*	
Task 10 Switched AV-NF	C < A*	

	Groups	**Comparisons with the literature and comments**
	Controls vs PWADHD	*Supported literature or inconsistencies*
EEG Measures Theta – Beta Ratio		
Task 1 Sustained AV	C > A*	Theta beta ratio was higher in all tasks except for task 9. Only task 9 supports previous studies (Loo & Makeig, 2012; Monastra et al., 2001; Snyder & Hall, 2006) suggesting that a higher theta beta ratio is associated with higher impulsivity and higher reaction times. This was confirmed in task 9 in which higher theta beta ratio was positively correlated to reaction times in behavioural data. Results suggests that this measure can assess impairments in PWADHD in attentional switching tasks in the visual domain.
Task 2 Sustained V	C > A*	
Task 3 Sustained V	C > A*	
Task 4 Sustained V	C > A*	
Task 5 Sustained V	C > A*	
Task 6 Selective AV	C > A*	
Task 7 Divided AV-WM	C > A*	
Task 8 Switched AV	C > A*	
Task 9 Switched V	C < A*	
Task 10 Switched AV-NF	C > A*	
EEG Measures Attention Values		
Task 1 Sustained AV	C > A*	Attention values were lower in PWADHD in all tasks that measured sustained attention (tasks 1, 2, 3, 4, 5) supporting results in Ochi et al. (2021) whereas in other tasks (tasks 6, 7, 8, 9, 10) attention values were higher in PWADHD. Results suggest that we expect a lower attention in PWADHD in sustained attention tasks.
Task 2 Sustained V	C > A*	
Task 3 Sustained V	C > A*	
Task 4 Sustained V	C > A*	
Task 5 Sustained V	C > A*	
Task 6 Selective AV	C < A	
Task 7 Divided AV-WM	C < A*	
Task 8 Switched AV	C < A*	
Task 9 Switched V	C < A*	
Task 10 Switched AV-NF	C < A*	
Network Models Behavioural Data		
Task 1 Sustained AV	C ≠ A	NM architecture was similar between groups in tasks 7, 8 and 10. For all tasks based on sustained attention (1, 2, 3, 4, 5) and one task based on switched attention with only visual stimuli (task 9) the NM architecture differed between controls and PWADHD suggesting that PWADHD are impaired in these type of attention in EF.
Task 2 Sustained V	C ≠ A	
Task 3 Sustained V	C ≠ A	
Task 4 Sustained V	C ≠ A	
Task 5 Sustained V	C ≠ A	
Task 7 Divided AV-WM	C = A	
Task 8 Switched AV	C = A	
Task 9 Switched V	C ≠ A	
Task 10 Switched AV-NF	C = A	

	Groups	Comparisons with the literature and comments
	Controls vs PWADHD	*Supported literature or inconsistencies*
Network Models Eye Data		
Task 1 Sustained AV	C ≠ A	Pattern of eye movements differed between groups in all tasks with a different NM architecture. This suggests that for different types of attention tasks, the pattern of eye movement differs.
Task 2 Sustained V	C ≠ A	
Task 3 Sustained V	C ≠ A	
Task 4 Sustained V	C ≠ A	
Task 5 Sustained V	C ≠ A	
Task 6 Selective AV	C ≠ A	
Task 7 Divided AV-WM	C ≠ A	
Task 8 Switched AV	C ≠ A	
Task 9 Switched V	C ≠ A	
Task 10 Switched AV-NF	C ≠ A	
Network Models Brain Data		
Task 1 Sustained AV	C ≠ A	Pattern of brain activity differed between groups in all tasks with a different NM architecture suggesting that alpha, beta, theta, theta-beta ratio and attention values differ for different attention tasks.
Task 2 Sustained V	C ≠ A	
Task 3 Sustained V	C ≠ A	
Task 4 Sustained V	C ≠ A	
Task 5 Sustained V	C ≠ A	
Task 6 Selective AV	C ≠ A	
Task 7 Divided AV-WM	C ≠ A	
Task 8 Switched AV	C ≠ A	
Task 9 Switched V	C ≠ A	
Task 10 Switched AV-NF	C ≠ A	

Note. C stands for Controls, A for PWADHD. The sign (*) shows that the group differed significantly. AV stands for audio-visual whereas V stands for visual. WM is abbreviation of Working Memory whereas NF is Neurofeedback. C = A means group had similar architecture in Network Models whereas C ≠ A shows that groups had a different architecture.

6. Chapter 6. Assessing Oculomotor Impairments in EF in PWADHD from Real-life VR attention tasks.

Chapter Summary

Oculomotor measures were assessed in PWADHD and compared to controls in all 10 VR tasks from Chapter Five. Pro saccade and anti saccade tasks distinguished PWADHD from controls in oculomotor measures. Impulsive behaviours were successfully assessed from higher NOS and higher NOF in PWADHD, and inattention symptoms were assessed from lower FD in PWADHD. Additionally, these tasks successfully assessed levels of wakefulness in PWADHD as determined by a higher NOB which correlates negatively with levels of wakefulness in line with the literature (Fried et al., 2014; Tanaka, 1999). PD was higher in PWADHD in both tasks suggesting that PD might be positively linked to impulsivity or wakefulness because the task was interesting instead of inattentiveness as the literature suggests (Fried et al., 2014; Munoz et al., 2003; Wainstein et al., 2017). However, for different attention tasks, PD varied. Overall PD and SMV might not be appropriate to assess ADHD symptoms in saccade and anti saccade tasks since the results are contradictory with results from other attention tasks in the literature. NMs in eye data differed between groups in all tasks showing that oculomotor measures have different architecture in each task.

6.1 Introduction

6.1.1 Executive Function and attention from the perspective of sight

Attention is the ability to focus on specific stimuli and ‘filter out' irrelevant information where the filtering is regarded as the fundamental components of attention (Knudsen, 2007). Being attentive to stimuli can have significant impact on other cognitive processes such as learning and memory. Attention can be overt (visible, such as looking at a target) or covert (not visible). According to Knudsen (2007), WM, salience filters, top-down sensitivity control, and competitive selection all function as a recurrent cycle in voluntary attention. The nervous system transmits information about the world to salience filters, which respond differently to unimportant versus important inputs (bottom-up). In various hierarchies, neural representations encode information about the world, movements, memories etc. To enter into the circuitry that underpins WM, a competitive attention mechanism picks the representation with the highest signal strength. WM can then alter the sensitivity of representations processed by directing top-down bias signals to these inputs. WM and competitive selection control eye movements and other orienting behaviours which changes how the world affects the neurological system.

Willcutt et al. (2005) reached to the conclusion that ADHD is associated with deficiencies in WM and several EFs, with inhibiting and organization being notably impaired, in their meta-analysis. Due to this, and in light of the growing evidence that EF deficiencies are prevalent in ADHD, some researchers have claimed that EF performance is the factor that most effectively distinguishes PWADHD (Boonstra et al., 2005). However, not all individuals with ADHD display deficiencies in such abilities, despite the fact that the majority of studies show poor performance in tasks involving EFs (Duff & Sulla, 2015; Nigg et al., 2005). According to Nigg et al. (2005), 50% of children with typical development showed deficits in at least one EF, compared to nearly 80% of CWADHD. Additionally, the ADHD group had deficiencies with different EFs. Similar findings were reported by Lambek et al. (2010), indicating that while there is a considerably larger deficit of the EFs in PWADHD, it is not necessarily the case for all EFs. This makes it necessary to explore further the many EFs and their potential and variable performance patterns in ADHD (Sonuga-Barke, 2005).

6.2 Experiment 6

This chapter aimed to understand in which attention task the pattern of eye measures distinguished PWADHD from controls. Specifically, which attention task correctly assesses ADHD traits from oculomotor measures? As indicated earlier oculomotor measures can distinguish PWADHD from controls (see Table 1.4 in introduction) on the NOS, SMV, NOF, FD, NOB, PD. Studies suggest that PWADHD have difficulties in inhibiting voluntary behaviour such as saccades and fixations (Munoz et al., 2003) but literature shows contradictive findings in eye measures in PWADHD possibly due to the attention task chosen. Hence, it was anticipated that for different EF we would expect a different pattern of the results since studies suggest that while EF is impaired in PWADHD, this is not necessarily the case for all types of EF abilities (Duff and Sulla, 2015; Lambek et al., 2010; Nigg et al., 2005).

The following hypothesis on physiological measures were tested in all 10 VR tasks. It was predicted that groups should differ from each other on the: NOS (H1, in tasks 4 and 5 it was expected a higher NOS in PWADHD as shown in Munoz et al., 2003), SMV (H2), NOF (H3, in tasks 4 and 5 it was expected a higher NOF in PWADHD taking into consideration that PWADHD have difficulties in inhibiting voluntarily behaviour and fixations as shown in Munoz et al., 2003), FD (H4), NOB (H5) and PD (H6).

6.3 Methods

6.3.1 Design

Experiment had a mixed design in which the within-participant factors were the tasks, and the between-participants factor was the participant group (controls vs PWADHD). The dependent variables were oculomotor measures.

6.4 Results

6.4.1 Experiment 6a Results

Table 6.1

Descriptive Statistics, hypothesis, and results for eye measures.

	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7	Task 8	Task 9	Task 10
H1: Groups should differ from each other in number of saccades.	Some outliers were removed $p = 0.844$ $p = 0.065$ NA **Rejected**	Some outliers were removed $p = 0.940$ $p = 0.055$ NA **Rejected**	Some outliers were removed $p = 0.243$ $p = 0.016$ NA **Accepted**	Some outliers were removed $p = 0.203$ $p = 0.008$ NA **Accepted**	Some outliers were removed $p = 0.082$ $p = 0.002$ NA **Accepted**	Some outliers were removed $p = 0.920$ $p = 0.002$ NA **Accepted**	Some outliers were removed $p = 0.183$ $p = 0.015$ NA **Accepted**	Some outliers were removed $p = 0.349$ $p = 0.007$ NA **Accepted**	Two outliers were removed $p = 0.500$ $p = 0.003$ NA **Accepted**	None $p = 0.128$ $p = 0.003$ NA **Accepted**
H2: Groups should differ from each other in saccade mean velocity.	Some outliers were removed $p = 0.975$ $p = 0.125$ NA **Rejected**	Some outliers were removed $p = 0.705$ $p = 0.002$ NA **Accepted**	Some outliers were removed $p = 0.549$ $p = 0.005$ NA **Accepted**	Some outliers were removed $p = 0.187$ $p = 0.001$ NA **Accepted**	Some outliers were removed $p = 0.322$ $p = 0.025$ NA **Accepted**	None $p = 0.894$ $p = 0.002$ NA **Accepted**	Some outliers were removed $p = 0.767$ $p = 0.011$ NA **Accepted**	Some outliers were removed $p = 0.026$ $p = 0.001$ $p < 0.001$ **Accepted**	Two outliers were removed $p = 0.109$ $p < 0.001$ NA **Accepted**	One outlier was removed $p = 0.855$ $p < 0.001$ NA **Accepted**
H3: Groups should differ from each other in number of fixations.	Some outliers were removed $p = 0.247$ $p = 0.032$ NA **Accepted**	Some outliers were removed $p = 0.798$ $p = 0.013$ NA **Accepted**	Some outliers were removed $p = 0.397$ $p = 0.003$ NA **Accepted**	Some outliers were removed $p = 0.236$ $p = 0.003$ NA **Accepted**	Some outliers were removed $p = 0.030$ $p = 0.004$ $p = 0.012$ **Accepted**	Some outliers were removed $p = 0.225$ $p < 0.001$ NA **Accepted**	Some outliers were removed $p = 0.324$ $p = 0.006$ NA **Accepted**	Some outliers were removed $p = 0.397$ $p = 0.001$ NA **Accepted**	One outlier was removed $p = 0.222$ $p < 0.001$ NA **Accepted**	Two outliers were removed $p = 0.374$ $p < 0.001$ NA **Accepted**
H4: Groups should differ from each other in fixation durations.	Some outliers were removed $p = 0.753$ $p = 0.003$ NA **Accepted**	Some outliers were removed $p = 0.250$ $p = 0.009$ NA **Accepted**	Some outliers were removed $p = 0.870$ $p = 0.022$ NA **Accepted**	Some outliers were removed $p = 0.297$ $p < 0.001$ NA **Accepted**	Some outliers were removed $p = 0.021$ $p = 0.005$ $p = 0.015$ **Accepted**	Some outliers were removed $p = 0.920$ $p < 0.001$ NA **Accepted**	Some outliers were removed $p = 0.134$ $p < 0.001$ NA **Accepted**	Some outliers were removed $p = 0.045$ $p = 0.001$ $p = 0.003$ **Accepted**	None $p = 0.628$ $p = 0.008$ NA **Accepted**	None $p = 0.016$ $p = 0.002$ $p = 0.006$ **Accepted**
H5: Groups should differ from each other in number of blinks.	Some outliers were removed $p = 0.496$ $p = 0.112$ NA **Rejected**	Some outliers were removed $p = 0.956$ $p = 0.008$ NA **Accepted**	Some outliers were removed $p = 0.870$ $p = 0.125$ NA **Rejected**	Some outliers were removed $p = 0.521$ $p = 0.009$ NA **Accepted**	Some outliers were removed $p = 0.529$ $p = 0.005$ NA **Accepted**	Some outliers were removed $p = 0.418$ $p = 0.011$ NA **Accepted**	Some outliers were removed $p = 0.020$ $p < 0.001$ $p < 0.001$ **Accepted**	Some outliers were removed $p = 0.121$ $p < 0.001$ NA **Accepted**	One outlier was removed $p = 0.008$ $p = 0.002$ $p = 0.002$ **Accepted**	One outlier was removed $p < 0.001$ $p = 0.006$ $p = 0.001$ **Accepted**

	Task 1	**Task 2**	**Task 3**	**Task 4**	**Task 5**	**Task 6**	**Task 7**	**Task 8**	**Task 9**	**Task 10**
H6: Groups should differ from each other in pupil diameter.	Some outliers were removed $p = 0.668$ $p = 0.005$ NA **Accepted**	Some outliers were removed $p = 0.649$ $p = 0.058$ NA **Rejected**	Some outliers were removed $p = 0.246$ $p = 0.013$ NA **Accepted**	Some outliers were removed $p = 0.223$ $p = 0.002$ NA **Accepted**	Some outliers were removed $p = 0.169$ $p < 0.001$ NA **Accepted**	None $p = 0.617$ $p = 0.013$ NA **Accepted**	Some outliers were removed $p = 0.164$ $p < 0.001$ NA **Accepted**	Some outliers were removed $p = 0.076$ $p = 0.010$ NA **Accepted**	Two outliers were removed $p = 0.189$ $p = 0.009$ NA **Accepted**	One outlier was removed $p = 0.158$ $p < 0.001$ NA **Accepted**

Task 1

Descriptive statistics (Table E6.1 in Appendix E) and Figure 6.1a shows that PWADHD recorded higher saccades compared to controls. Groups did not differ significantly from each other as shown in Table 6.1. Hence H1 in task 1 was not accepted. Figure 6.2a shows that saccade mean velocities were lower in PWADHD. Groups did not differ significantly from each other. H2 was rejected. Figure 6.3a shows that NOF are lower in PWADHD. Groups differed significantly from each other. Therefore, H3 was supported. Groups differed from each other significantly with PWADHD having lower FD compared to controls. See Figure 6.4a for more information. H4 was supported. A higher NOB in PWADHD was recorded although no significant difference between groups was observed. See Figure 6.5a for more information. H5 was not supported. PWADHD had higher PD (see Figure 6.6a). Groups differed significantly from each other and H6 is accepted.

Task 2

NOS were lower in PWADHD compared to controls as shown in Figure 6.1b and Table E6.1 in Appendix E. See Table 6.1 for more information. Groups did not differ significantly. Hence H1 in task 2 was not supported. Groups differed significantly in SMV with PWADHD recording lower values as visualised in Figure 6.2b. Therefore, H2 is accepted. H3 was accepted because NOF differed significantly between groups with lower values observed in PWADHD compared to controls (see Figure 6.3b). PWADHD had significantly lower FD compared to controls as shown in Figure 6.4b accepting H4. Groups differed significantly in NOB with PWADHD recording higher values as shown in Figure 6.5b. Hence H5 was accepted. PD was higher in PWADHD and groups did not differed significantly from each other rejecting H6. See Figure 6.6b for more information.

Task 3

H1 in task 3 was supported as groups differed significantly from each other (see Table 6.1). NOS were lower in PWADHD compared to controls (see Figure 6.1c and Table E6.1 in Appendix E). PWADHD had significantly lower SMV compared to controls (see Figure 6.2c). Hence H2 was accepted. Groups differed significantly from each other in NOF with lower values recorded in PWADHD (see Figure 6.3c). H3 was supported. FD were significantly lower in PWADHD as shown in Figure 6.4c. H4 is accepted. NOB were higher in PWADHD, but groups did not differ significantly. Hence H5 is rejected. Figure 6.5c shows a visual presentation of the results. PD was significantly higher in PWADHD. Hence, H6 was accepted. See Figure 6.6c for more information.

Task 4

NOS differed significantly in groups (see Table 6.1) with PWADHD recording higher values (see Figure 6.1d and Table E6.1 in Appendix E). Hence, H1 in task 4 was supported. Significantly lower SMV were observed in PWADHD accepting H2. Figure 6.2d shows a visualization of the results. NOF were significantly higher in PWADHD compared to controls accepting H3 (see Figure 6.3d). PWADHD had significantly lower FD as shown in Figure 6.4d. H4 was supported. Groups differed significantly in NOB accepting H5. PWADHD recorded a higher NOB (see Figure 6.5d). PD was significantly higher in PWADHD as shown in Figure 6.6d. H6 was supported.

Task 5

Groups differed significantly on NOS (see Table 6.1), hence H1 in task 5 is supported. PWADHD recorded higher NOS values as shown in Figure 6.1e and Table E6.1 in Appendix E. SMV was significantly lower in PWADHD compared to controls (Figure 6.2e). H2 is accepted. H3 was supported as NOF differed significantly between groups with higher values observed in PWADHD (see Figure 6.3e). PWADHD recorded significantly lower FD (see

Figure 6.4e). Hence H4 is supported. A higher NOB was observed in PWADHD compared to controls as shown in Figure 6.5e. Groups differed significantly accepting H5. PD was significantly higher in PWADHD supporting H6. See Figure 6.6e for more information.

Task 6

Groups differed significantly from each other (see Table 6.1). Figure 6.1f and Table E6.1 in Appendix E shows that PWADHD had lower NOS compared to controls. H1 in task 6 was accepted. PWADHD recorded significantly lower SMV compared to controls (Figure 6.2f). Hence H2 is accepted. NOF differed significantly between groups accepting H3. Figure 6.3f shows that NOF was higher in PWADHD. FD were significantly higher in PWADHD compared to controls accepting H4. See Figure 6.4f for more information. H5 was supported as groups differed significantly in NOB with lower values recorded in PWADHD (see Figure 6.5f). Groups differed significantly in PD accepting H6. PWADHD had lower PD compared to controls (see Figure 6.6f).

Task 7

Groups differed significantly in NOS with PWADHD recording higher values accepting H1 in task 7 (see Table 6.1, Figure 6.1g and Table E6.1 in Appendix E). H2 was accepted as groups differed significantly with lower SMV obtained by PWADHD (see Figure 6.2g). NOF were significantly lower in PWADHD (Figure 6.3g). Hence H3 was accepted. Groups differed significantly on FD accepting H4. Figure 6.4g shows that PWADHD recorded lower values. NOB were significantly higher in PWADHD (Figure 6.5g). Therefore, H5 was supported. PD was significantly higher in PWADHD accepting H6. Figure 6.6g shows more information.

Task 8

H1 for task 8 is accepted as groups differed significantly from each other (see Table 6.1) with PWADHD recording lower NOS compared to controls (see Figure 6.1h and Table E6.1 in Appendix E). PWADHD had significantly lower SMV than controls (Figure 6.2h). H2 was supported. Groups differed significantly with PWADHD having lower NOF (see Figure 6.3h). H3 was accepted. FD were significantly lower in PWADHD accepting H4. Figure 6.4h shows a visual representation of the results. PWADHD had significantly lower NOB compared to controls (see Figure 6.5h). H5 was supported. PD was significantly lower in PWADHD as shown in Figure 6.6h. Hence, H6 was accepted.

Task 9

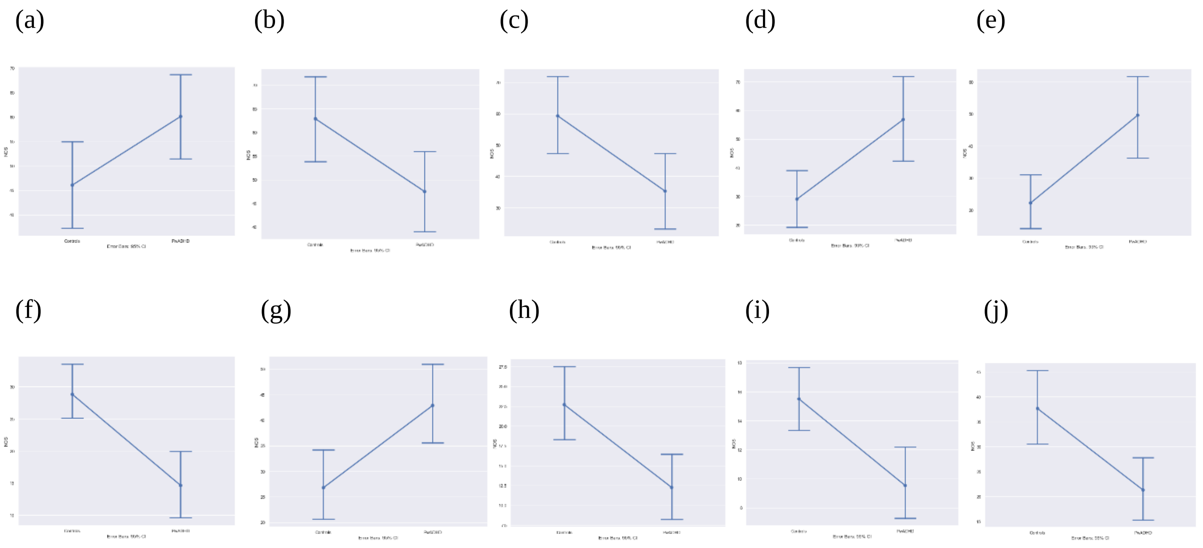
Groups differed significantly in NOS (see Table 6.1) with PWADHD recording lower scores (see Figure 6.1i and Table E6.1 in Appendix E). H1 in task 9 was accepted. SMV was significantly higher in PWADHD accepting H2. See Figure 6.2i for more information. H3 was supported since groups differed significantly in NOF. PWADHD had lower NOF (see Figure 6.3i). FD were significantly lower in PWADHD compared to controls. Hence H4 was supported. See Figure 6.4i for more information. Groups differed significantly in NOB with PWADHD having higher values as shown in Figure 6.5i. H5 was supported. PD was significantly lower in PWADHD (Figure 6.6i) accepting H6.

Task 10

There was a significant difference between the groups in NOS (see Table 6.1) with lower scores obtained in PWADHD (see Figure 6.1j and Table E6.1 in Appendix E). H1 for task 10 was supported. SMV was significantly lower in PWADHD compared to controls accepting H2. See Figure 6.2j for more information. PWADHD had significantly lower NOF accepting H3 (Figure 6.3j). FD were significantly lower in PWADHD accepting H4. See Figure 6.4j for a visual representation of the results. NOB were significantly higher in PWADHD compared to controls. Therefore, H5 was supported. See Figure 6.5j for more information. PWADHD recorded a lower PD (see Figure 6.6j). Groups differed significantly accepting H6.

Figure 6.1

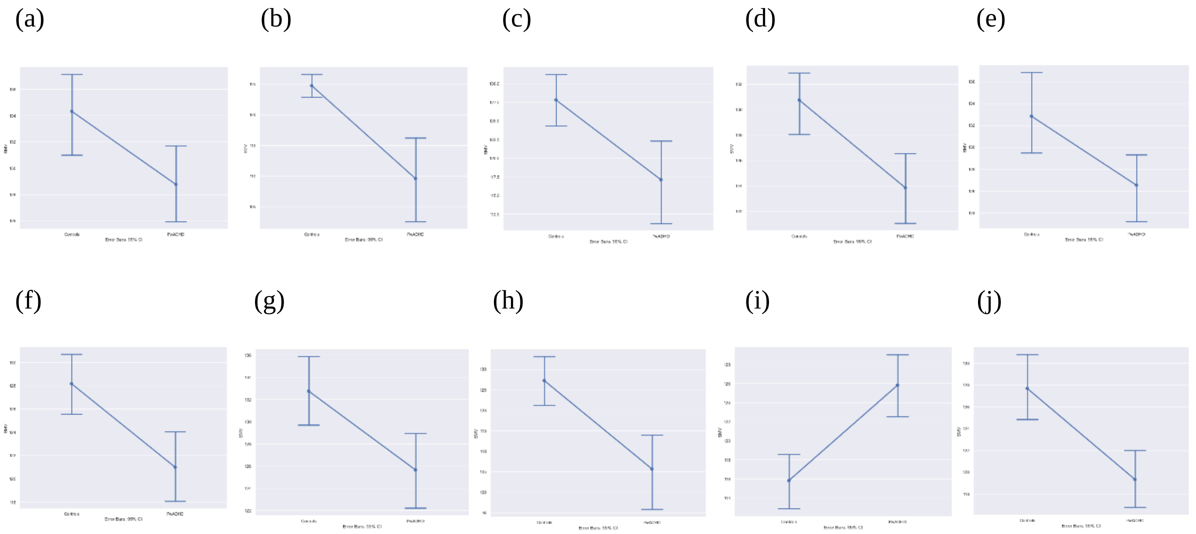
Mean NOS in controls and PWADHD for all 10 tasks ordered alphabetically from a to j. Left x - axis represent controls and right x - axis represent PWADHD in each graph. Error bars represent ± 2 Standard Error [SE].


(a) (b) (c) (d) (e)

(f) (g) (h) (i) (j)

Figure 6.2

Mean SMV in controls and PWADHD for all 10 tasks ordered alphabetically from a to j. Left x - axis represent controls and right x - axis represent PWADHD in each graph. Error bars represent ± 2 Standard Error [SE].


(a) (b) (c) (d) (e)

(f) (g) (h) (i) (j)

Figure 6.3

Mean NOF in controls and PWADHD for all 10 tasks ordered alphabetically from a to j. Left x - axis represent controls and right x - axis represent PWADHD in each graph. Error bars represent ± 2 Standard Error [SE].

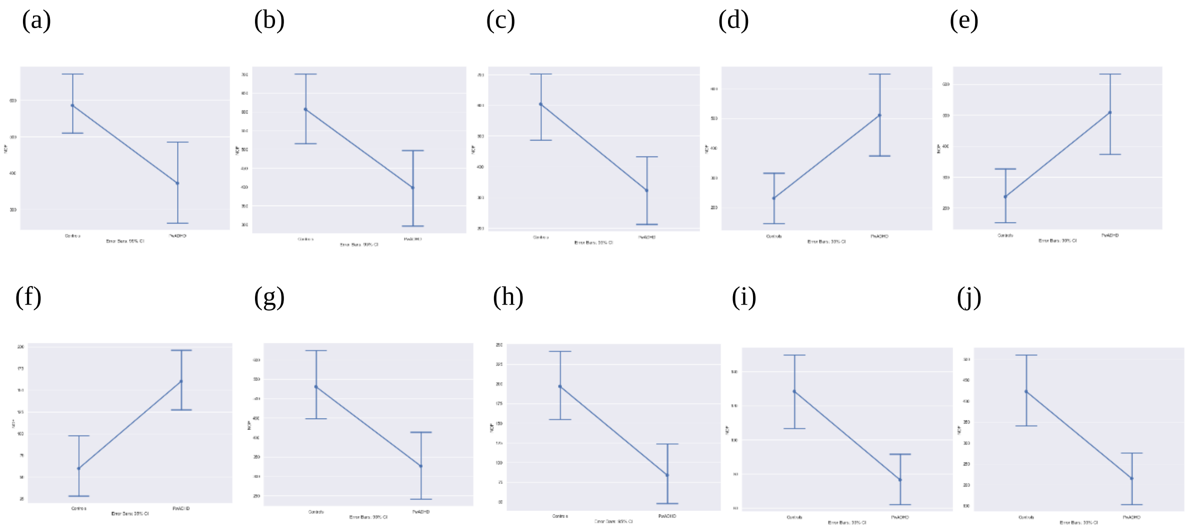


Figure 6.4

Mean FD in controls and PWADHD for all 10 tasks ordered alphabetically from a to j. Left x - axis represent controls and right x - axis represent PWADHD in each graph. Error bars represent ± 2 Standard Error [SE].

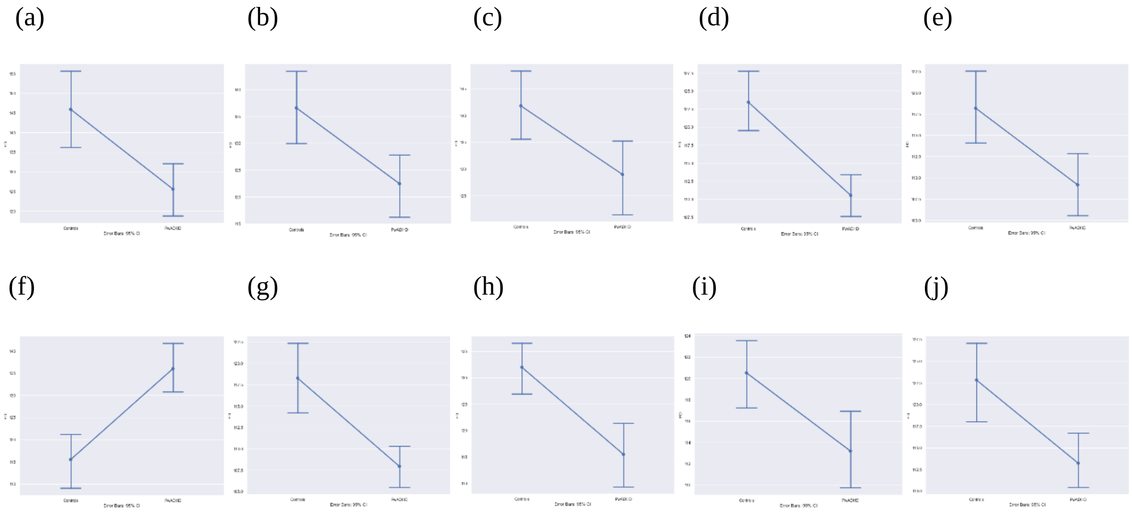
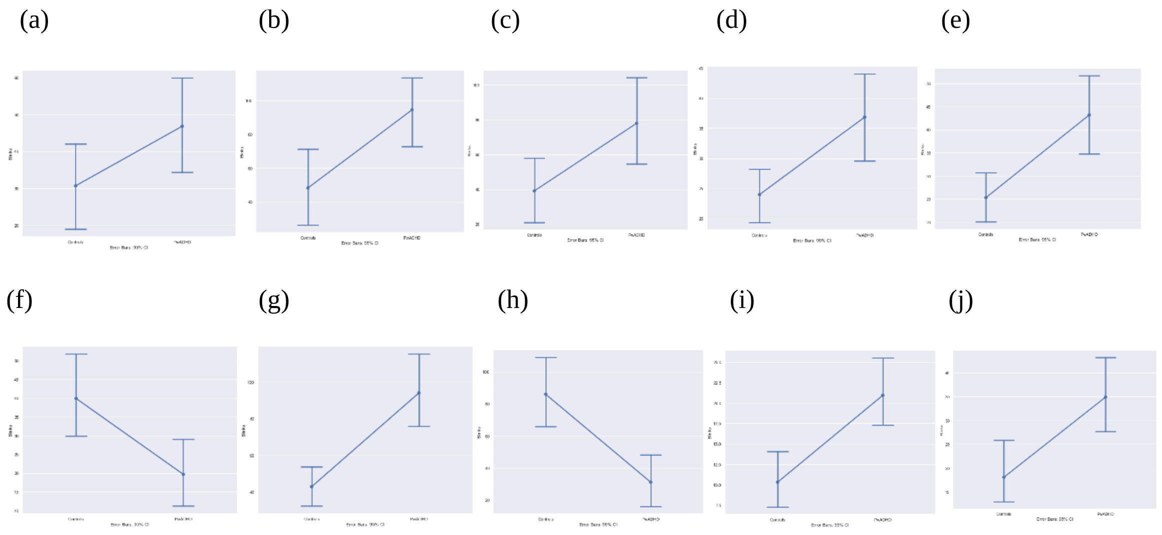


Figure 6.5

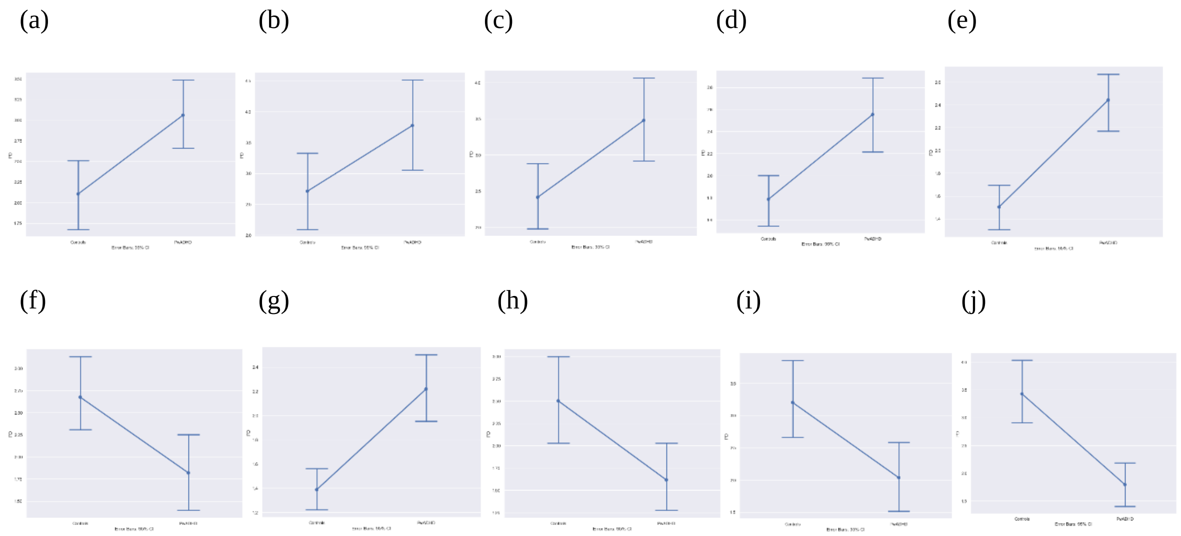
Mean number of blinks, NOB in controls and PWADHD for all 10 tasks ordered alphabetically from a to j. Left x - axis represent controls and right x - axis represent PWADHD in each graph. Error bars represent ± 2 Standard Error [SE].


(a) (b) (c) (d) (e)

(f) (g) (h) (i) (j)

Figure 6.6

Mean pupil diameter, PB in controls and PWADHD for all 10 tasks ordered alphabetically from a to j. Left x - axis represent controls and right x - axis represent PWADHD in each graph. Error bars represent ± 2 Standard Error [SE].


(a) (b) (c) (d) (e)

(f) (g) (h) (i) (j)

6.4.2 Experiment 6b Results

NMs in eye data show different architecture in all tasks between groups which suggests that in all types of attention, we would expect different pattern of eye movements. With regards to oculomotor measures in sustained attention tasks, NMs show that the measures in PWADHD that differed from controls and influenced other nodes were: NOF (tasks 1, 2), NOS and NOF (task 3), NOS, NOF and FD (task 4), NOS, PD and FD (task 5). Results confirm previous findings that the pro saccade and anti saccade correctly assessed impulsive behaviours (NOF, NOS) and inattentiveness (FD) from oculomotor measures. In task 5, PD shows that it can assess impulsivity whereas NOF was not loaded onto NM. In tasks (tasks 6, 7, 8, 10) NOF and NOS were the measures that differed and influenced other nodes while in task 9 FD differed. Results in task 9 suggest that only inattentiveness can be assessed in PWADHD from eye movements.

Figure 6.7

NMs plotted for oculomotor measures for sustained attention tasks (from task 1 to task 5). For each task, top row shows data from controls, bottom row shows data for PWADHD. NOS, SMV, NOF, FD, NOB, PD stand for Number of Saccades, Saccade Mean Velocity, Number of Fixations, Fixation Durations, Number of Blinks, Pupil Diameter. The letter C or A in nodes represent controls and PWADHD respectively. For each task only significant variables are included between controls and PWADHD.

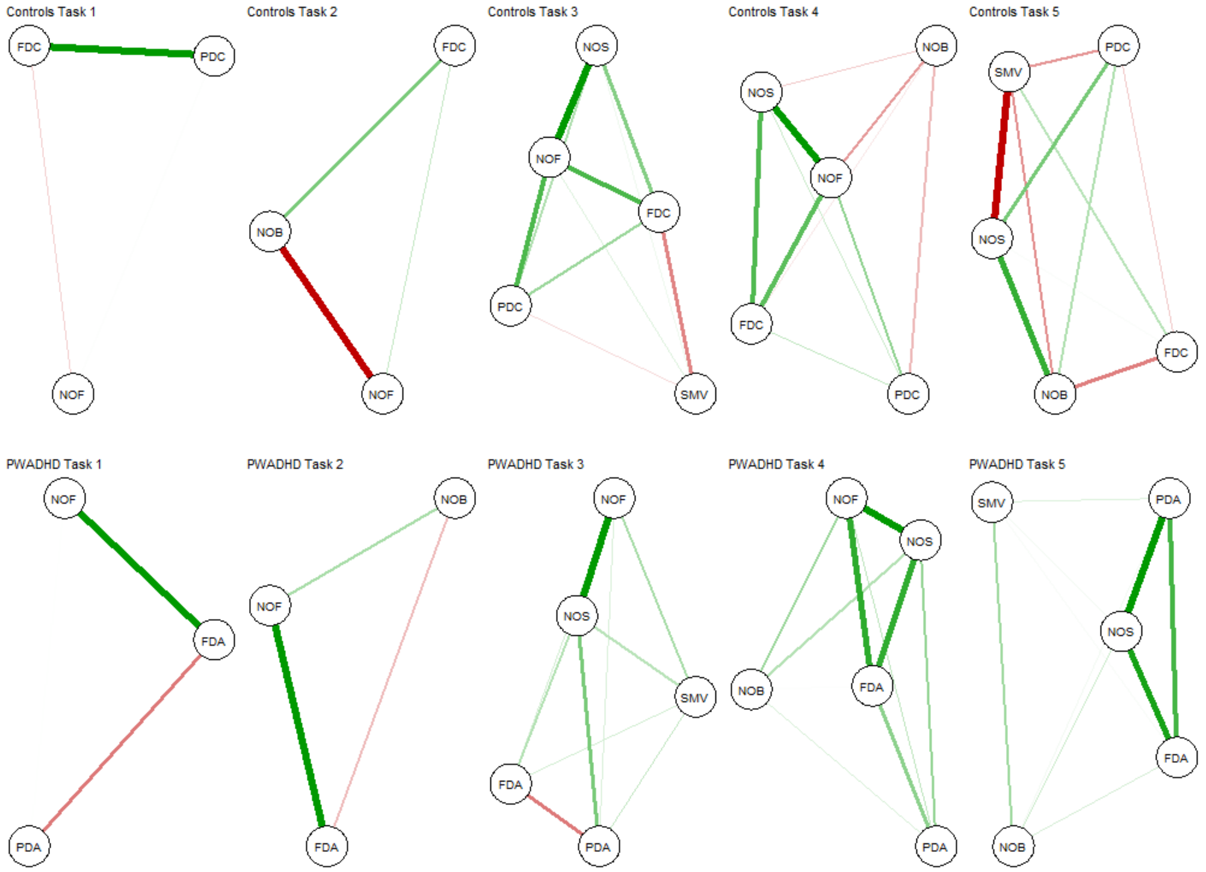


Figure 6.8

NMs for oculomotor measures for selective attention task (task 6). Left NM shows oculomotor measures in task 6 for controls whereas right NM shows data for PWADHD. NOS, SMV, NOF, FD, NOB, PD stand for Number of Saccades, Saccade Mean Velocity, Number of Fixations, Fixation Durations, Number of Blinks, Pupil Diameter. The letter C or A in nodes represent controls and PWADHD respectively. For task 6 only significant variables are included between controls and PWADHD.

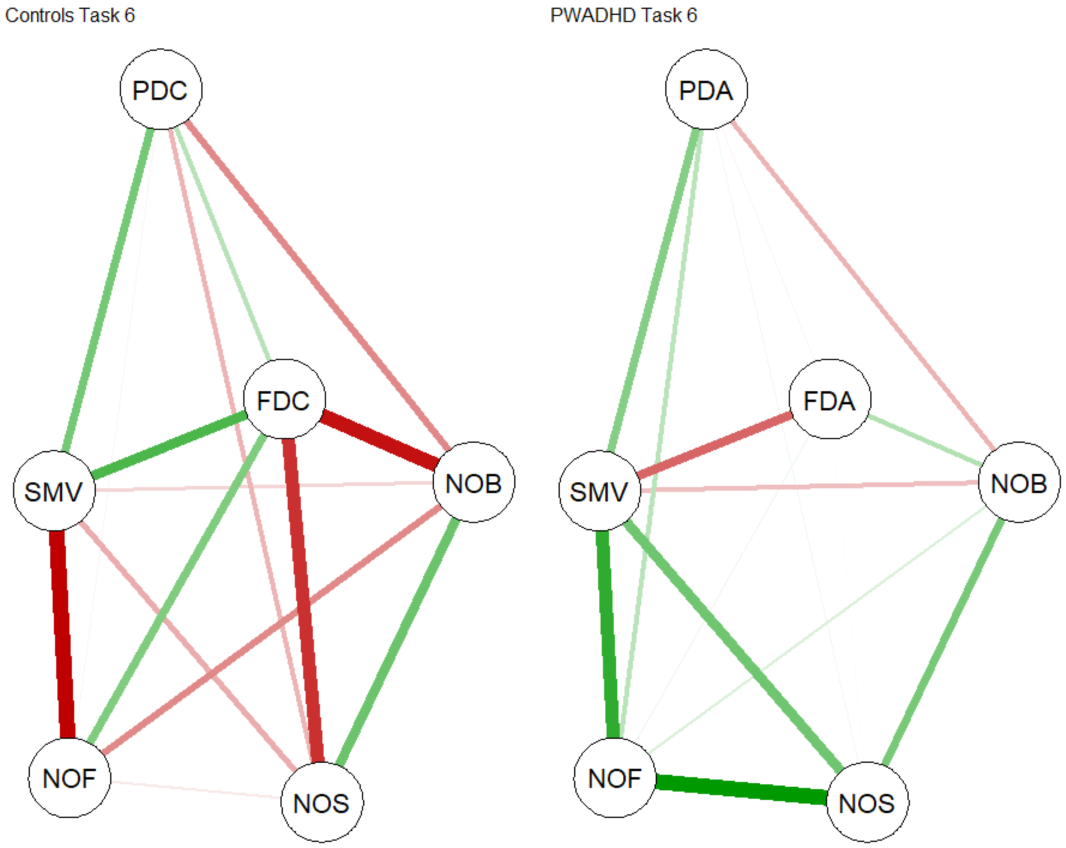


Figure 6.9

NMs for oculomotor measures for divided attention task (task 7). Left NM shows oculomotor measures in task 7 for controls whereas right NM shows data for PWADHD. NOS, SMV, NOF, FD, NOB, PD stand for Number of Saccades, Saccade Mean Velocity, Number of Fixations, Fixation Durations, Number of Blinks, Pupil Diameter. The letter C or A in nodes represent controls and PWADHD respectively. For task 7 only significant variables are included between controls and PWADHD.

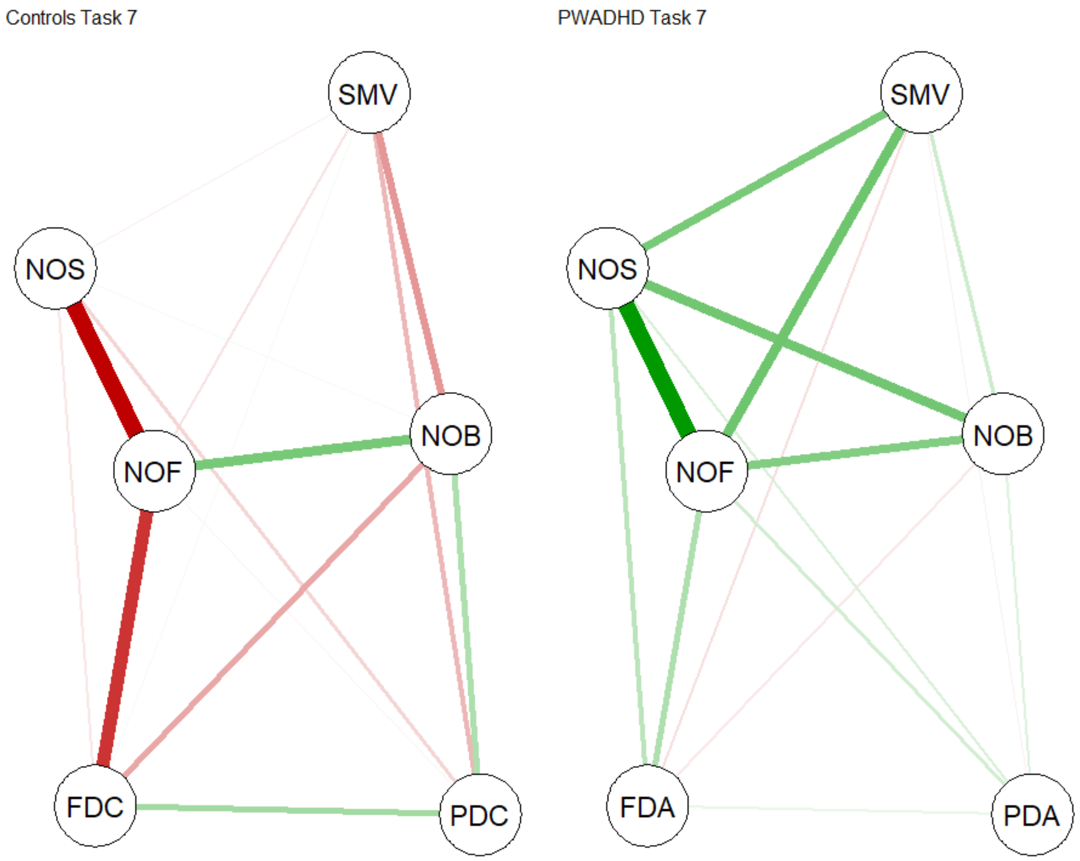
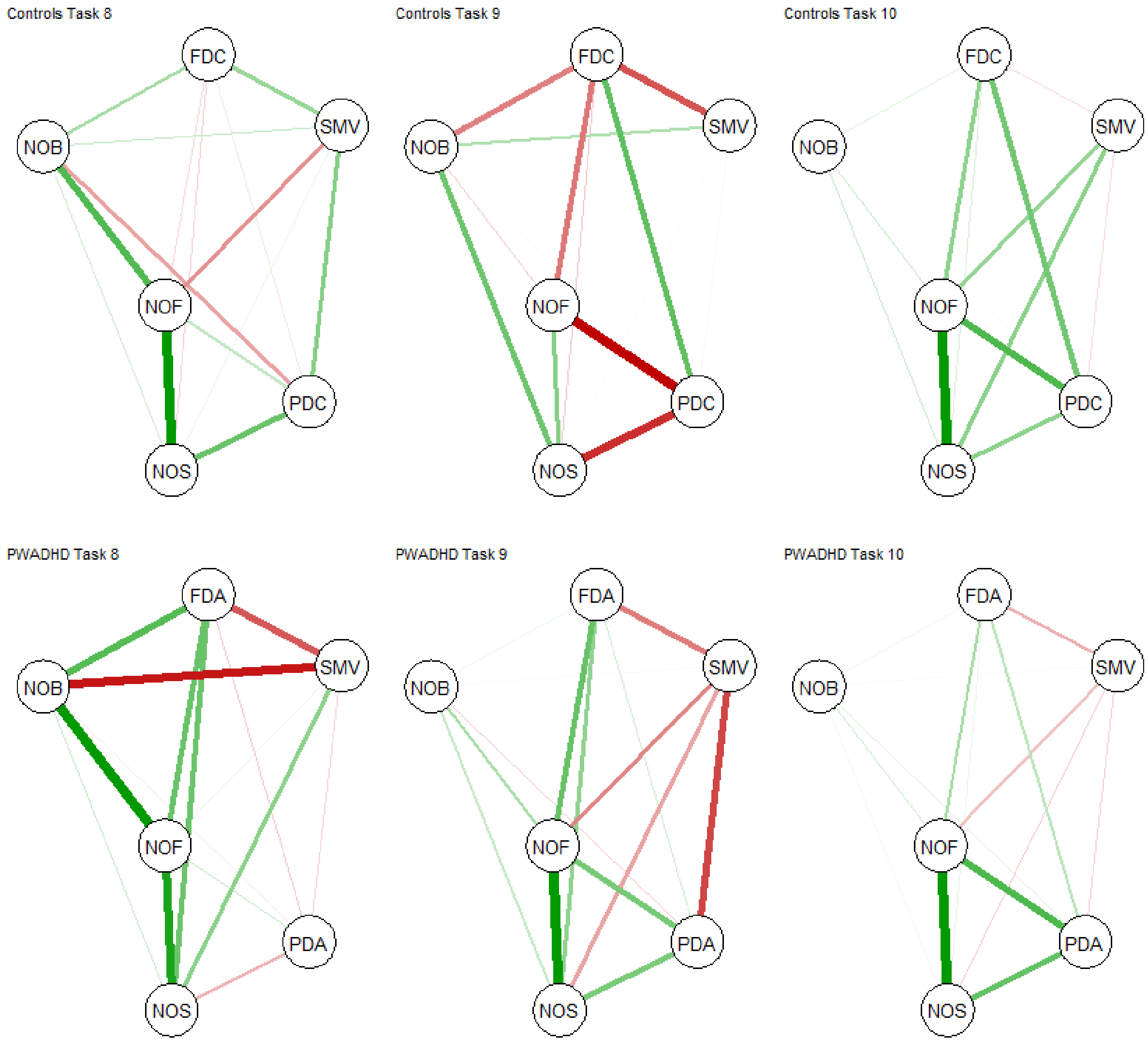


Figure 6.10

NMs for oculomotor measures for switched attention tasks (task 8, 9, 10). NMs in top row shows oculomotor measures in task 8, 9 and 10 for controls whereas NMs in bottom row shows data for PWADHD. NOS, SMV, NOF, FD, NOB, PD stand for Number of Saccades, Saccade Mean Velocity, Number of Fixations, Fixation Durations, Number of Blinks, Pupil Diameter. The letter C or A in nodes represent controls and PWADHD respectively. For all tasks only significant variables are included between controls and PWADHD.



6.5 Discussion

With regards to oculomotor measures, in task 1 significant differences between groups were observed in NOF (p = 0.032), FD (p = 0.003), PD (p = 0.005) with lower NOF scores, FD scores and higher PD in PWADHD. The results suggest that in a prolonged fixation task, impulsive behaviour is lower (NOF) replicating findings in Gould et al. (2001), and a lower FD is associated with lower attention (Karatekin & Asarnow, 1999). Studies (Fried et al., 2014; Munoz et al., 2003; Wainstein et al., 2017) show that PWADHD have lower PD because a lower PD is associated with lower levels of attention, but it can be argued that different types of attention tasks can show different results. Furthermore, previous studies have not assessed oculomotor measures in VR in PWADHD before. It is possible that participants found the task interesting and hence their PD was larger, or PD is linked to impulsive behaviour instead of inattentiveness although this can again differ in different attention tasks. In task 2 (TFT) and task 3 (SART) visual sustained attention, SMV, NOF, FD differed significantly between groups for TFT (p = 0.002, p = 0.013, p = 0.009) and for SART (p = 0.005, p = 0.003, p = 0.022) respectively with lower values recoded in PWADHD in all measures. The results suggest that in these tasks, impulsive behaviour (as assessed by NOF, similar as in Gould et al. (2001)) and attention (as assessed by FD) is lower in PWADHD (as in Karatekin & Asarnow, 1999). SMV was positively correlated to NOF in both tasks (p = 0.029, p = 0.037) which suggests that SMV is linked to impulsivity (findings on SMV replicate Munoz et al. (2003)). Additionally, NOB in TFT was significantly higher in PWADHD (p = 0.008) while NOS and PD differed significantly in SART (p = 0.016, p = 0.013) with lower NOS and higher PD in PWADHD. It has been suggested that the NOB are negatively connected with wakefulness (Tanaka, 1999) and a higher NOB has been observed in PWADHD (Fried et al., 2014). Higher NOB in PWADHD in TFT shows that this measure can successfully distinguish PWADHD, and this group had lower levels of wakefulness. A higher PD observed in PWADHD did not replicate previous studies that suggest that a lower PD in PWADHD (Fried et al., 2014; Munoz et al., 2003; Wainstein et al., 2017) is correlated to lower levels of attention. It can be argued that PD might differ in different attention tasks and can be affected by light. Since VR technology makes the task more interesting and the light is constant and controlled in all participants, this finding suggest that PD might not be an appropriate measure to determine attention impairments in PWADHD but instead PD might be linked to the level of finding the task more interesting and appealing and levels of impulsivity. It can also be argued that since previous studies have not assessed oculomotor measures in PWADHD in real-life scenarios to date but instead have used scenarios that have little meaning for participants, PD in VR in real-life scenarios can give us better insights on PD for PWADHD. Results on lower NOS in PWADHD in SART do not replicate findings in Munoz et al. (2003) and this might suggest that although tasks introduced in Munoz and the SART task, both measure sustained attention, a different pattern of the results in oculomotor measures can be obtained for different sustained attention tasks. Results from task 4 (pro saccade) and task 5 (anti saccade) introduced in Munoz et al. (2003), and measured visual sustained attention replicated the findings achieved in Munoz et al's study. In both tasks, PWADHD had significantly higher NOS ($p = 0.008$, $p = 0.002$), higher NOF ($p = 0.003$; $p = 0.012$), higher NOB ($p = 0.009$, $p = 0.005$), higher PD ($p = 0.002$, $p < 0.001$) while SMV ($p = 0.001$, $p = 0.025$) and FD ($p < 0.001$, $p = 0.015$) was lower. Similarly, as in Munoz et al. (2003) the findings suggest that higher impulsive behaviours (as shown by higher NOS and NOF), lower attention levels (as shown by lower FD) and lower wakefulness levels (assessed by higher NOB) can successfully assess symptoms of ADHD in pro saccade and anti saccade sustained attention task. Again, higher PD values can suggest higher levels of interest in the task from PWADHD. Additionally, a higher PD was positively correlated with NOS and NOF in task 4 ($p = 0.009$, $p = 0.008$) and task 5 ($p < 0.001$, $p = 0.002$) suggesting that PD is linked positively to impulsive behaviour instead of inattentiveness as previous studies suggest. SMV acted differently from tasks 2 and 3 was not positively correlated to impulsivity (NOF, NOS) which suggests that SMV in task 4 and 5 might not be an appropriate measure to distinguish PWADHD from controls. So far, the sustained pro saccade and anti saccade tasks (Munoz et al., 2003) can give us clear insights in the diagnosis of ADHD but SMV and PD might not be appropriate measures to assess ADHD in these tasks. In task 6 selective attention, all oculomotor measures differed significantly between the groups with lower values on NOS ($p = 0.002$), SMV ($p = 0.002$), NOB ($p = 0.011$), PD ($p = 0.013$) and higher NOF ($p < 0.001$), FD ($p < 0.001$) observed in PWADHD. Results suggest that a different pattern of oculomotor measure is observed in PWADHD in selective attention task compared to sustained attention tasks. Hence it can be concluded that selective attention tasks might not be appropriate to assess levels of impulsivity and inattentiveness from oculomotor measures in PWADHD. Furthermore, higher levels of FD can suggest that PWADHD have higher levels of attention in selective attention tasks. In divided attention task 7, PWADHD had significantly higher NOS ($p = 0.015$), NOB ($p < 0.001$), PD ($p < 0.001$), and lower SMV ($p = 0.011$), NOF ($p = 0.006$), FD ($p < 0.001$) compared to controls. Divided attention tasks can detect inattentiveness and impulsivity with higher NOS and lower FD. However, again it can be concluded that such tasks might not be appropriate to assess ADHD since the results are contradictory (e.g., higher impulsivity, which is assessed by higher NOS and NOF, shows that in PWADHD, NOS is higher but NOF is lower). In switched attention tasks (task 8, 9 and 10), groups differed significantly in all oculomotor measures but the pattern of the results was not the same for all measures. In the three tasks, PWADHD had lower NOS ($p = 0.007$; $p = 0.003$; $p = 0.003$), lower NOF ($p = 0.001$, $p < 0.001$, $p < 0.001$), lower FD ($p = 0.001$, $p = 0.008$, $p = 0.002$), lower PD ($p = 0.010$, $p = 0.009$, $p < 0.001$). Such results suggest that switched attention tasks might not be appropriate to assess impulsive behaviours from oculomotor measures but can correctly determine attentiveness. In PWADHD compared to controls while SMV ($p = 0.001$) and NOB ($p < 0.001$) were lower in task 8, values were higher in task 9 ($p < 0.001$, $p =$

0.002) whereas in task 10 SMV ($p < 0.001$) was lower, and NOB ($p = 0.00$) was higher. The difference between tasks 8 and 9 can show that different domains affect oculomotor behaviours differently. Task 8 included both audio and visual stimuli while task 9 had only visual stimuli and higher NOB in task 9 suggest lower levels of wakefulness maybe due to levels of fatigue or possibly due to a loss of interest in the task as the task had only visual stimuli. Similarly, as in task 9, in task 10 PWADHD had higher NOB suggesting a decrease in wakefulness. There are contradictory results in switched attention tasks which can be due to level of interest and fatigue in the task and besides FD values that suggest lower attention span, other measures do not show clear insights in assessing ADHD symptoms. Tasks 4 and 5 correctly assessed impulsive behaviours with higher NOS and NOF suggesting an inability to suppress reflexive and voluntary behaviour as shown in Munoz et al. (2003) findings. Symptoms of inattention were also determined in PWADHD with lower FD in the three tasks. The results suggests that while sustained attention tasks (task 4 and 5) assessed both impulsive and inattention behaviour switched attention task (task 9) determined only inattention in PWADHD in oculomotor measures.

Results from NMs showed different architectures between groups in all tasks implying that we expect a different pattern of eye movements in different attentional tasks (see Figure 6.7, Figure 6.10). The two tasks that differed the most between groups on physiological measures were pro saccade and anti saccade sustained attention tasks introduced in Munoz et al. (2003) and task 9 that drew upon switched attention. Such results are supported from behavioral data (Chapter 5) showing that the three tasks have a high diagnostic possibility in ADHD.

Results suggest that: 1- NOS and NOF are positively correlated to higher impulsive behavior in ADHD while FD correlate negatively to attention. 2- PD is correlated positively to higher impulsivity instead of higher inattentiveness in PWADHD. 3- A higher NOB show lower levels of wakefulness in PWADHD. 4- Eye measures differ across tasks and differ also in tasks that measure the same attention type.

7. Chapter 7. Assessing Brain Activity Impairments in EF in PWADHD from Real-life VR attention tasks.

Chapter Summary

Extending the results from the 10 VR tasks from Chapter Five in brain activity, from the EEG, pro saccade assessed better inattention symptoms with lower levels of beta and lower attention values, both suggesting lower attention in PWADHD. Although TBR is claimed in the literature to be a good indicator of ADHD with an increase of theta/beta ratio observed in this group (Loo & Makeig, 2012; Monastra et al., 2001; Snyder & Hall, 2006), this was not supported in sustained attention tasks, nor in selective and divided attention task but was only observed in one task that measured switched attention in the visual domain (task 9). TBR in switched attention task in the visual domain was positively correlated to longer RTs in the task supporting previous studies. In this task, a higher theta activity showed higher inattentiveness in PWADHD and TBR which successfully distinguished this group from controls. NMs in brain data differed between groups in all tasks showing that the pattern of brain measures differs across tasks and the frontal cortex is impaired in PWADHD.

7.1 Introduction

7.1.1 Executive Function and Neurofeedback therapy in attention

According to Fuster (2008), EFs are localized in the frontal cortex. Neuropsychological impairments in the frontal lobes, cause issues in EFs, along with impulsive, hyperactive, and inattentive behaviours. As a result, ADHD has also been associated with the frontal cortex (Geurts et al., 2004). The fact that this has been observed in both childhood and adulthood suggests that the pattern is stable (Biederman et al., 2007). During the 1960s, Neal Miller suggested that humans could be taught to control their autonomic processes (Miller, 1969). Kamiya (1968) created a series of tests that demonstrated that people could be taught to control their brain electrical activity and enter the "alpha state," a mental state associated with emotions of calm. Many consider Joe Kamiya to be the "father" of modern NF. NF has been used for patients with ADHD and other neurological disorders to train their brains since the 1970s. In 1976, studies and case reports about the effectiveness of NF were published. Since then, dozens of studies have been published, often with improved methodological bases. Brainwave changes are observable and appear to last after the therapy is completed. Beyond the study setting, improved brainwaves may lead to improved behaviour, such as maintained focus, reduced impulsivity, and reduced distractibility. NF aims to help patients increase their high-frequency brain wave ratio over time, resulting in improved attention and self-control. NF therapy aims to boost the brain's capacity and propensity for beta waves, which are linked to efficient information processing and problem solving. Patients complain of incomplete work, disorganisation, and distractibility when there is a high number of theta waves present. NF is a neurobehavioural treatment that aims to help people gain self-control over brain activity patterns and apply these skills in everyday situations (Gevensleben et al., 2009). The purpose of neurofeedback in PWADHD is to reduce the frequency of delta and theta waves. NF is a sub-type of biofeedback that is separate from the other physiological aspects. Biofeedback is a technique for teaching yourself how to adjust your own physiological activity by monitoring biological data such as respiration rates, muscular activity, and heart rate in real time. NF is a form of training in which patient learn to regulate their EEG patterns and has emerged as one of the most promising therapy alternatives for PWADHD (Heinrich et al., 2007). These neurophysiological patterns are represented by measurements that are translated into visual or audio signals and transmitted back in real time. Positive reinforcement is given to changes that are made in the correct direction. NF training can be delivered whilst playing a computer game, making it appealing to both children and adults.

NF is being increasingly investigated as a therapeutic option for PWADHD with promising findings (Gevensleben et al., 2009). In recent years NF has been suggested as an option for treatment of attention (Enriquez-Geppert et al., 2019; Moriyama et al., 2012). Moriyama et al. (2012) reviewed existing literature on NF to inform readers on the use of NF as an alternative treatment for ADHD. The authors emphasized that studies have revealed no safety concerns, and NF appears to be well tolerated and accepted. Long-term effects of NF were supported by follow-up investigations. There is currently no data available to inform clinicians on the predictors of NF response and the best treatment approach. However, NF is a viable therapeutic option for ADHD, but further research is needed to support its use. Moriyama et al. (2012) concluded that most ADHD therapy procedures using NF, aim to increase Beta frequencies and decrease Theta frequencies. In Gevensleben et al's (2009) study, 102 CWADHD were randomly assigned in two groups. In one group children conducted a computerised attention skills training (AST) and in the other group children conducted a NF training (with theta/beta frequency training and slow cortical potentials SCP training). The goal was to reduce activity in the theta band (4–8 Hz) of the EEG whilst also increasing activity in the beta band (13–20 Hz), which correlates to a focused but relaxed alert state. From parent and teacher ratings, improvements in the NF group were higher than in the AST group. However, the findings do not show significant group differences as they are based on ratings.

In an NF game design to train sustained attention in adults (Ochi et al., 2021) 17 participants (age range 18-30 yrs) were divided into two groups: 1- normal group (N = 14); 2- ADHD group (N = 3) based on the ASRS. During the game when the participants lost their attention (based on an attention threshold of 50), the brightness of the game view decreased. Once users' level of attention was higher than the threshold the brightness would increase again, and users would win points. Their results from a t-test suggested that there was a significant difference in users' level of attention (as assessed by T.O.V.A pre and post training) with higher attention levels observed in the normal group using the NF game. The authors concluded that NF can be an effective type of treatment.

The findings of Mercado et al's (2020) in a 10-week study with 26 children with severe autism confirmed NF therapy as a tool to help children with autism spectrum disorder (CWASD). The children's task was to put lost farm animals back in their pens. The farmer pushed a truck and caught the animals if the child's attention was above the threshold and the speed of the truck and music volume increased. Short instructions were given from the farmer to the player if the attention was below the threshold. In the pre- and post-assessment evaluation, all CWASD improved their attention, attentional control, and sustained attention and two CWASD no longer showed attention deficits. The visual stimuli were distributed in the main screen in such a way that the programme was not overloaded with visual stimuli. The authors concluded that participants were able to concentrate on only one part of the screen because of this and were able to achieve greater results without having to juggle between many distractions on different parts of the screen.

Jirayucharoensak et al. (2019) investigated the clinical efficacy of a game-based neurofeedback training (NFT) system in sustained attention in patients with amnestic mild cognitive impairment (aMCI) and healthy elderly adults. The power spectrum of the alpha and beta bands were examined. Four games were included in the NFT procedure, all of which were aimed at improving attention span and cognitive function. In the first game, the players used their attention level to control the speed of a bear's walk. If the players attention level was higher than the threshold (>50%), the bear ran quickly and points were gathered. In the second game the player needed to cheer up a character in the game if user attention was above the threshold. In the third game, players adjusted the heat of a fire to cook meals using their attention level. In the last game, participants used their attention levels to control the speed of a paper plane. When the level of attention was high, the paper plane moved quickly and flew away from the obstacles. If the users' attention level was over a certain threshold during the last game, the character had a basketball shot in the game. It was reported that NFT increased rapid visual processing, spatial working memory (SWM), sustained attention, and strategy.

There are several studies that show that tasks based in NF can increase cognition in a variety of attention tasks, but there are some limitations that should be addressed to improve the experience. For example, there is a lack of customized and realistic tasks that employ 3D graphics for more engaging experiences. To address this, novel Brain Computer Interfaces (BCI) are now wearable and can be used in tasks with NF for attention treatment. Blandon et al. (2016) developed a 3D VR BCI videogame with three different game levels to address the limitations associated with more realistic and interactive NF videogames for attention treatment. The authors conducted a pilot study with 7 CWADHD to analyse the impact of the videogame in training sustained attention in CWADHD. At the first level, children had to acquire equipment for a canopy ride (if their concentration level was equal or more than 50%). In the second level, before arriving at the canopy road users had to repair six paths to climb a mountain. For the child to reach the mountain, the child's attention level needed to increase by 10% on each path. Children at the third level had to collect and place carrots in their basket using their sustained attention. The results (using a MATLAB toolbox that authors developed named NeuroRead) suggested improvement of attention in the second session of NF treatment in the first and third level as well as higher resting state in the power of the alpha and beta bands. However, this study had the limitation of having a small number of participants. The results from this study support the positive aspects that NF treatment has but further investigation with a larger sample is necessary to confirm conclusions.

7.2 Experiment 7

In this chapter EEG data was assessed in PWADHD and compared to controls with the aim to understand measures that assessed PWADHD traits and if frontal cortex is impaired in this group. Since there are contradictive findings from the literature in PWADHD (see Table 1.7 in introduction) it was anticipated that there would be different pattern of brain measures in

PWADHD for different types of attention in EF. NF studies in ADHD (Blandon et al., 2016; Gevensleben et al., 2009; Moriyama et al., 2012) aim to decrease theta, TBR (associated with inattentiveness and higher RTs) and increase alpha and beta waves (linked to a relaxed state and attentiveness). For all 10 tasks it was predicted that groups should differ from each other on: alpha (H1, alpha is expected to be higher in PWADHD in task that measure sustained attention as suggested from Loo et al. (2009) although results might differ in the type of the task), beta (H2), theta (H3), TBR (H4), attention values (H5, it was expected that lower attention values will be recorded in PWADHD in sustained attention tasks as shown in Ochi et al. (2021) but results might differ in other attention tasks).

7.3 Methods

7.3.1 Design

A mixed design was used in this experiment with tasks being within-participant factors and groups (controls vs PWADHD) being the between-participants factor. The dependent variables were EEG data.

7.4 Results

7.4.1 *Experiment 7a Results*

Table 7.1

Descriptive Statistics, hypothesis, and results for EEG measures.

	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7	Task 8	Task 9	Task 10
H1: Groups should differ from each other in alpha activity.	Some outliers were removed $p = 0.962$ $p = 0.008$ NA **Accepted**	Some outliers were removed $p = 0.237$ $p = 0.003$ NA **Accepted**	Some outliers were removed $p = 0.002$ $p < 0.001$ $p = 0.003$ **Accepted**	Some outliers were removed $p = 0.040$ $p = 0.008$ $p = 0.004$ **Accepted**	Some outliers were removed $p = 0.795$ $p = 0.006$ NA **Accepted**	One outlier was removed $p = 0.111$ $p = 0.003$ NA **Accepted**	None $p = 0.022$ $p < 0.001$ $p < 0.001$ **Accepted**	None $p = 0.026$ $p < 0.001$ $p < 0.001$ **Accepted**	None $p = 0.050$ $p < 0.001$ NA **Accepted**	None $p = 0.089$ $p < 0.001$ NA **Accepted**
H2: Groups should differ from each other in beta activity.	Some outliers were removed $p = 0.304$ $p = 0.006$ NA **Accepted**	Some outliers were removed $p = 0.312$ $p = 0.003$ NA **Accepted**	Some outliers were removed $p = 0.323$ $p < 0.001$ NA **Accepted**	Some outliers were removed $p = 0.907$ $p = 0.018$ NA **Accepted**	Some outliers were removed $p = 0.511$ $p = 0.009$ NA **Accepted**	One outlier was removed $p = 0.983$ $p < 0.001$ NA **Accepted**	None $p = 0.111$ $p < 0.001$ NA **Accepted**	None $p = 0.294$ $p = 0.002$ NA **Accepted**	None $p = 0.884$ $p < 0.001$ NA **Accepted**	One outlier was removed $p = 0.289$ $p < 0.001$ NA **Accepted**
H3: Groups should differ from each other in theta activity.	Some outliers were removed $p = 0.075$ $p = 0.007$ NA **Accepted**	Some outliers were removed $p = 0.286$ $p = 0.009$ NA **Accepted**	Two outliers were removed $p = 0.113$ $p < 0.001$ NA **Accepted**	Two outliers were removed $p = 0.703$ $p = 0.017$ NA **Accepted**	Two outliers were removed $p = 0.007$ $p = 0.002$ $p = 0.005$ **Accepted**	None $p = 0.357$ $p < 0.001$ NA **Accepted**	None $p = 0.004$ $p < 0.001$ $p < 0.001$ **Accepted**	Some outliers were removed $p = 0.144$ $p = 0.003$ NA **Accepted**	None $p = 0.067$ $p < 0.001$ NA **Accepted**	None $p = 0.009$ $p < 0.001$ $p < 0.001$ **Accepted**
H4: Groups should differ from each other in TBR.	Some outliers were removed $p = 0.072$ $p = 0.008$ NA **Accepted**	Some outliers were removed $p = 0.168$ $p = 0.003$ NA **Accepted**	Some outliers were removed $p = 0.006$ $p = 0.001$ $p < 0.001$ **Accepted**	Some outliers were removed $p = 0.156$ $p = 0.001$ NA **Accepted**	Some outliers were removed $p = 0.470$ $p = 0.001$ NA **Accepted**	One outlier was removed $p = 0.355$ $p = 0.006$ NA **Accepted**	Two outliers were removed $p = 0.654$ $p = 0.002$ NA **Accepted**	Two outliers were removed $p = 0.713$ $p < 0.001$ NA **Accepted**	None $p = 0.566$ $p < 0.001$ NA **Accepted**	One outlier was removed $p = 0.798$ $p < 0.001$ NA **Accepted**
H5: Groups should differ from each other in attention values.	Some outliers were removed $p = 0.735$ $p < 0.001$ NA **Accepted**	Some outliers were removed $p = 0.210$ $p = 0.004$ NA **Accepted**	None $p = 0.242$ $p = 0.001$ NA **Accepted**	None $p = 0.081$ $p = 0.009$ NA **Accepted**	None $p = 0.002$ $p = 0.003$ $p = 0.008$ **Accepted**	Some outliers were removed $p = 0.577$ $p = 0.056$ NA **Rejected**	Two outliers were removed $p = 0.003$ $p < 0.001$ $p < 0.001$ **Accepted**	One outlier was removed $p = 0.067$ $p = 0.005$ NA **Accepted**	One outlier was removed $p = 0.261$ $p = 0.001$ NA **Accepted**	Some outliers were removed $p < 0.001$ $p < 0.001$ $p = 0.005$ **Accepted**

Task 1

H1 was supported because groups differed significantly from each other with PWADHD having a lower alpha activity as shown in Figure 7.1a and Table F7.1 in Appendix F. PWADHD recorded higher beta activity and differed significantly from controls (see Figure 7.2a). Hence, H2 is accepted. A lower theta activity was observed in PWADHD (Figure 7.3a). Groups differed significantly. H3 was supported. There was a significant difference between groups in TBR values with lower values recorded in PWADHD. See Figure 7.4a for more information. H4 was supported. Attention values are lower in PWADHD (Figure 7.5a) and groups differed significantly. Therefore, H5 was accepted.

Task 2

Groups differed significantly in alpha activity with PWADHD recording lower values. See Figure 7.1b for a visualization of the results. H1 was supported. PWADHD had significantly higher beta values as shown in Figure 7.2b. Hence H2 is supported. Theta activity was significantly lower in PWADHD. See Figure 7.3b for more information. H3 was accepted. H4 was accepted because groups differed significantly in TBR with lower values obtained from PWADHD. Figure 7.4b gives more information. Groups differed significantly in attention values accepting H5. Figure 7.5b shows that PWADHD had lower attention values. See Table F7.1 in Appendix F for more information.

Task 3

There was a significant difference between groups in alpha activity with PWADHD having higher values (see Figure 7.1c). Hence H1 was accepted. Groups differed significantly in beta values with PWADHD recording higher values as shown in Figure 7.2c. H2 was supported. Figure 7.3c shows lower theta activity in PWADHD. Groups differed significantly accepting H3. PWADHD scored significantly lower in TBR values accepting H4. Figure 7.4c shows a visual representation of the results. Attention values were significantly lower in PWADHD and therefore H5 was supported. See Figure 7.5c for more information.

Task 4

H1 was supported because groups differed significantly in alpha activity with PWADHD having higher values (see Figure 7.1d). Beta activity was significantly lower in PWADHD accepting H2. See Figure 7.2d for more information. Groups differed significantly in theta activity with PWADHD recording lower values (see Figure 7.3d). H3 was accepted. TBR values were significantly lower in PWADHD accepting H4. See Figure 7.4d for more information. PWADHD had significantly lower attention values compared to controls (see Figure 7.5d). Therefore, H5 was accepted.

Task 5

Alpha was significantly higher in PWADHD accepting H1. See Figure 7.1e for more information. Groups differed significantly in beta activity with PWADHD recording higher values (see Figure 7.2e). Hence, H2 was supported. Theta activity was significantly lower in PWADHD accepting H3. See Figure 7.3e for more information. H4 was supported because groups differed significantly in theta beta ratio with PWADHD recording lower values (see Figure 7.4e). Attention was significantly lower in PWADHD accepting H5 (Figure 7.5e).

Task 6

Groups differed significantly on alpha activity with PWADHD having lower values as shown in Figure 7.1f. H1 is accepted. H2 was accepted as groups differed significantly in beta activity. Lower values were recorded in PWADHD (see Figure 7.2f). Theta activity was significantly lower in PWADHD (see Figure 7.3f). Groups differed significantly, hence H3 was supported. Groups differed significantly in theta beta ratio accepting H4 with PWADHD having lower values (see Figure 7.4f). Attention values were higher in PWADHD but differences were not significant rejecting H5 (Figure 7.5f).

Task 7

Groups differed significantly in alpha activity with PWADHD recording higher values (see Figure 7.1g). Hence H1 was supported. Beta activity was significantly higher in PWADHD accepting H2 (Figure 7.2g). Groups differed significantly in theta activity accepting H3 with higher values recorded in PWADHD (see Figure 7.3g). Theta beta ratio was significantly lower in PWADHD (Figure 7.4g). Hence H4 was supported. Attention values were significantly higher in PWADHD accepting H5. See Figure 7.5g for more information.

Task 8

Groups differed significantly in alpha activity accepting H1. PWADHD recorded higher values as shown in Figure 7.1h. Beta activity was significantly higher in PWADHD. Hence H2 was supported. See Figure 7.2h for more information. Groups differed significantly in theta activity with PWADHD having lower values (see Figure 7.3h). H3 was accepted. Theta beta ratio was significantly lower in PWADHD accepting H4 (Figure 7.4h). Attention values were significantly higher in PWADHD accepting H5. See Figure 7.5h for more information.

Task 9

H1 was accepted as groups differed significantly in alpha activity with PWADHD recording higher values (see Figure 7.1i). Beta activity was significantly higher in PWADHD accepting H2 (see Figure 7.2i). Groups differed significantly in theta activity hence H3 was supported. PWADHD had higher theta activity compared to controls as shown in Figure 7.3i. Theta beta ratio was significantly higher in PWADHD. See Figure 7.4i for more information. Therefore, H4 was supported. Groups differed significantly in attention values with higher scores obtained from PWADHD (see Figure 7.5i). H5 was accepted.

Task 10

Alpha activity differed significantly between groups with PWADHD having higher values (see Figure 7.1j). H1 was accepted. PWADHD had significantly higher beta activity compared to controls accepting H2. See Figure 7.2j for more information. Groups differed significantly in theta activity with higher values observed in PWADHD. Hence H3 was accepted. See Figure 7.3j for more information. Theta beta ratio was significantly lower in PWADHD accepting H4. Figure 7.4j shows a visual representation of the results. Attention values differed significantly between groups with PWADHD recording higher values (see Figure 7.5j). Hence, H5 was accepted.

Figure 7.1

Mean alpha activity between groups for all 10 tasks ordered alphabetically from a to j. Left x - axis represent controls and right x - axis represent PWADHD in each graph. Error bars represent ± 2 Standard Error [SE].

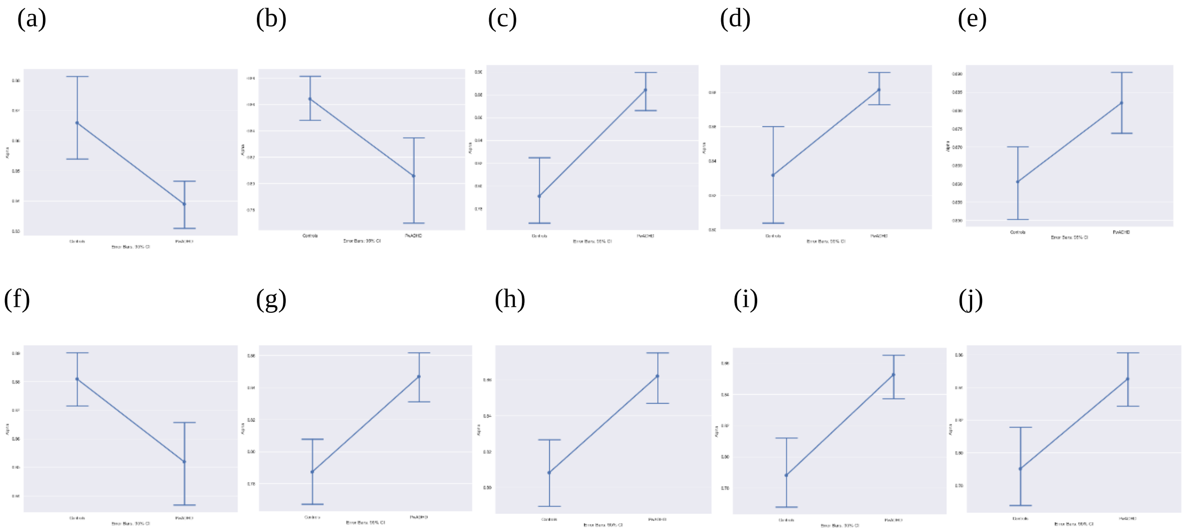
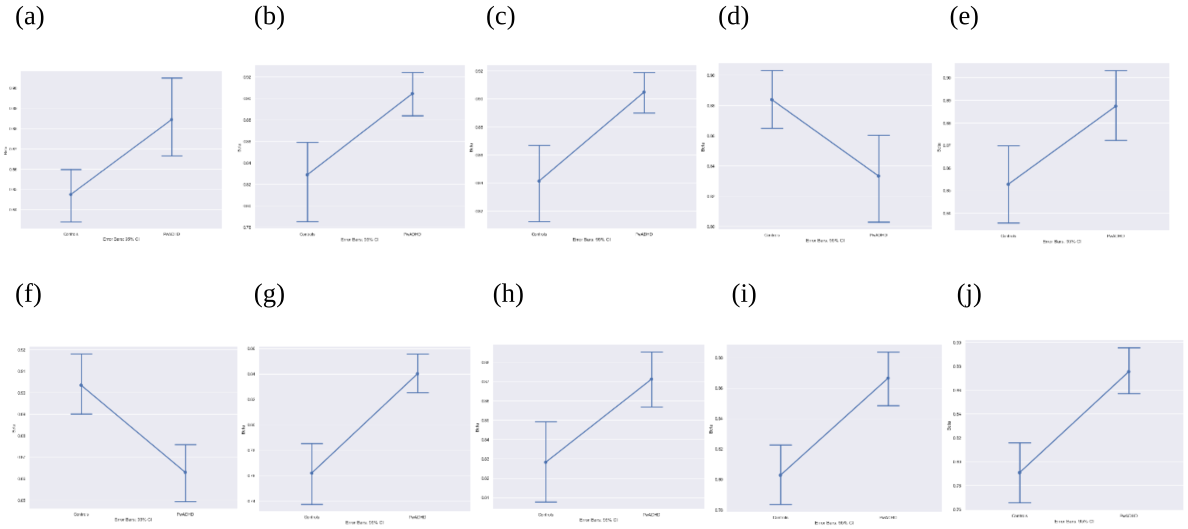


Figure 7.2

Mean beta activity between groups for all 10 tasks ordered alphabetically from a to j. Left x - axis represent controls and right x - axis represent PWADHD in each graph. Error bars represent ± 2 Standard Error [SE].

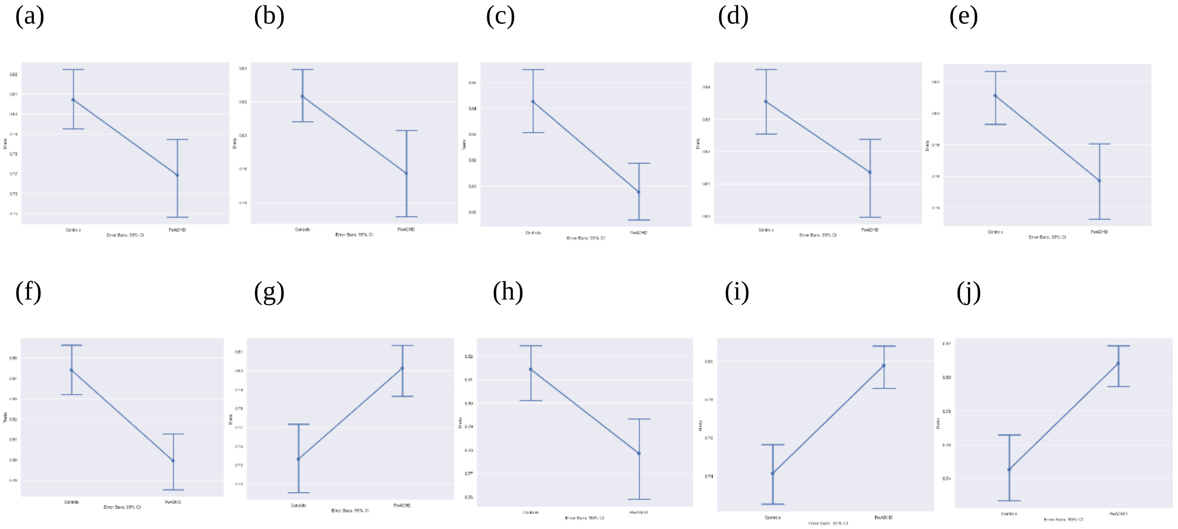


(a) (b) (c) (d) (e)

(f) (g) (h) (i) (j)

Figure 7.3

Mean theta activity between groups for all 10 tasks ordered alphabetically from a to j. Left x - axis represent controls and right x - axis represent PWADHD in each graph. Error bars represent ± 2 Standard Error [SE].



(a) (b) (c) (d) (e)

(f) (g) (h) (i) (j)

Figure 7.4

Mean TBR for controls and PWADHD for all 10 tasks ordered alphabetically from a to j. Left x - axis represent controls and right x - axis represent PWADHD in each graph. Error bars represent ± 2 Standard Error [SE].

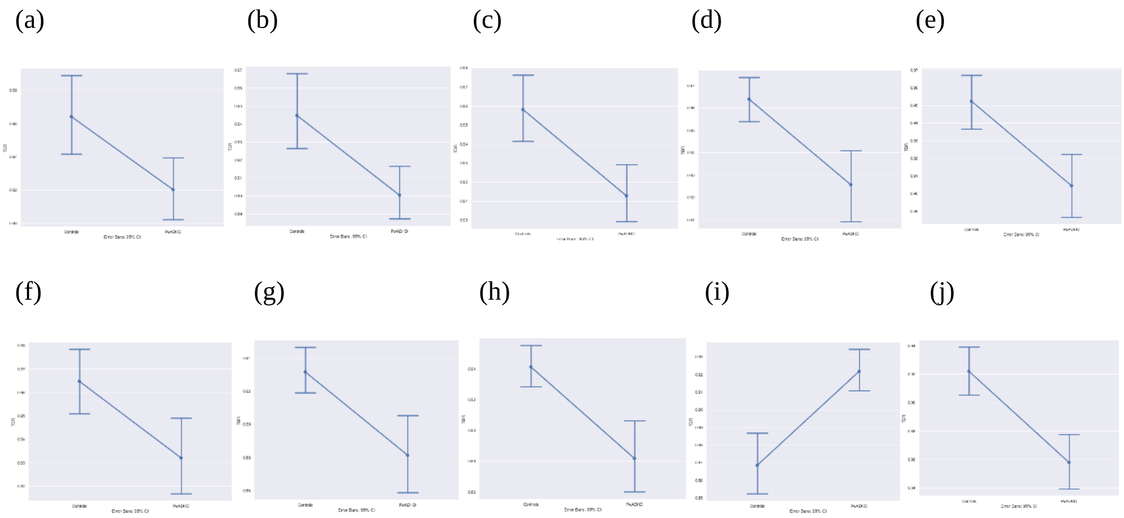
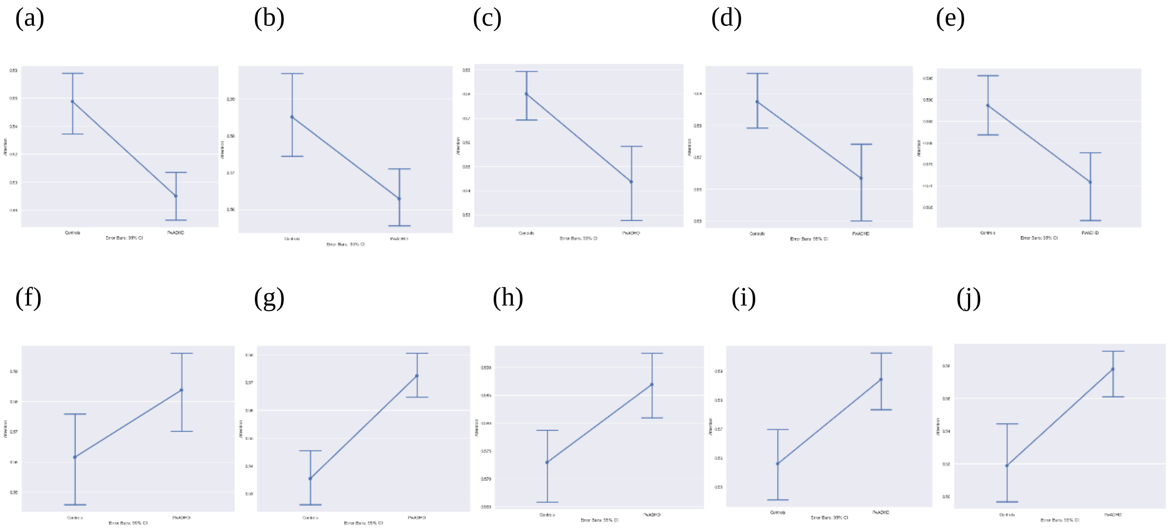


Figure 7.5

Mean attention values between groups for all 10 tasks ordered alphabetically from a to j. Left x - axis represent controls and right x - axis represent PWADHD in each graph. Error bars represent ± 2 Standard Error [SE].



7.4.2 Experiment 7b Results

A different architecture is observed in brain data from NMs in all tasks. From EEG data, the measures in PWADHD that differed from controls and effected other nodes in EEG were: alpha (task 1), TBR (task 2), attention values (task 3), beta (task 4), beta and attention values (task 5), alpha and theta (task 6), theta (task 7), attention values (task 8), theta and TBR (task 9) and beta (task 10). Results show that different EEG measures are affected in different tasks. For pro saccade and anti saccade (tasks 4 and 5), beta and attention values assess inattentiveness whereas for task 9, theta and TBR can correctly distinguish PWADHD from controls.

Figure 7.6

NMs for EEG data for sustained attention tasks (task 1, 2, 3, 4, 5). NMs in top row shows EEG measures for controls whereas NMs in bottom row shows data for PWADHD. ALC, BEC, THC, TBC, AVC stand for Alpha Controls, Beta Controls, Theta Controls, Theta-Beta Ratio Controls, Attention Values Controls. The letter A instead of letter C in nodes represent PWADHD. For all tasks only significant variables are included between controls and PWADHD.

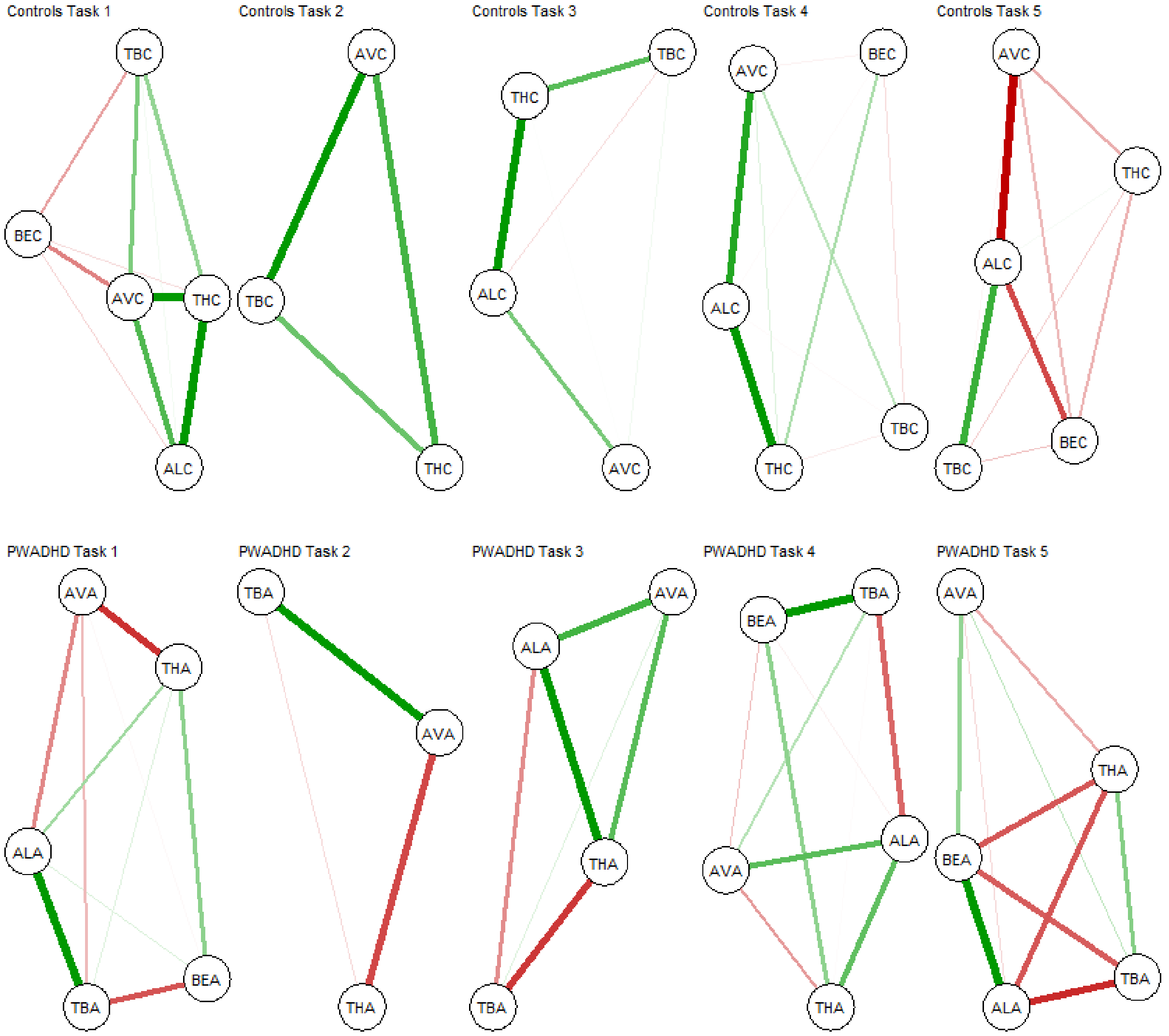


Figure 7.7

NMs for EEG data for selective attention task (task 6). Left NM shows EEG measures for controls whereas right NM represents EEG data for PWADHD. ALC, BEC, THC, TBC, AVC stand for Alpha, Beta, Theta, Theta-Beta Ratio, Attention Values for Controls. The letter A instead of letter C in nodes represent PWADHD.

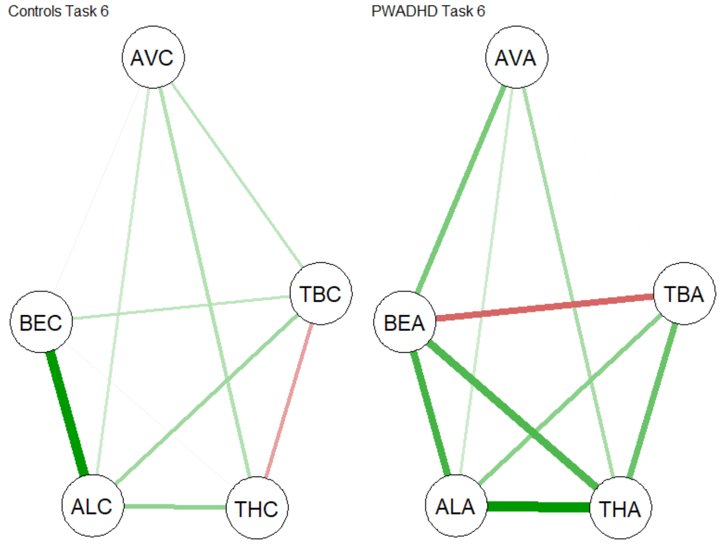


Figure 7.8

NMs for EEG data for divided attention task (task 7). Left NM shows EEG measures for controls whereas right NM represents EEG data for PWADHD. ALC, BEC, THC, TBC, AVC stand for Alpha Controls, Beta Controls, Theta Controls, Theta-Beta Ratio Controls, Attention Values Controls. The letter A instead of letter C in nodes represent PWADHD. For task 7 only significant variables are included between controls and PWADHD.

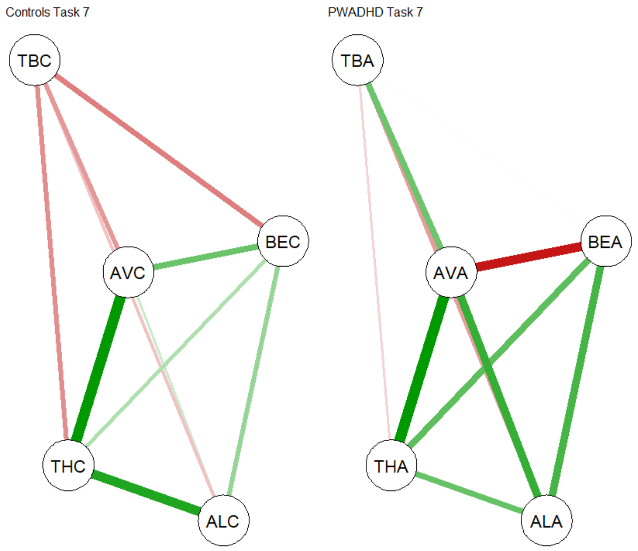
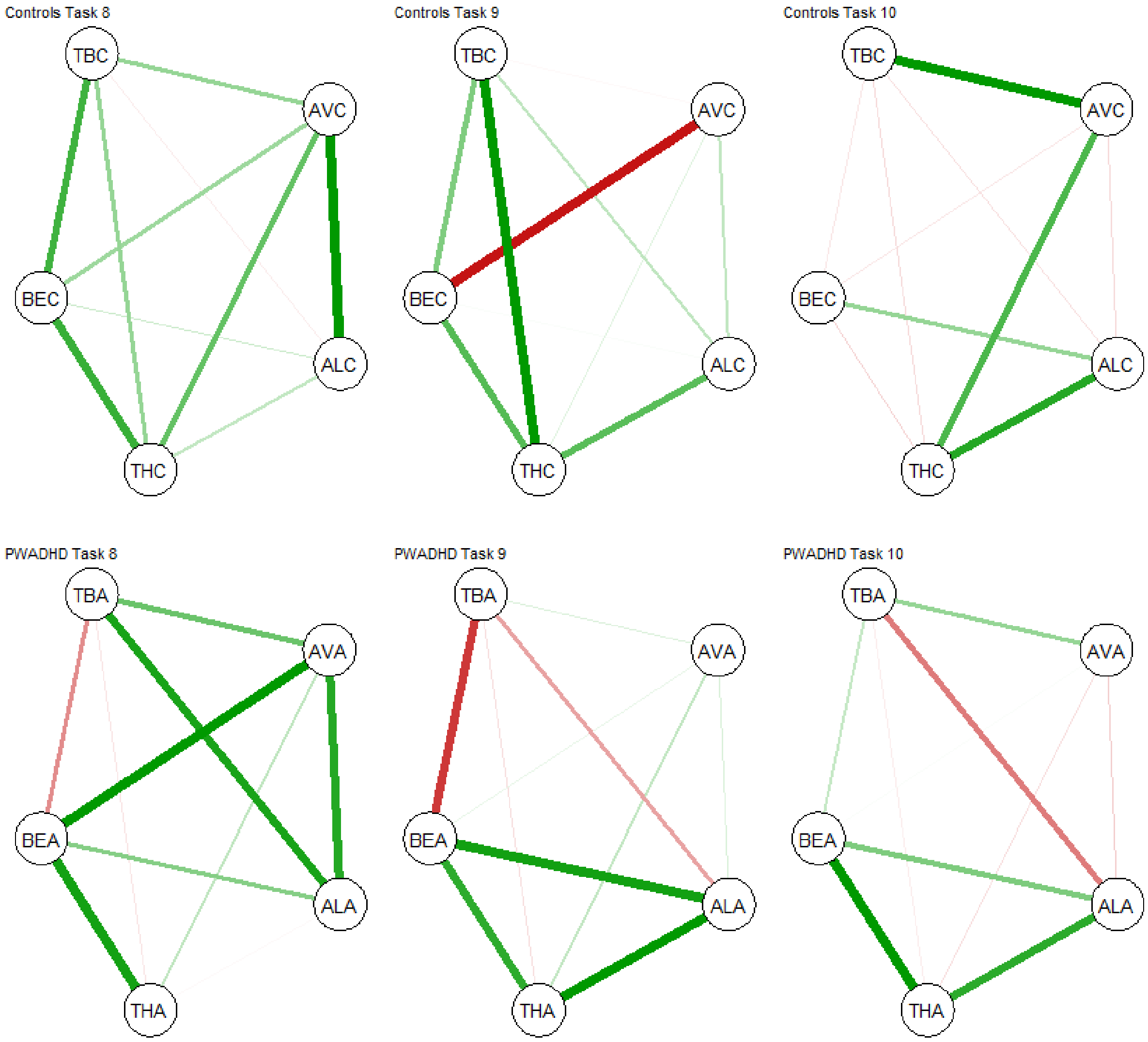


Figure 7.9

NMs for EEG data for switched attention tasks (task 8, 9, 10). NMs in top row shows EEG measures for controls whereas NMs in bottom row represents EEG data for PWADHD. ALC, BEC, THC, TBC, AVC stand for Alpha Controls, Beta Controls, Theta Controls, Theta-Beta Ratio Controls, Attention Values Controls. The letter A instead of letter C in nodes represent PWADHD. For task 7 only significant variables are included between controls and PWADHD.



7.5 Discussion

All EEG measures differed significantly between the groups and the pattern of results varied for different attention tasks. Furthermore, the pattern also differed in the tasks that drew upon the same attention type. For sustained attention task 1, alpha ($p = 0.008$), theta ($p = 0.007$), TBR ($p = 0.008$) and attention values ($p < 0.001$) were lower in PWADHD compared to controls whilst beta ($p = 0.006$) was higher in PWADHD. The results suggests that while wakefulness was lower in PWADHD (as assessed by lower alpha) similar as in previous studies (El-Sayed et al., 2002; Lazzaro et al., 1998) but differed from findings in Loo et al. (2009) that suggested that alpha is higher in PWADHD in sustained attention tasks, attention values were lower (as in Ochi et al. (2021) sustained attention task). Results on theta replicate those from research (Bresnahan & Berry, 2002) but results on TBR do not replicate those in previous studies (Loo & Makeig, 2012; Monastra et al., 2001; Snyder & Hall, 2006) that suggest that PWADHD have higher TBR associated with higher impulsive behaviour but instead show similar results as in Ogrim et al. (2012) that TBR is not a good indicator to assess ADHD in this task. Beta was higher in PWADHD ($p = 0.006$) compared to controls, similar as in some studies (Chabot & Serfontein, 1996; Clarke, 2002; Clarke et al., 2011; Loo et al., 2009) that suggest higher values in PWADHD. It can be concluded that since higher alpha measures wakefulness, higher beta is related to attentiveness, higher theta is linked to inattentiveness and while higher TBR measures impulsivity, the two measures that give us clear insights in PWADHD in this type of attention task were alpha and attention values. It can be argued however that the pattern of other measures can differ based on the attention task. In task 2 TFT and 3 SART that drew upon sustained attention, beta was higher in PWADHD in both tasks ($p = 0.003$, $p < 0.001$), while theta ($p = 0.009$, $p < 0.001$), TBR ($p = 0.003$, $p = 0.001$) and attention values ($p = 0.004$, $p = 0.001$) were lower. Alpha differed in tasks, with lower values observed from PWADHD in TFT ($p = 0.003$) and higher in SART ($p < 0.001$) as compared to controls. Whilst in both tasks, attention values gave us insights on attention levels in PWADHD (as in

Ochi et al. (2021)), alpha values showed lower states of wakefulness in TFT suggesting that TFT might be a more appropriate task to assess ADHD. PWADHD might have had higher levels of wakefulness in SART because SART requires from participants a higher attention to inhibit responses in a high go, low no-go task. Results on TBR again suggest that in this type of attention task this measure is not affected. Results on theta and beta also suggest that these measures do not give us information about inattentiveness in PWADHD although they do replicate previous findings from research. In task 4 (pro saccade) and task 5 (anti saccade), beta differed between tasks with lower values recorded in PWADHD ($p = 0.018$) in task 4 and higher values ($p = 0.009$) in task 5 whilst the pattern of all other EEG measures were the same in both tasks. Alpha ($p = 0.008$, $p = 0.006$) was higher in PWADHD whilst theta ($p = 0.017$, $p = 0.002$), TBR ($p = 0.001$, $p = 0.001$) and attention values ($p = 0.009$, $p = 0.003$) were lower in PWADHD in both tasks. A lower beta in task 4 replicates findings from other studies (El-Sayed et al., 2002; Lazzaro et al., 1998) whilst higher beta in task 5 replicated findings in other studies (Chabot & Serfontein, 1996; Clarke, 2002; Clarke et al., 2011; Loo et al., 2009) suggesting different pattern of beta measure for different tasks. Loo et al. (2009) findings were supported in alpha suggesting higher levels of relaxation in PWADHD but results in theta and TBR were not replicated. Results suggest that in pro saccade and anti saccade tasks, lower attention values (seen in Ochi et al., 2021) and lower beta values in task 4 can correctly assess inattention symptoms in PWADHD. Higher beta levels in task 5 can be due to a higher complexity in the task that required from participants to maintain a higher focus. A different pattern of the results is observed in selective attention task (task 6). While attention values ($p = 0.056$) were higher in PWADHD not replicating findings from Ochi et al. (2021), alpha ($p = 0.003$), beta ($p < 0.001$), theta ($p < 0.001$) and TBR ($p = 0.006$) were lower. Such findings suggest that selective attention task might not be appropriate to assess ADHD symptoms as shown from higher attention values in PWADHD, lower theta and lower TBR. It is suggested that PWADHD performs better than controls in the famous invisible Gorilla task (replicating findings in Grossman et al., 2015) showing little or no attention blindness and such claim is supported in this task. Task 7 that measured divided attention showed higher activity in PWADHD in alpha ($p < 0.00$), beta ($p < 0.001$), theta ($p < 0.001$) and attention values ($p < 0.001$) while TBR was lower ($p = 0.002$). While higher theta suggests inattentiveness in PWADHD, other values do not show clear evidence that this type of attention can assess impairments in PWADHD. Tasks that drew upon switched attention (8, 9 and 10), show similar pattern in alpha ($p < 0.001$, $p < 0.001$, $p < 0.001$), beta ($p = 0.002$, $p < 0.001$, $p < 0.001$), attention values ($p = 0.005$, $p = 0.001$, $p < 0.001$) which were higher in PWADHD suggesting that in these types of tasks PWADHD show no impairments in these EEG measures. However, while theta ($p = 0.003$) and TBR ($p < 0.001$) were lower in PWADHD in task 8, the pattern was higher theta ($p < 0.001$) and TBR ($p < 0.001$) in task 9 suggesting that in task 9 switched attention that assessed PWADHD only in the visual domain can give evidence in higher impulsivity and inattentiveness in PWADHD supporting previous literature on theta (Bresnahan & Berry, 2002) and TBR (Loo & Makeig, 2012; Monastra et al., 2001; Snyder & Hall, 2006). Furthermore, TBR in task 9 showed a positive association with higher RTs ($p = 0.001$) supporting previous claim on TBR that an increase in TBR is correlated positively to RTs (Loo & Makeig, 2012; van Dongen-Boomsma et al., 2010). The results suggest that while the positive correlation between TBR and RT is true, this is only the case in visual switched attention task. In task 10, theta ($p < 0.001$) was higher while TBR was lower ($p < 0.001$) showing that this task can measure inattentiveness but not impulsive behaviours in PWADHD.

Results from NMs in brain activity, showed different architectures between groups in all tasks (see Figure 7.6, Figure 7.9). EEG data showed lower attention values (as seen in Ochi et al., 2021) in task 4 and 5 and lower beta values in pro saccade task suggesting that the task assessed inattentiveness in PWADHD while higher theta and higher TBR were observed in

PWADHD in task 9 replicating previous studies on theta (Bresnahan & Berry, 2002) and TBR (Loo & Makeig, 2012; Monastra et al., 2001; Snyder & Hall, 2006). Furthermore, TBR was positively associated with RTs in task 9 supporting the claim on TBR in PWADHD (Loo & Makeig, 2012; van Dongen-Boomsma et al., 2010).

Findings show that: 1- Lower beta values and lower attention values in EEG data show lower abilities to maintain attention in the task while alpha activity is correlated positively with levels of wakefulness. 2- Findings on TBR suggest that this measure might not be a good indicator of ADHD in sustained attention tasks (Ogrim et al., 2012) but only in attentional switching task based purely on visual stimuli (Loo & Makeig, 2012; van Dongen-Boomsma et al., 2010). 3- EEG measures are different on each task. 4- Prefrontal cortex is impaired in PWADHD (Geurts et al., 2004) as shown from the EEG data.

8. Chapter 8. A Network Model Approach for Assessing Comorbidity between Stuttering and ADHD

8.1 Introduction

Literature suggests that fluency, attention and WM are frequently affected in people who stutter or who have ADHD. Conventionally, this has been considered sufficient to designate the disorders as comorbid. Previous experiments in this thesis showed that there are differences in attention, fluency, cognitive and physiological responses between controls, PWADHD and PWS. These suggest that claims about comorbidity between ADHD and stuttering are overstated. Therefore, it is necessary that the strength of the relationship between these symptoms should be assessed in a different approach to determine connectivity in the cognitive architecture of people with these disorders. This would provide further support for/against comorbidity for the disorders and give a clearer indication how these participant groups differ from typical samples. An emerging approach to comorbidity is network modelling (Borsboom & Cramer, 2013). Networks involve nodes and edges. Mental disorders are described as an interconnected web of symptoms and according to network theorists, the disorders are emerging phenomena that originate from direct interactions amongst their symptoms, rather than underlying factors that cause symptoms to appear (Jones et al., 2019). Mental disorders often have many symptoms in common (shown in NM as nodes). For example, obsessive-compulsive disorder (OCD) symptoms, are associated with guilt, which in turn is a cause of depression (Kim et al., 2011). Experiencing certain symptoms of one disorder causes risk for other disorders, resulting in diagnostic comorbidity. NM allow any patterns across participant groups (controls, PWADHD, PWS) to be established.

Studies (Alm & Risberg, 2007; Arndt & Healey, 2001; Donaher & Richels, 2012; Druker et al., 2019; Riley & Riley, 1979; Riley & Riley, 2000) suggest attention problems in children and adults who stutter and stuttering symptoms in AWADHD (Biederman et al., 1993) based on scales, questionnaires and interviews. Research on reading and attention tasks has also suggested fluency issues in PWADHD (Engelhardt et al., 2010; Jacobson et al., 2011; Tucha et al., 2005) and attention impairments in PWS (Andreou & Trott 2013; Blood et al., 2007; Bosshardt, 1999; Heitmann et al., 2004; Ratcliff-Baird, 2002). Inferential analysis techniques were almost similar across studies. Comorbidity between attention and stuttering has been based on the significance of the results from descriptive statistics, t-tests, ANOVA, Pearson correlations and multiple regression. However, there are limitations of such statistical analyses that need to be addressed. It has been suggested that such techniques bring uncertainties (Jeon, 2015; Last et al., 2007) and there is a need for contemporary approaches (such as NMs) to assess comorbidity between mental disorders. Literature suggests that PWS and PWADHD are both likely to exhibit symptoms of WM impairments. Phonological working memory (PWM) impairment in particular has been validated as a reliable indicator to identify phonological encoding deficits in PWS (Bakhtiar et al., 2007; Byrd et al., 2015; Hakim and Ratner, 2004) and PWADHD (Marchetta et al. 2008; Martinussen et al., 2005). Results suggest that it is appropriate to investigate the way PWM problems affect attention in PWADHD and PWS utilizing NM. To date, no literature has assessed comorbidity between PWS and PWADHD utilizing NMs and how WM links to attention. Network models (Cramer et al., 2010a) are investigated in this chapter to assess if attention and stuttering are comorbid between PWS and PWADHD and how WM problems affect both disorders.

8.2 Experiment 8

The main purpose of this experiment was to understand the attentional ability of controls, AWS and AWADHD traits by using a NM and to understand how these patterns are affected when other performance indicators such as WM are included in the model. Previous studies have emphasized that attention is impaired in both PWS and PWADHD and both disorders share comorbidities such as stuttering and attention problems (Arndt & Healey, 2001; Donaher & Richels, 2012; Lee et al., 2017; Riley & Riley, 2000). Whilst previous studies have explored such comorbidities with different analysis techniques such as descriptive statistics, t-tests, ANOVA, Pearson correlations and multiple regression (Alm and Risberg, 2007; Arndt and Healey, 2001; Biederman et al., 1993; Blood et al., 2007; Donaher & Richels, 2012; Heitmann et al., 2004; Riley & Riley, 2000), no studies have explored comorbidities between PWS and PWADHD using NM approaches. Moreover, no studies have investigated if symptoms of attention are impaired in the same way in PWADHD and PWS and how other performance indicators such as WM can affect the patterns of attention in PWS and PWADHD. Specifically, are symptoms of ASRS, SSI-3 and UNWR comorbid between PWS and PWADHD? How does WM affect attention in each group? In this study it was hypothesised that whilst attention is impaired in both PWS and PWADHD, attention issues are different in these groups in terms of links with other performance indicators (based on results achieved in previous experiments conducted in this thesis). More specifically it was predicted that the way in which attention and WM are connected for PWS differs from that of PWADHD and fluent speakers. It was predicted that: H1: the way ASRS, SSI-3, UNWR symptoms are connected to each other in NM should be different between groups. H2: In controls, high UNWR scores (high WM abilities) should be directed negatively with low ASRS scores (low attention issues). H3: It is not clear at present how WM scores would correlate with ASRS scores (positively or negatively) in PWS and PWADHD, but the direction is examined.

8.3 Methods

8.3.1 Participants

Sixty-seven controls (Mean age: 24.25, SD: 6.709, 42 Females, 25 Males), seventy-nine PWADHD (Mean age: 24.66, SD: 5.154, 35 Females, 44 Males) and thirty-three PWS (Mean age: 34.18, SD: 11.796, 14 Females, 19 Males) were included from all experiments. Controls were recruited from UCL SONA. PWADHD were recruited from online ADHD groups and forums. PWS were recruited from online self-help groups in London and Manchester. All experiments were approved by UCL Research Ethics Committee (6252/002). Participants were compensated for participating in the studies and for travelling expenses for those travelling within the M25 area. Participants received an information sheet and a consent form to sign prior to conducting the experiment. With a total of 179 participants, power analysis revealed that with an effect size of 0.8 in one way ANOVA, there is an 86% to detect an actual effect.

8.3.2 Design

Participants in every experiment completed the ASRS questionnaire, read two short paragraphs from the SSI-3 manual and conducted the UNWR task. Depending on the experiment and the order of the participants, the three tasks were counterbalanced. The dependent variables were ASRS, SSI-3, UNWR and the between-participants factor was the participants' group.

8.3.3 Materials

The ASRS questionnaire was implemented online and contained 6 questions for participants to answer from never to very often. The questions were then scored based on the ASRS scale. The total score on ASRS was the sum of all scores achieved from all the questions. A total score ranged between 0 to 25 as the maximum score. A higher score indicated more symptoms of ADHD. The dependent variable in ASRS was the total score. In the SSI-3, the video for each participant was analyzed based on the frequency of stuttering (e.g., pauses, repetition), duration and physical concomitants (e.g., jaw tension). The total score was the sum of all these variables, and the percentile and severity of stuttering were determined by the total score. The total score was the dependent variable in SSI-3. A higher total score indicated more symptoms of fluency. UNWR was implemented online, and for each set of non-words, participants were scored on how many words they repeated correctly. A total score on UNWR (maximum score to obtain was 32) was the dependent variable. A higher UNWR score indicated a better WM.

8.3.4 Measures

1-Adult ADHD Self-Report Scale Screener, (ASRS; Ustun et al., 2017)

2-Stuttering Severity Instrument version 3, (SSI-3; Riley, 1994)

3-Universal Non-Word Repetition Test, (UNWR; Howell et al.'s 2016)

8.3.5 Procedure

First participants were assessed in a vision and hearing test. For the vision test, participants were asked to sit one meter away from the computer screen and indicate what direction of a progressively smaller stimuli ("E") was facing with left eye covered. This procedure was then repeated for the right eye. The stated direction of the stimulus from the participant was inputted by the experimenter with the right mouse click on the appropriate direction shown on the website. Participants progressed in the study only when they had stated the correct direction of the stimulus for both eyes. In the hearing test, participants responded out loud if they heard an auditory stimulus that was played by the experimenter in the Optimus Nova 626 headphones at the following intensities (decibels, dB): 50, 45, 40, 35, 30, 25, 20, 15, 10, and 0; and at the following frequencies (kilohertz, kHz): .25, .5, 1, 2, 4, and 8. Participants looked at the computer screen, so they were unaware of the intensity and frequency of the stimulus. To proceed with the next measures, participants had to successfully hear the stimulus below 20dB or at 20dB per each frequency. Depending on the users ID, participants then either completed ASRS, SSI-3, experiment and UNWR or first they completed UNWR, experiment, ASRS, SSI-3. In the ASRS questionnaire online users gave answers to 6 questions from never to very often. Then they read two short paragraphs from SSI-3 manual while they were being videorecorded (participants gave consent to be videorecorded). UNWR was implemented online[19] and was based on the UNWR original version by Howell et al. (2016)[20]. All the non-word sounds were downloaded from the UNWR original version. UNWR consisted of 4 sets with 12 non-words in total and two practice non words in each set. Experimenter first played the 2 practice non words for users to get familiar with the level and then played only 8 non-words in each set. The online version had a button that randomly played the non-words and the experimenter pressed that button 8 times. In UNWR, participants were asked not to look at the computer

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[19] Online version of UNWR: https://fjordakazazi.github.io/WM/

[20] UNWR original version: http://fistproject.org/resources/

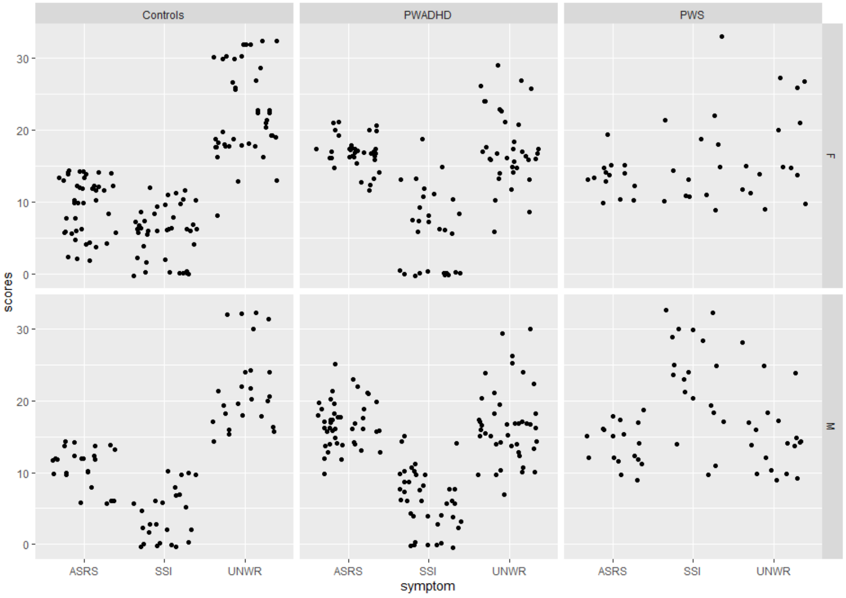
screen, hear the non-words played in the Optimus Nova 626 headphones by the experiment on a mouse click and repeat out loud the non-words. If the user correctly repeated the non-word, experimenter continued pressing the button. Otherwise, the task ended. If the participants repeated all the 8 non words correctly, they progressed to the next set. Experimenter also took in consideration participants' accent if they came from a different country.

8.4 Results

8.4.1 Experiment 8a Results

Figure 8.1

Ggplot conducted in R for the three dependent variables ASRS, SSI and UNWR in Controls, PWADHD, PWS for females (top row) and males (bottom row). Each symptom is shown in x -axis whereas y axis represents the scores in both genders.



Syntax model = lmer(target ~ fixed1 + fixed2+ (1|random1) + (1|random2), data=data)

A Linear Mixed Model (LMM) was conducted to understand if gender influenced the three dependent variables ASRS, SSI-3, UNWR. Two models were created. The first model looked at the effect of two fixed factors: 1- symptoms of ASRS, SSI-3, UNWR and 2- gender and the two random factors (participant, group) had on the scores. The second model looked at the effect of one fixed factor: 1- symptoms of ASRS, SSI-3, UNWR and two random factors (participant, group) had on the scores. Therefore, one model includes gender, and the other model does not include gender. After the models were generated using LMM, they were compared using ANOVA to understand whether removing the fixed factor gender would significantly impact the scores. No significant difference between the likelihood of the two models was observed ($\chi2(1) = 0.201$, $p=0.653$). Hence, gender did not affect the scores and our data can be employed in a NM to get reliable results.

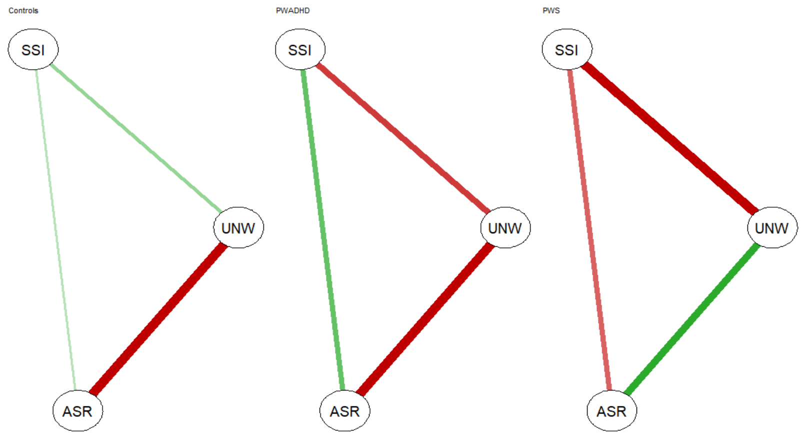
8.4.2 Experiment 8b Results

According to Epskamp et al. (2017a), the strength of the connection between two nodes in psychological networks NM is a metric determined from the data. The parameters will be more likely to be estimated correctly as the sample size increases. The more computing capacity we need to estimate the network (more participants), the more accurate the edges will be estimated. With a total sample size of 179 participants and power analysis showing that there is an 86% of detecting an actual effect, NM will be reliable. The relationships between different symptoms were examined using network analysis, and the relevance of each symptom was determined for each group (controls, PWADHD and PWS). A pairwise Markov random field (PMRF) was used to generate the network model. PMRF is a popular network model for estimating psychological networks and contains nodes that represent variables and edges without an arrowhead (Epskamp et al., 2017b). The size and density of the edges between the nodes represent the strength of connectedness. This indicates conditional dependence between symptoms. Typically, NM has two steps: (1) estimating a statistical model on data, from which some parameters can be represented as a weighted network between observed data, and (2) analysing the weighted NM using a graph to show the most central nodes. Centrality can be used to investigate the position of nodes in a network. Measures of centrality are strength, closeness and betweenness. According to Borsboom et al. (2021) the distinction between sparse and dense networks is crucial in terms of global topologies. In sparse networks few edges are compared to the entire number of possible edges. In dense networks there are a lot of edges present. For two reasons, this distinction is important: (1) optimal estimate processes may be sparsity-dependent; for example, regularization-based approaches should perform well if data are generated from a sparse network, but not in dense networks and (2) individual nodes are often more important in sparse networks than in dense networks, because all nodes in dense networks have a similar large number of edges. In the following analysis, a sparse network (Epskamp et al., 2017b) was created, and a regularization parameter was used (LASSO - least absolute shrinkage and selection operator) for the correlation networks as it performs well in a sparse network and limits the number of spurious relationships (Hevey, 2018). Although there are several lasso approaches, the graphical LASSO (glasso, Friedman et al., 2007) is recommended for its ease of use in analysis. EBIC Extended Bayesian Information Criterion (Chen & Chen, 2008) was employed to choose the best NM, which is particularly effective in identifying the actual network structure (van Borkulo et al., 2014), especially when the true network is sparse. As a result, for the sparse network, EBICglasso approach was adopted. The tuning parameter λ was set at 0.2 and the gamma γ was set to 0.2 (γ is typically set between 0 and 0.5; Foygel & Drton, 2010). The higher the tuning parameter, the more edges from the network are deleted (Hevey, 2018). A popular strategy for ensuring that the optimal tuning and gamma parameter is chosen is to estimate several networks with various values (Hevey, 2018). In the networks no difference was observed in the NM for different tuning and gamma parameters. The NM graph was visualised with the R package qgraph developed by Epskamp et al. (2012). The networks were built using standardised diagnostic measures (ASRS, SSI-3, and UNWR) because they assess common symptoms of the disorders. The network demonstrates the relationships between the symptoms. Positive and negative correlations (connections between nodes) are represented by green and red edges respectively. The degree of correlation is shown by the thickness of the edges. High ASRS suggests attention issues, high SSI-3 suggests poor fluency and high UNWR shows good WM abilities.

As shown in Figure 8.2, NMs differed between groups accepting H1. NM for controls shows the link between attention and WM is important but neither of these relates to fluency measure. Direction is high ASRS scores (poorer attention) lower WM scores with a correlation of -0.34 for controls (see Table 8.1) accepting H2. A positive weak correlation is seen between SSI-3 and ASRS (high disfluency high attention problems) and between SSI-3 and UNWR (high disfluency, high WM) with coefficients 0.09 and 0.14 respectively as shown in Table 8.1. For PWADHD poorer attention (high ASRS scores), poorer fluency (higher SSI-3 scores) correlation 0.15 and low WM scores with a correlation coefficient -0.26. High WM scores better fluency (low SSI-3 scores with correlation coefficient -0.2) and better attention (low ASRS scores). PWS lost the link attention and WM suggesting that having good attention abilities did not help WM (with a positive coefficient 0.19). PWS have high WM (UNWR) scores, low fluency (SSI-3) scores as with PWADHD with a correlation coefficient of -0.23. There is a lesser indication that low fluency (high SSI-3 scores) is associated with poor attention scores (high ASRS scores with a negative correlation of -0.14 as would expect). With regards to H3 the link between UNWR and ASRS for PWADHD was similar to controls but for PWS this pattern was lost. See Figure 8.2 for a visualization of the results. Figure 8.3 shows that PWADHD is similar to controls in ASRS, SSI-3, UNWR but both differ from PWS.

Figure 8.2

Network models for ASRS, SSI-3 and UNWR in controls, PWADHD and PWS.



Note. Green and red connections between nodes are represented by positive and negative correlations respectively. A positive sign means that nodes covary in the same direction, whereas a negative sign means they covary in the opposite way. The degree of correlation is shown by the thickness of the connections. The green line between ASR and SSI in the middle NM, indicates PWADHD who have high ASRS scores are more disfluent, but this is opposite for PWS as shown in the third NM. The PWS who have high ASRS scores are more fluent.

Figure 8.3

Network models for ASRS in all groups (left NM), SSI-3 for all groups (middle NM) and UNWR in all groups (right NM).

Note. Letter “C” in ASRSC, SSIC, UNWRC stands for Controls, letter “A” in ASRSA, SSIA, UNWRA stands for ADHD and letter “S” in ASRS, SSIS, UNWRS stand for PWS.

Table 8.1

Correlations coefficients for Controls, PWADHD and PWS for each indicator.

	SSI-UNWR	ASRS-UNWR	ASRS-SSI
Controls	0.14	-0.34	0.09
PWADHD	-0.2	-0.26	0.15
PWS	-0.23	0.19	-0.14

Note. All coefficients for each group are retrieved from NM

Looking at the networks in Figure 8.2 and correlation matrices in Table 8.1, fluency (SSI-3) is not important in controls but there is a strong negative link between ADHD measure (ASRS) and UNWR performance. Attention impacts WM which affects a whole host of things. PWS are immune to this as the variation in attention ability doesn't affect WM. To understand whether this is caused by e ceiling effect, means of all groups in all measures are shown in Table 8.2. We can conclude that there isn't a ceiling issue in ASRS and UNWR since the highest score to obtain in ASRS is 25 and the highest score to get in UNWR is 32. PWS scores for ASRS and UNWR are 13.72 and 15.94 respectively (see Table 8.2).

Table 8.2

Means for ASRS, SSI-3 and UNWR in controls, PWADHD, PWS.

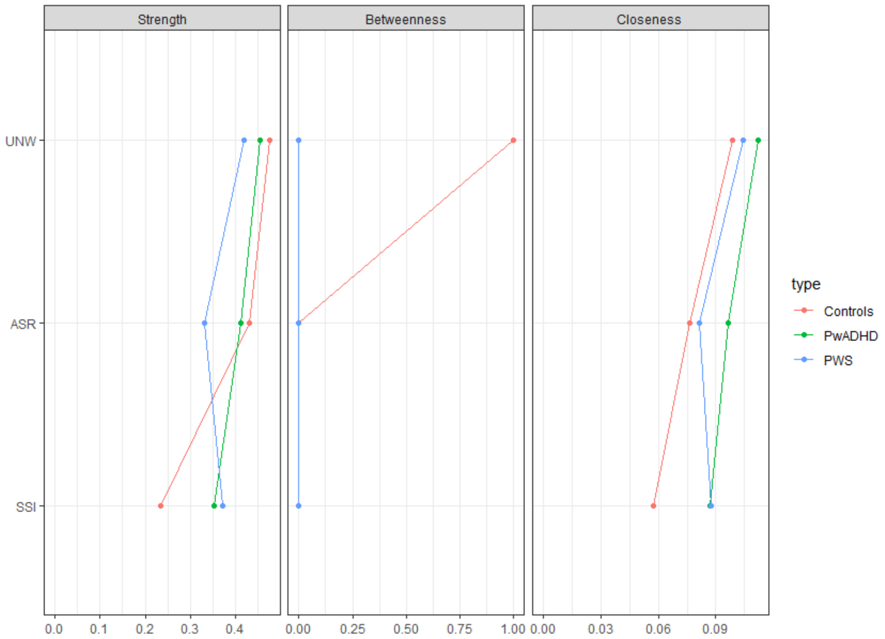
	Means		
Measure	**ASRS**	**SSI**	**UNWR**
Controls	9.95	5.11	22.12
PWADHD	16.84	6.15	17.04
PWS	13.72	20	15.94

In a NM, edges are the lines that connect the nodes or the symptoms (nodes are presented in circles, Borsboom, 2017). Centrality is an important concept of NM (Hevey, 2018) that shows which symptoms are the most central and important that have the strongest association with other symptoms. The centrality of each node in the network indicates its importance (central nodes are more important than peripheral nodes). The importance of each measure is shown by centrality measures. In a network, node centrality can be calculated using strength centrality, betweenness centrality and closeness centrality. Such analyses can be done using the qgraph package in R (Epskamp et al., 2012) or by using the bootnet package (Epskamp et al., 2018). Strength is mostly about understanding the most central symptom. Strength centrality is a measure of the absolute value of the edge weights connected to a node (Jones et al., 2019). Betweenness centrality measures how many times/percentage a node is on the shortest path between two other nodes and can be used to predict which nodes are likely to function as connecting groups in a network. High betweenness nodes are important for connecting groups. Closeness estimates how close a node is to all other nodes on average in terms of the edge distance. This can be calculated by getting the average of the path from one node to every other node in the network. The lowest average for a node indicates that that node is closest to other nodes in the network. In psychological networks, strength has received the most attention, whereas betweenness and closeness centrality are less popular (Epskamp et al., 2018; Forbes et al., 2017). The absolute value of every edge that connects SSI-3 with ASRS and SSI-3 with UNWR can be summed to understand the strength of SSI-3. For example, if SSI-3 with ASRS has an edge weight of -0.21 and SSI-3 with UNWR has an edge weight of -0.43, the strength of SSI-3 with ASRS and SSI-3 with UNWR would be 0.21 + 0.43 = 0.64. For betweenness, we can count/get the percentage of the number of times the SSI-3 node is on the shortest path between ASRS and UNWR nodes. Betweenness is commonly used to understand whether one node plays a key role in connecting nodes with each other. For example, in the case where there are many nodes in a network model, some nodes can act as a bridge to connect some groups of nodes with other groups of nodes. In our case, we do not have a key node that connects groups of nodes because SSI-3, ASRS and UNWR are connected with each other. For the closeness of SSI-3 to other nodes, we can determine it by taking the average distance between the SSI-3 nodes with ASRS and UNWR.

Figure 8.4 shows that in controls, PWS and PWADHD, UNWR is the most central factor as observed from strength. This suggests that WM is important and has strong connections to other nodes. With respect to betweenness only in UNWR for controls have importance in acting as a bridge to other nodes. UNWR has the highest closeness in controls, PWS and PWADHD, suggesting WM is an important factor in all groups that also has strong connections to other nodes.

Figure 8.4

Centrality of the symptoms for ASRS, SSI-3 and UNWR in controls, PWADHD and PWS ordered by strength.



8.5 Discussion

In this experiment it was hypothesised that the way attention, fluency and WM problems operate differently between controls, PWS and PWADHD. NMs differed between participant groups. WM affected attention in controls as expected with a higher WM linked to lower attention problems. This pattern was the same for PWADHD but differed in PWS suggesting that WM abilities does not have the same affect in attention. Although WM is a strong factor in all groups as assessed by strength centrality, the way it operates between PWADHD and PWS is different. To conclude, the results suggest that WM, attention and fluency problems are not comorbid between PWADHD and PWS according to NMs. Furthermore, the way the three symptoms operate in PWADHD is similar to how they operate in controls, but both differ from PWS. Results from this experiment confirm previous findings in the studies that we conducted. In previous experiments, performance of PWADHD differed from PWS suggesting that disorders are not comorbid. Although frontal cortex is impaired in both groups, and both disorders suffer from attention, fluency and WM memory problems, comorbidity is limited as shown from different architecture in NMs in behavioural data, oculomotor measures and cognitive abilities.

9. Chapter 9. General Discussion

9.1 Introduction

Research suggests that stuttering and ADHD are ‘comorbid’ due to the shared symptoms of attention, stuttering and working memory problems occurring in both disorders. This thesis investigated similarities between stuttering and ADHD on these shared factors that distinguish them from typical controls. This was done in two main ways: (1) by comparing the groups on attention capabilities using a range of cognitive, behavioural and physiological measures in web and VR approaches; and (2) by utilizing network models to compare the architecture of the groups representing participants’ performance on these measures.

The literature on ADHD and stuttering and the associated problems of working memory for both disorders was reviewed in Chapter 1. This chapter included a review of previous approaches to assess ADHD symptoms in PWS (Alm & Risberg, 2007; Andreou & Trott, 2013; Arndt & Healey, 2001; Blood et al., 2007; Bosshardt, 1999; Donaher & Richels, 2012; Druker et al., 2019; Heitmann et al., 2004; Ratcliff-Baird, 2002; Riley & Riley, 1979; Riley & Riley, 2000) and disfluency in PWADHD (Biederman et al., 1993; Engelhardt et al., 2010; Jacobson et al., 2011; Tucha et al., 2005) with emphasis on the methodology used. Limitations of the methodological aspects were emphasized for each study stressing the need for more appropriate and comprehensive statistical approaches to assess comorbidity in stuttering and ADHD (Jeon, 2015; Lash et al., 2007) were considered. Comorbidity was then discussed in detail before the network model approach, along with its pros and cons was introduced. In a network model perspective, comorbidity between disorders is assessed by comparing the clusters of symptoms assigned to a single underlying cause (Borsboom & Cramer, 2013; Cramer et al., 2010a; Epskamp et al., 2017a; Epskamp et al., 2017b). The next part of the chapter introduces VR technology as an effective way to measure with precision attention from behavioural, oculomotor, and EEG activity simultaneously. VR technology offers a safe environment to capture these measures and it has gained an emerging popularity in rehabilitation (Keshner, 2004). Finally, a review of studies that assessed eye behaviour and EEG activity in PWADHD and PWS was made with the aim of understanding the most important measures to detect attention problems in both groups and distinguish them from controls.

In chapter 2, two experiments were conducted. Experiment 1 used Fairnie et al.'s (2016) auditory selective and dual attention task in which the performance of controls and PWS were compared in the load theory of attention. This examined whether the performance of PWS differed significantly from controls and if the task can be used to assess attention problems in PWS when the cognitive load enhanced until it exceeded the perceptual capacity. Experiment 2 used the same task paradigm in both visual and audio domains in VR to investigate behavioural and oculomotor measures of PWS and PWADHD in all modality conditions and to see whether groups differed significantly from controls and in which sensory domain. Furthermore, NM were conducted to understand whether PWS and PWADHD were comorbid in these measures and which domain was affected in both disorders.

Chapter 3 addressed the importance of considering the gender imbalance in research before assessing the cognitive differences between groups for making an accurate diagnosis. A Linear Mixed-effect Model (LMM), approach was utilised for assessing gender inequality across controls, PWADHD and PWS before investigating differences between groups in a task that drew upon selective attention in the visual domain.

Cognitive, behavioural and physiological measures were assessed in PWS, PWADHD and compared to controls in Chapter 4 in a VR environment. The aim was to understand if visual selective attention tasks can assess attention problems in PWS and PWADHD. Specifically, are PWS impaired in selective attention tasks as the literature suggests (Doneva et al., 2018) and is the frontal cortex the most important region involved in speech similarly as in PWADHD (Geurts et al., 2004)? This chapter also aimed to address inconsistencies from the literature on PWADHD in selective attention tasks (Douglas & Peters, 1979; Carter et al., 1995; van der Meere & Sergeant, 1988). NMs were conducted to compare groups and draw further conclusions on this matter and whether disorders were comorbid in the measures tested.

Ten VR tasks that measured sustained, selective, divided and switched attention in different domains of EF, were tested in PWADHD and compared to controls in Chapters 5, 6 and 7. An extensive analysis was made from cognitive, behavioural, questionnaires data (Chapter 5), eye (Chapter 6) and EEG measures (Chapter 7). The aim was to understand which particular attention task in EF correctly assessed ADHD traits from the measures tested and significantly distinguished them from controls utilizing different statistical analysis including NMs.

Chapter 8 utilised NMs on all controls, PWS and PWADHD on cognitive factors including attention, stuttering, and WM. The aim was to investigate the comorbidity between PWS and PWADHD by assessing the strength of the relationship between these symptoms. The pattern and architecture of these symptoms in NMs was compared with the NM architecture of controls.

9.2 Report of main findings

The outcomes of Experiment 1 in Chapter 2, point towards PWS having poorer performance in selective and divided auditory attention suggesting that PWS show impairments when processing demands are enhanced. These results were confirmed in Experiment 2, which evaluated the performance of controls, PWS, and PWADHD in the audio, visual, and audio-visual domains. Results showed that while performance on selective attention tasks declined under high load in all groups, audio was more affected in PWS whereas audio and audio-visual were affected in PWADHD. The results from NM showed that the measures examined were similar in controls and PWADHD but different from PWS, indicating that comorbidity between PWS and PWADHD is limited and that selective attention tasks are impaired in PWS suggesting that such tasks can assess attention problems in PWS but not in PWADHD. Finally, the load theory of attention was confirmed which suggests that when the cognitive load is higher, the distractor processing is reduced (Fairnie et al., 2016; Forster et al., 2014; Lavie et al., 2014; Lavie, 2005) as assessed from the ability to detect a critical stimulus presented in the dual task condition.

LMM correctly determined that the gender imbalance across controls, PWS and PWADHD did not affect the results on an online visual selective attention task in Chapter 3. Significant differences were observed between PWADHD and PWS showing that comorbidity between disorders is overstated. PWS had the lowest performance with the highest RTs. Hence further assessment on behavioural and physiological measurements between the groups in a VR selective attention task were made in Chapter 4.

In Chapter 4, PWS and PWADHD differed from controls with a lower performance recorded on the task. Selective attention task assessed impulsive behaviours in PWADHD with a higher number of saccades, fixations and saccade mean velocity whilst for PWS symptoms of impulsivity were not present. Instead, the task determined inattention symptoms in PWS as shown by lower fixation durations, but this was not the case for PWADHD. Theta and TBR were both lower in PWADHD suggesting that symptoms of inattention and impulsivity were not present in this group from EEG data. For PWS there was a trend for higher theta although not significant suggesting higher inattentiveness in this group. Results from NMs show that controls and PWADHD differed from PWS in the task performance. NMs on oculomotor measures showed a different pattern between all groups suggesting that eye behaviour differed across groups whereas PWS and PWADHD had a similar NM architecture in EEG data indicating that the frontal cortex is impaired in both groups. Experiment confirmed that the comorbidity between PWS and PWADHD is limited and attention problems were better assessed in PWS suggesting that this group is impaired in selective attention.

The results in Chapters 5, 6 and 7 showed that sustained attention tasks regardless of the domain assessed and attentional switching task in the visual domain correctly assessed

ADHD traits in PWADHD based on behavioural, physiological measures and NMs. Furthermore, from all sustained attention tasks, the two main tasks that better assessed ADHD traits were the pro saccade (task 4) and anti saccade (task 5) tasks introduced in Munoz et al. (2003). In both tasks PWADHD had lower performance with lower accuracy and longer RTs compared to controls. Impulsivity and inattentiveness were significantly higher in PWADHD as shown from higher number of saccades, higher number of fixations and lower fixation durations. A higher number of blinks recorded in PWADHD showed lower levels of wakefulness in PWADHD in line with the literature (Fried et al., 2014; Tanaka, 1999). Pupil diameter was higher suggesting that this measure might be correlated to impulsivity instead of inattentiveness as literature suggests (Fried et al., 2014; Munoz et al., 2003; Wainstein et al., 2017). From the EEG, inattention was assessed in the pro saccade task with lower levels of beta and attention values. TBR in sustained attention tasks was not higher in PWADHD as literature suggests (Loo & Makeig, 2012; Monastra et al., 2001; Snyder & Hall, 2006). A higher TBR was only evident in the task that measured attentional switching (task 9) and it was positively correlated to RT and theta supporting previous research. In task 9, groups differed significantly in the task performance with lower accuracy and higher RT to complete the task in PWADHD. Higher impulsivity was indicated by a higher saccade mean velocity whilst a lower attention and wakefulness were shown with lower fixation durations and a higher number of blinks in PWADHD respectively. Theta activity and TBR were significantly higher in PWADHD, suggesting lower levels of attentiveness instead of higher impulsivity. In all sustained attention tasks and the attentional switching task in the visual domain (task 9), network models from behavioural data revealed a distinct architecture between groups, supporting earlier findings in this study. All tasks had different NM architecture in the eye and brain data, demonstrating that the pattern of the measures of the eyes and the brain varies among tasks. Finally, questionnaire data revealed that, on average, PWADHD were more easily distracted and had lower task confidence compared to controls. For both groups the tasks were engaging, and all participants felt present in the virtual reality environment.

NMs in Chapter 8 showed the way symptoms of inattention, disfluency and WM operate differently between controls, PWS and PWADHD suggesting that the symptoms of both disorders are not comorbid confirming previous results in previous experiments. In controls and PWADHD a higher WM was linked to lower attention problems, but this was not the case for PWS showing that WM abilities do not have the same effect on attention between PWADHD and PWS. Strength centrality showed that WM is a strong factor in all groups but the way it operates between PWADHD and PWS is different.

9.3 Summary and Implications

Studies assessed cognitive, behavioural and physiological measures in PWS and PWADHD in detail by utilizing powerful technologies with contemporary methodology to understand comorbidity between disorders and the type of attention impaired in PWS and PWADHD. Furthermore, studies aimed at understanding whether frontal cortex is affected in both disorders. All experiments suggest that symptoms of both disorders are not comorbid as assessed from NMs. WM is a strong factor affected in both disorders, but the way that it is linked to attention differs in PWS and PWADHD. NMs architecture between controls and PWADHD are similar, but both differ from PWS. Executive function is impaired in both disorders but in different types of attention. Whilst inattention is better assessed in PWS in auditory selective attention tasks, this is not the case for PWADHD. In contrast, PWADHD have highest attention in selective attention tasks. For PWADHD, inattentiveness behaviour is correctly assessed in sustained attention tasks in any domain and attentional switching task in the visual domain. Furthermore, pro saccade and anti saccade tasks can better assess ADHD traits in PWADHD. With regards to the oculomotor measures, NMs showed a different pattern of results between groups for different tasks. A lower fixation duration in both groups assessed inattention in selective attention tasks for PWS and in sustained and switched attention tasks in PWADHD. Higher number of fixations and saccades assessed impulsivity in PWADHD in sustained attention tasks while a higher saccade mean velocity assessed impulsivity in the switched attention task, whereas for PWS, impulsive symptoms were not present in the selective attention task. Results from the EEG suggested that in both groups the frontal cortex is impaired. A higher theta suggested inattentiveness in PWS whilst lower beta and attention values in sustained attention tasks and higher theta and higher TBR in switched attention task showed higher inattentiveness and impulsivity in PWADHD. Finally, participants found the tasks interesting and felt present in VR showing that with this technology, researchers can create a controlled and safe environment while collecting precise data. Furthermore, making the tasks interactive and including real-life scenarios can decrease levels of fatigue and losing interest on the task both of which can impact the data collected.

The results show that assessing PWS in attentional demanding tasks (specifically in selective and divided attention tasks) in which the Load Theory of Attention applies can correctly determine impairments in this group. It has been suggested that PWS require more cognitive processing capacity to produce speech and enhancing processing demands can interfere with their ability to execute speech fluently (Bosshardt, 2006). Hence, training PWS in attentional demanding dual tasks would train their cognitive processing capacity and, subsequently, their speech. Also, training PWS in selective attention would help them focus their attention on relevant information, such as the information they would like to express, instead of concentrating on distractions, including their speech disfluency or people's reactions. Impairments of PWS particularly in the auditory domain suggest that focusing on their speech can increase their disfluency. Again, this shows an impairment in selective attention for this group. PWADHD show impairments mostly in the visual domain in sustained and attentional switching tasks, indicating that the way attention and WM problems operate between groups is different. For PWADHD, training in sustained attention tasks would help them focus on specific visual or auditory information for longer periods of time. Furthermore, the ability of PWADHD to switch their visual attention from one information to the next would be enhanced if this group is trained in attentional switching ability (since their WM would be trained). All measures tested, analysis and results from NM suggest that symptoms between PWS and PWADHD have different architectures. Hence comorbidity between disorders is limited in contrast to what literature suggests. While WM is a strong factor contributing to attention and disfluency, its relationship with other symptoms differs. However, results successfully determined executive function impairments in the frontal cortex in both groups as seen from NMs in EEG data. Hence PWADHD and PWS would benefit from therapies that aim to strengthen attention in the executive function in the frontal cortex. Results also showed that NM is an effective technique to determine similarities and differences between disorders. Its ease of use and excellent visualizations make this technique more effective than utilising traditional statistical methods. With NMs, clinicians would not only achieve a better explanation of what is causing mental disorders and their comorbidity with other disorders but also would help them to develop new treatment strategies. EXPLAN model (Howell & Au-Yeung, 2002) which applies to both fluent speakers and speakers who stutter, links stuttering to how language factors and motor processing interact. Implications on how this links to task performance in PWS in auditory attentional demanding tasks will be shown below. EXPLAN theory has a different view on fluent speech compared to the Levelt's work which focuses on errors. The main factor that links to stuttering according to EXPLAN model is on timing. The theory is that neither language planning, nor motor factors alone can influence disfluent speech. Language processing (PLAN) and motor programming (EX) are two processes that are embodied in EXPLAN. These procedures can take different times to complete. The process of planning provides a linguistic representation for execution process to use. Phonological complexity can affect the time of planning and execution of speech. Based on the information that has been sent from the language system, the execution procedure implements speech plan. The concept is that before the speaker performs the motor process, speech must be planned and finished. Crucially, the timing of the two operations must synchronize in order to avoid disfluency. For speech to be performed fluently, PLAN and EX are two distinct operations that carry out in synchronisation in a chained way (Howell & Au-Yeung 2002). This lets planning to proceed without terminating the execution of a former word. Auditory load in selective and divided attention tasks impacts their cognitive processing capacity or the language processing (PLAN). The more complex is the cognitive/phonological demand, the more timing it is required for execution process (EX) in PWS to perform or their ability to correctly speak fluently (as seen from higher reaction times in this group; see Figure 2.2 row 2 in chapter 2). Since it is important for both processes to be timed together to execute speech fluently, an inaccurate timing, effects their performance in the task and subsequently their speech. In controls, PLAN and EX operate in parallel and are timed together allowing for each respond to auditory stimuli to continue without being affected from the previous stimuli. In PWS, task performance on current presented stimuli will be affected from the previous auditory stimuli played since the timing on PLAN and EX on the previous stimuli will not operate in parallel and the higher the phonological demand, the lower the ability to execute the response correctly for the current stimuli (as shown in Figure 2.2 row 1 in chapter 2). Adding to this that PWS are impacted in selective attention tasks, this group would focus on their previous response to stimuli not allowing enough timing for the next PLAN and EX response to current stimuli and therefore being less accurate in task performance and subsequently their speech.

9.4 Limitations and Future Directions

While the studies assessed symptoms of attention, fluency and WM in powerful and contemporary technologies, there are some limitations that need to be addressed. First, for more reliable findings, it is better to match participants in number and age between groups. Although it is difficult to find an equal number of participants with ADHD and who stutter especially if the study is conducted in person and not online, more reliable results can be drawn. It should however be noted that throughout the studies difficulties have been encountered for PWADHD and PWS to participate in the study, with some participants forgetting the day of the study and others postponing the day. Therefore, more efforts need to be made for more interactive and appealing VR scenarios. Another limitation to be addressed was the EEG device utilized. Although the technology provided a vast amount of data, it should be noted that it is new in the market and might need further testing to understand whether the data is reliable. Although it should also be considered that the EEG device utilised in the experiments was made purposely for VR and currently there are no other EEG devices that can be attached to the VR headset. To utilize an EEG device not made for VR can cause discomfort and can further change how the VR headset is placed onto the participants' head interfering with the data collected from the eye tracker and the task. There is currently no other technology in the market to collect eye and brain data in VR. Efforts have been made however from the HTC Vive company in a new VR technology with EEG and eye tracker add on, but the product has not been released to the market as yet. Until then, the VR headset, eye tracker add on and the EEG utilized in this thesis are the most appropriate technology. Another limitation was not to consider symptoms of anxiety and how it affected other symptoms in PWS and PWADHD. Literature shows contradictory results with some studies suggesting that symptoms of anxiety are present in PWS (Kraaimaat et al., 2002) and PWADHD (Pliszka, 1989) and others showing no evidence of anxiety in both groups (Cox et al., 1984; Molt & Guilford, 1979; Vance et al., 2013). However, this can be due to trait and state anxiety. Endler and Parker (1990) explained trait anxiety as a personality feature and state anxiety as an emotional reaction that happens in the moment. Their model suggests that state anxiety is an interaction between a trait anxiety component and a stressful event or demanding situations. For instance, a person who stutters would see speaking on the phone as a stressful event (social aspect is a trait anxiety) which leads to higher states of anxiety. Craig (1990) found that PWS has significantly higher levels of trait and state anxiety compared to controls in demanding speech situations. Davis et al. (2006), compared young individuals who persist in their stutter to those who had recovered and fluent speakers to understand if there were differences in trait and state anxiety levels. Authors administered The State-Trait Anxiety Inventory in four speaking situations. Their findings showed that higher levels of state anxiety were present in persistent group compared to recovered and controls. Such results indicated that more challenging states can affect higher anxiety levels and subsequently speaking problems. Anxiety can also depend on stuttering severity. Fitzgerald et al. (1992) found higher anxiety levels in PWS with higher stuttering severity. Therefore, it would have been appropriate to assess anxiety levels in PWS and PWADHD and its role in attention and stuttering problems. As described above, for PWS, state anxiety could load onto the EXPLAN model in auditory selective and divided attentional demanding tasks and could have played a role on the timing between PLAN and EX. Further to this, it could have been appropriate to assess state anxiety in visual sustained and switched attention tasks PWADHD and its role on other symptoms. Also, NM architecture and comorbidity between symptoms could have changed if state anxiety would have been included. Lastly, taking into consideration the severity of stuttering, attention and hyperactivity problems (utilising ASRS v1.1) as well differences between genders would allow for a better understanding how anxiety and working memory problems affect stuttering and ADHD traits. In addition to this, investigating how symptoms operate between groups while taking into consideration age differences could also give us more insights.

Based on the results of the studies in this thesis, future studies should point towards assessing and training PWADHD in attentional demanding sustained and switched tasks and PWS in selective, divided attentional demanding tasks. Additionally, to compare comorbidity between PWS and PWADHD, symptoms of hyperactivity in PWADHD and anxiety for all groups can be investigated with NMs. A control in age, gender, stuttering and ADHD severity, could give further insights on how differences between these independent measures affect task performance and architecture of the symptoms.

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Appendices

Appendix A. Chapter 2: Results for experiments 1 and 2

ITD, IAD

The sounds in Experiment 1 and Experiment 2b are displayed with ITD and IAD around the user:

1. **Interaural Time Differences (ITD):** When the sound was in front of the user 0 degrees azimuth, the sound was heard in both ears, when the sound played on the left, participants heard it from the left ear and the same for the right ear.
2. **Interaural Amplitude Differences (IAD):** The rate (volume) of the sound was decreased by 50% when the sound was in the second outer circle.

Calculation of Detection Sensitivity

Figure A2.1

Formula to calculate DS.

$$A = \begin{cases} \dfrac{3}{4} + \dfrac{H-F}{4} - F(1-H) & \text{if} \quad F \le 0.5 \le H\,; \\ \dfrac{3}{4} + \dfrac{H-F}{4} - \dfrac{F}{4H} & \text{if} \quad F \le H < 0.5\,; \\ \dfrac{3}{4} + \dfrac{H-F}{4} - \dfrac{1-H}{4(1-F)} & \text{if} \quad 0.5 < F \le H\,. \end{cases}$$

Results for Accuracies, Reaction Times, Detection Sensitivity

Table A2.1

Descriptive Statistics for accuracy, RT and DS.

		Controls			*PWS*			
		M	**SD**	**N**	**M**	**SD**	**N**	***Cohen's d***
Accuracy	***1***	92.95	7.751	28	86.47	11.683	25	0.472
	2	86.00	10.698	28	77.47	12.695	25	0.521
	3	82.85	13.250	28	72.90	15.970	25	0.486
	4	80.22	14.508	28	68.40	16.343	25	0.548
RT	***1***	866.43	181.17	12	904.01	210.52	11	0.132
	2	971.06	181.33	11	1135.84	185.53	10	0.618
	3	993.57	232.19	12	1180.04	280.00	10	0.517
	4	999.68	183.96	12	1231.68	324.20	10	0.638
DS	***1***	0.9509	0.3210	22	0.7284	0.1957	25	0.566
	2	0.8840	0.0983	28	0.6920	0.1881	24	0.944
	3	0.8805	0.1196	28	0.6884	0.1645	25	0.962
	4	0.8530	0.1734	28	0.6577	0.1853	25	0.778

Note. Cohen's d represents the effect size: d = 0.2 is small effect; d = 0.5 is medium effect; d = 0.8 is large effect.

Results for ASRS, SSI-3 and UNWR

Table A2.2

Descriptive Statistics for ASRS, SSI-3, UNWR.

	Controls			*PWADHD*			*PWS*			***Omega squared***
	M	**SD**	**N**	**M**	**SD**	**N**	**M**	**SD**	**N**	
ASRS	10.41	4.521	22	17.6	2.366	10	12	1.633	4	0.380
SSI-3	6.10	3.936	21	6.14	4.298	**7**	29.33	4.041	3	0.740
UNWR	19.64	6.028	22	14.00	3.162	9	11.25	2.217	4	0.248

Note. Omega squared represents the effect size: $\omega^2 = 0.01$ is small effect; $\omega^2 = 0.06$ is medium effect; $\omega^2 = 0.14$ is large effect.

Results for Accuracies, Reaction Times, Detection Sensitivity

Table A2.3

Descriptive Statistics for accuracies, reaction times, detection sensitivity across levels, conditions and groups.

		Controls			***PWADHD***			***PWS***			***Omega squared***
		M	**SD**	**N**	**M**	**SD**	**N**	**M**	**SD**	**N**	
Accuracy L1	***A***	17.09	2.114	22	17.10	1.524	10	14.75	2.630	4	0.071
	V	15.64	4.510	22	18.60	2.271	10	18.50	1.00	4	0.099
	AV	17.68	2.102	22	19.00	1.491	10	18.25	1.258	4	0.036
Accuracy L4	***A***	12.36	2.752	22	12.50	2.991	10	12.75	1.708	4	0.056
	V	15.14	3.895	22	17.50	2.877	10	15.75	3.096	4	0.036
	AV	15.73	3.561	22	17.30	2.058	10	16.75	2.217	4	0.003
RT L1	***A***	2510	457.9	22	2470	454.4	10	2938	291.6	4	0.051
	V	2871	753.1	22	2445	321.0	10	2406	249.9	4	0.056
	AV	2576	628.1	22	2404	282.9	8	2707	275.7	4	0.031
RT L4	***A***	3127	752.4	21	3107	585.3	10	3404	199.5	3	0.046
	V	3004	785.6	22	3391	610.6	10	2559	289.4	3	0.046
	AV	2988	819.9	22	2865	424.7	10	2778	208.5	3	0.048
DS L1	***A***	0.849	0.030	22	0.836	0.041	10	0.757	0.016	4	0.409
	V	0.823	0.051	22	0.841	0.456	10	0.867	0.015	4	0.035
	AV	0.852	0.034	22	0.847	0.029	10	0.852	0.028	4	0.055
DS L4	***A***	0.787	0.037	22	0.791	0.021	10	0.780	0.026	4	0.048
	V	0.805	0.045	22	0.836	0.043	10	0.866	0.015	4	0.151
	AV	0.850	0.223	22	0.860	0.141	10	0.862	0.0144	4	0.015

Note. L1 and L4 represent load levels 1 and 4. RT stands for reaction times and DS stands for detection sensitivity. A, V and AV stand for audio, visual and audio-visual respectively. Omega squared represents the effect size: $\omega^2 = 0.01$ is small effect; $\omega^2 = 0.06$ is medium effect; $\omega^2 = 0.14$ is large effect.

Results for Gaze Velocity and Pupil Diameter

Table A2.4

Descriptive Statistics for gaze velocity and pupil diameter across levels, conditions and groups.

		Controls			***PWADHD***			***PWS***			***Omega squared***
		M	**SD**	**N**	**M**	**SD**	**N**	**M**	**SD**	**N**	
GV L1	***A***	3542	6439	22	4088	9659	10	1789	23147	2	0.086
	V	3390	8863	21	3314	6574	10	5313	7573	3	0.057
	AV	3740	8895	21	1588	4124	10	7853	23312	2	0.808
GV L4	***A***	3411	9040	22	5378	11093	10	5325	7809	3	0.049
	V	5258	13835	21	3599	9359	10	40014	25563	2	0.257
	AV	5048	14342	21	3926	8695	10	3318	2765	3	0.059
PD L1	***A***	2.64	1.03	22	2.92	0.99	9	1.60	0.52	4	0.074
	V	2.56	1.02	22	2.66	1.15	10	3.37	0.31	3	0.006
	AV	2.53	1.11	22	3.08	1.08	10	2.41	0.49	3	0.001
PD L4	***A***	2.74	1.26	22	2.89	1.05	10	1.88	0.54	4	0.008
	V	2.56	1.01	22	2.65	1.00	10	2.10	0.44	4	0.029
	AV	2.63	0.81	22	2.47	0.95	9	1.79	0.51	4	0.050

Note. L1 and L4 represent load levels 1 and 4. GV stands for gaze velocity and PD stands for pupil diameter. A, V and AV stand for audio, visual and audio-visual respectively. Omega squared represents the effect size: $\omega^2 = 0.01$ is small effect; $\omega^2 = 0.06$ is medium effect; $\omega^2 = 0.14$ is large effect.

Results for Pupil Distribution

Figure A2.2

Average Pupil Distribution per group condition and level.

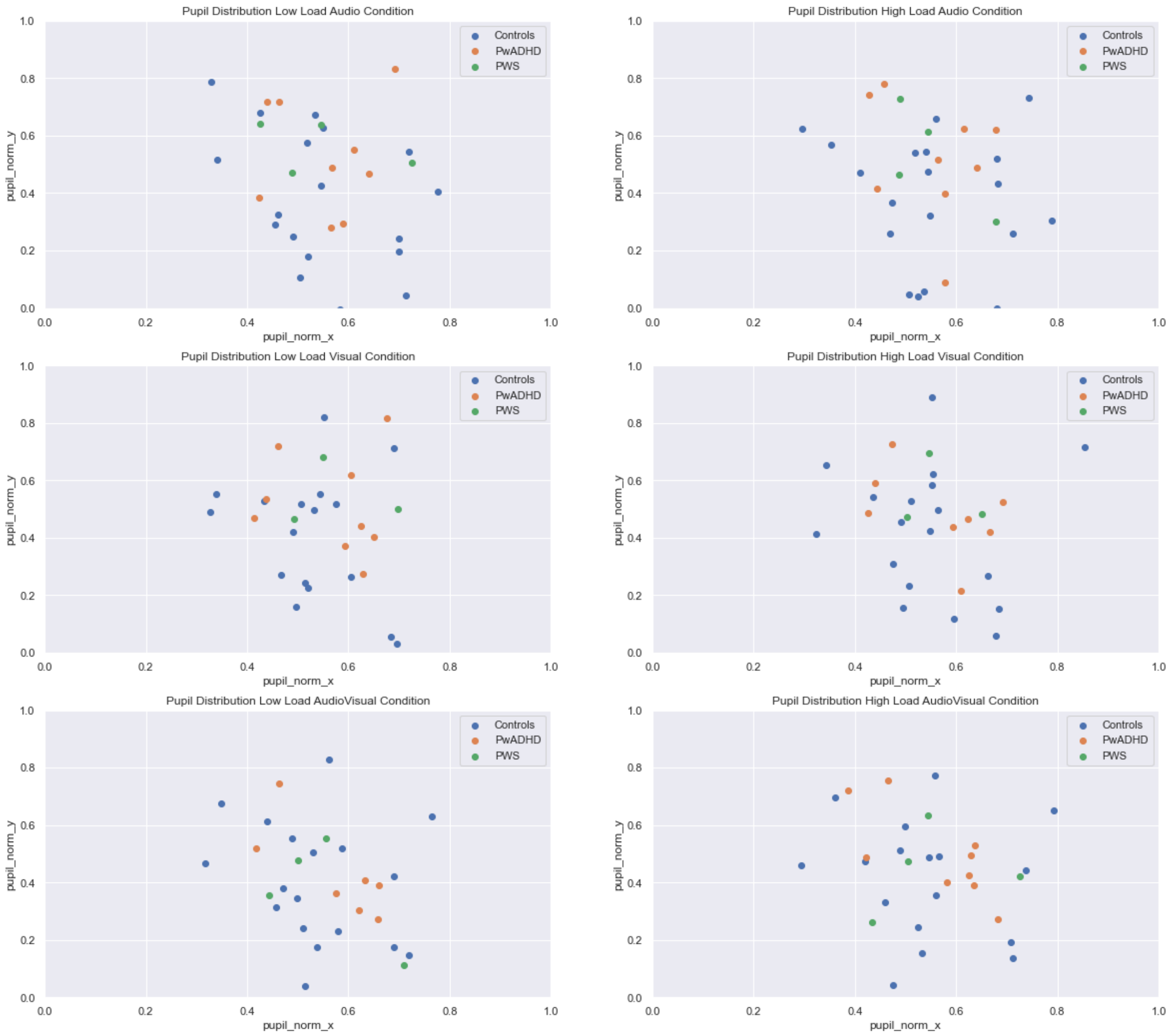


Figure A2.3

Pupil Distribution of all controls per condition and level.

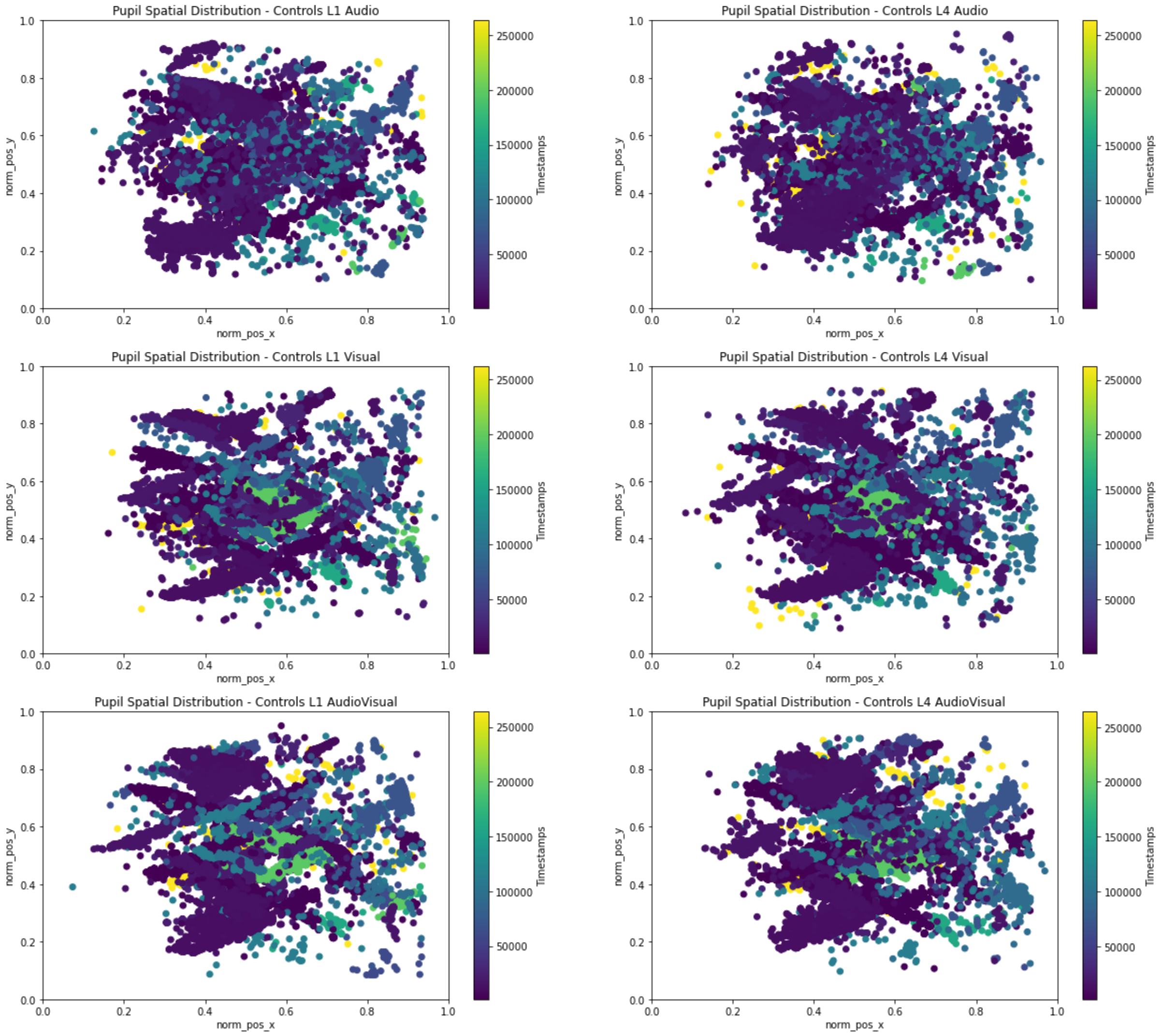


Figure A2.4

Pupil Distribution of all PWADHD per condition and level.

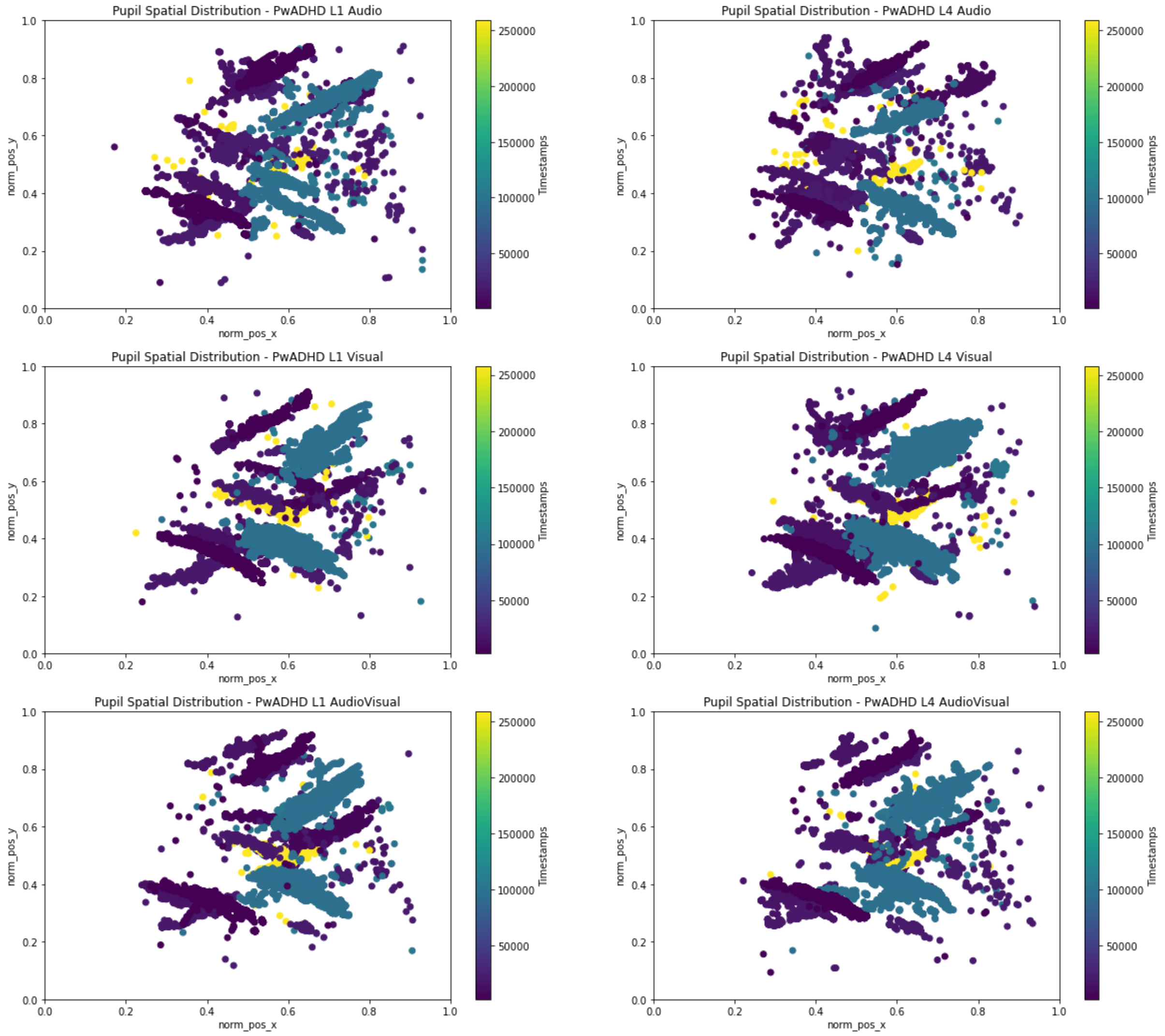
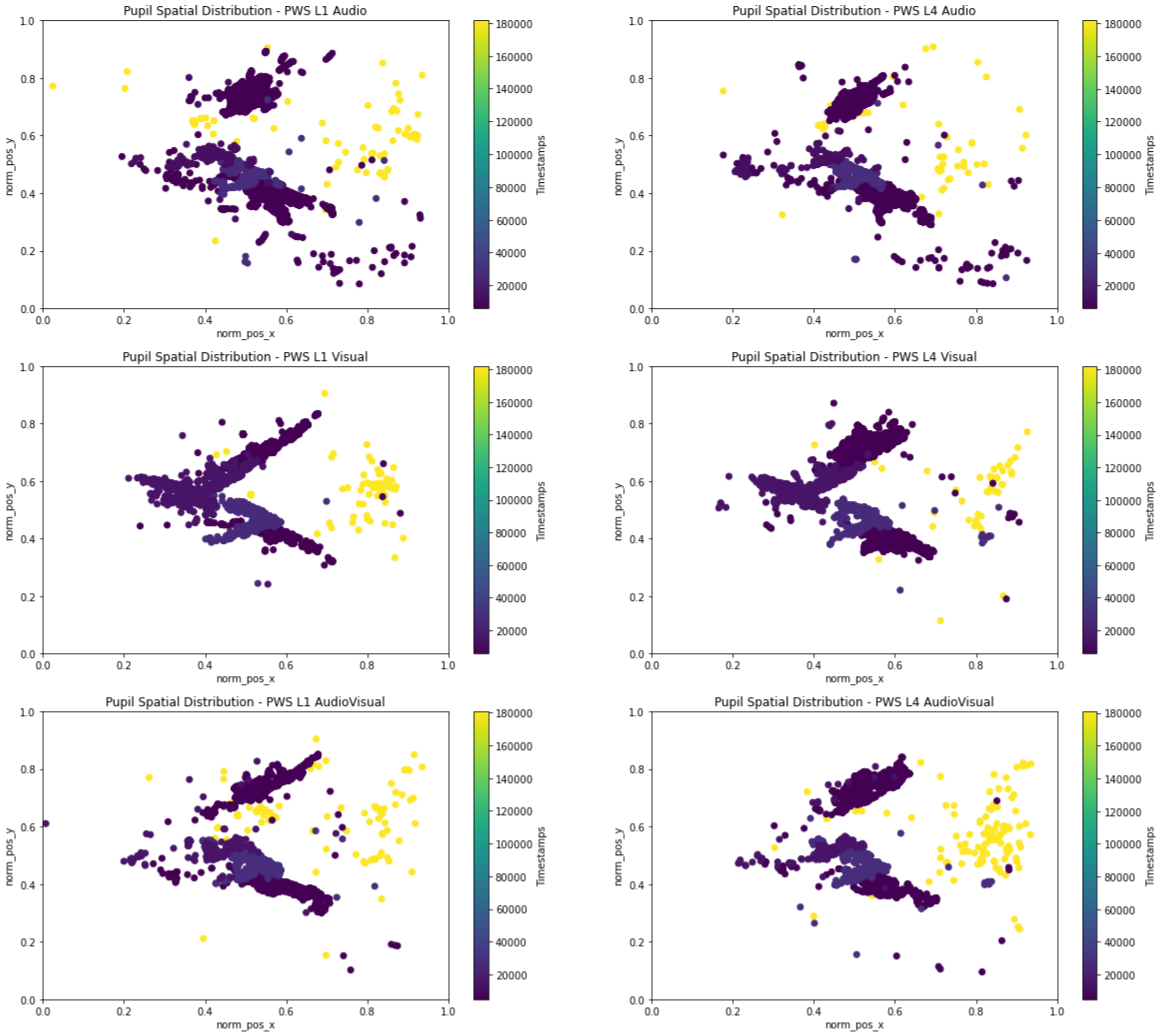


Figure A2.5

Pupil Distribution of all PWS per condition and level.



Appendix B. Chapter 3: Results for experiment 3

Results for ASRS, SSI-3 and UNWR

Table B3.1

Descriptive Statistics for ASRS, SSI-3, UNWR across groups.

	Controls			***PWADHD***			***PWS***			
	M	**SD**	**N**	**M**	**SD**	**N**	**M**	**SD**	**N**	***Omega squared***
ASRS	11.18	3.283	17	19.13	1.821	16	14.40	2.798	15	0.568
SSI-3	7.67	2.00	18	8.60	3.312	15	21.75	6.781	16	0.673
UNWR	19.61	3.883	18	15.25	2.463	16	13.44	2.658	16	0.356

Note. Omega squared represents the effect size: $\omega^2 = 0.01$ is small effect; $\omega^2 = 0.06$ is medium effect; $\omega^2 = 0.14$ is large effect.

Table B3.2

Descriptive Statistics for ASRS, SSI-3, UNWR across genders for each group.

		Females			***Males***			
		M	**SD**	**N**	**M**	**SD**	**N**	***Cohen's d***
Controls	***ASRS***	11.13	3.384	16	12.00	.	1	.
	SSI-3	7.56	2.032	16	8.50	2.121	2	0.431
	UNWR	19.69	4.062	16	19.00	2.828	2	0.161
PWADHD	***ASRS***	17.87	1.959	8	17.64	3.835	14	0.038
	SSI-3	11.57	6.579	7	13.86	9.314	14	0.137
	UNWR	16.00	1.512	8	14.57	2.472	14	0.358
PWS	***ASRS***	12.50	0.707	2	15.29	2.628	7	.
	SSI-3	16.00	4.243	2	21.25	7.106	8	.
	UNWR	11.50	3.536	2	13.00	2.976	8	.

Note. Cohen's d represents the effect size: d = 0.2 is small effect; d = 0.5 is medium effect; d = 0.8 is large effect.

Results for RT

Table B3.3

Mean and SD for RTs in controls PWADHD and PWS groups in both levels.

		Controls			***PWADHD***			***PWS***			***Omega squared***
		M	**SD**	**N**	**M**	**SD**	**N**	**M**	**SD**	**N**	
RT	***L1***	25818	9761.5	15	24196	7151.4	14	28431	10692.3	14	0.012
	L2	28185	10486.2	15	26502	9026.7	14	37106	11545.0	15	0.133

Note. RT stands for reaction time. L1 and L2 represent load levels 1 and 2. Omega squared represents the effect size: $\omega^2 = 0.01$ is small effect; $\omega^2 = 0.06$ is medium effect; $\omega^2 = 0.14$ is large effect.

Table B3.4

Mean and SD for RTs in controls PWADHD and PWS groups in both levels across genders.

		Females			***Males***			***Cohen's d***
		M	**SD**	**N**	**M**	**SD**	**N**	
Controls RT	***L1***	26336	9913	14	18564	.	1	.
	L2	29083	10266	14	15617	.	1	.
PWADHD RT	***L1***	28403	5621.6	5	21858	7077	9	0.493
	L2	27694	8932.6	5	25840	9546	9	0.099
PWS RT	***L1***	29823	3937.2	3	28051	12032	11	0.046
	L2	29352	5092.7	4	39926	12083	11	0.381

Note. RT represents reaction times. L1 and L2 stands for levels 1 and 2. Cohen's d represents the effect size: d = 0.2 is small effect; d = 0.5 is medium effect; d = 0.8 is large effect.

Appendix C. Chapter 4: Results for experiment 4

Results for ASRS, SSI-3 and UNWR

Table C4.1

Descriptive Statistics for ASRS, SSI-3, UNWR across groups.

	Controls			*PWADHD*			*PWS*			*Omega squared*
	M	**SD**	**N**	**M**	**SD**	**N**	**M**	**SD**	**N**	
ASRS	9.60	2.797	10	16.5	2.726	8	13.89	2.848	9	0.540
SSI-3	8	2.309	10	7.5	2.507	8	17.33	6.557	9	0.524
UNWR	31.7	0.675	10	26.5	1.773	8	24	3.536	9	0.615

Note. Omega squared represents the effect size: $\omega^2 = 0.01$ is small effect; $\omega^2 = 0.06$ is medium effect; $\omega^2 = 0.14$ is large effect.

Results for Fish consumed, and Total Scores achieved in the game

Table C4.2

Mean and SD for task performance across groups.

		Controls			*PWADHD*			*PWS*			*Omega squared*
		M	**SD**	**N**	**M**	**SD**	**N**	**M**	**SD**	**N**	
Scores	***FC***	423.78	132.8	9	104.71	61.808	7	105.38	119.504	8	0.516
	TS	5968	1978.9	9	3439.57	1629.7	7	1972.1	1388.6	9	0.437

Note. FC stands for fish consumed; TS stands for total score. Omega squared represents the effect size: $\omega^2 = 0.01$ is small effect; $\omega^2 = 0.06$ is medium effect; $\omega^2 = 0.14$ is large effect.

Results for physiological measures

Table C4.3

Mean and SD for oculomotor and brain activity measures.

		Controls			***PWADHD***			***PWS***			***Omega squared***
		M	**SD**	**N**	**M**	**SD**	**N**	**M**	**SD**	**N**	
Measures	***NOS***	641.8	213.3	6	743.2	165.0	7	342.1	161.1	6	0.408
	SMV	315	54.79	9	375.5	52.1	7	293.6	49.7	7	0.197
	NOF	485	174.7	7	744.7	164.8	7	336.3	178.8	6	0.326
	FD	309.2	25.9	7	322.9	37.7	8	264.9	26.6	6	0.404
	Alpha	0.060	0.038	9	0.027	0.017	7	0.120	0.046	4	0.449
	Beta	0.019	0.022	8	0.076	0.015	3	0.021	0.026	9	0.304
	Theta	0.603	0.049	8	0.473	0.046	7	0.572	0.065	9	0.393
	TBR	2.02	0.684	7	0.806	0.097	7	1.581	0.325	7	0.207

Note. NOS, SMV, NOF, FD, TBR stands for number of saccades, saccade mean velocity, number of fixations, fixation durations and theta-beta ratio respectively. Omega squared represents the effect size: $\omega^2 = 0.01$ is small effect; $\omega^2 = 0.06$ is medium effect; $\omega^2 = 0.14$ is large effect.

Appendix D. Chapter 5: Results for experiment 5

Results for ASRS, SSI-3 and UNWR

Table D5.1

Descriptive Statistics for ASRS, SSI-3, UNWR.

	Controls			***PWADHD***			***Cohen's d***
	M	**SD**	**N**	**M**	**SD**	**N**	
ASRS	10.50	2.902	14	16.00	2.179	17	1.399
SSI-3	2.07	2.868	14	8.08	4.890	13	1.049
UNWR	20.71	4.027	14	14.25	4.683	16	0.963

Note. Cohen's d represents the effect size: d = 0.2 is small effect; d = 0.5 is medium effect; d = 0.8 is large effect.

Results in behavioural data

Table D5.2

Descriptive Statistics for behavioural data in each task across groups.

		Controls			***PWADHD***			***Cohen's d***
		M	**SD**	**N**	**M**	**SD**	**N**	
Task 1	***TLV***	368091	42157	6	247844	73605	10	1.001
Task 2	***CR***	24.79	0.579	14	22.24	2.016	17	1.060
	IR	0.21	0.426	14	1.53	1.007	17	1.060
	RT	628.2	49.34	13	692.5	70.71	12	0.734
Task 3	***CR***	198.57	1.785	14	193.24	5.540	17	0.800
	IR	3.36	1.646	14	5.24	1.786	17	0.701
	RT	527.78	50.46	14	604.23	68.46	15	0.842
Task 4	***CR***	43.15	6.669	13	33.38	10.728	13	0.740
	IR	1.54	2.066	13	15.80	5.978	10	2.449
	RT	651.15	66.38	8	760.5	111.16	12	0.655
	LCD	32.18	9.282	11	17.94	9.711	17	0.877
	LID	1.71	2.091	14	6.00	3.571	17	0.920
Task 5	***CR***	40.25	8.181	12	27.86	11.5	14	0.790
	IR	2.14	2.413	14	11.20	4.638	10	1.912
	RT	750.8	80.6	10	871.34	167.45	16	0.492
	LCD	32.89	8.866	9	16.47	10.730	17	0.873
	LID	4.93	5.427	14	12.25	8.001	12	0.769
Task 7	***MP***	8.29	5.150	14	16.65	5.722	17	0.982
	TCT	343887	72331	13	423254	76958	17	0.663
Task 8	***TCT***	77442	54053	11	145651	62049	11	0.786
Task 9	***PP***	3.50	2.767	14	8.27	3.90	15	0.934
	TCT	8618	5096.6	11	18090	6305	12	1.076
Task 10	***SAT***	75.75	8.355	14	84.88	6.392	17	0.800
	TCT	225877	55616.9	13	153279	52182.3	16	0.862

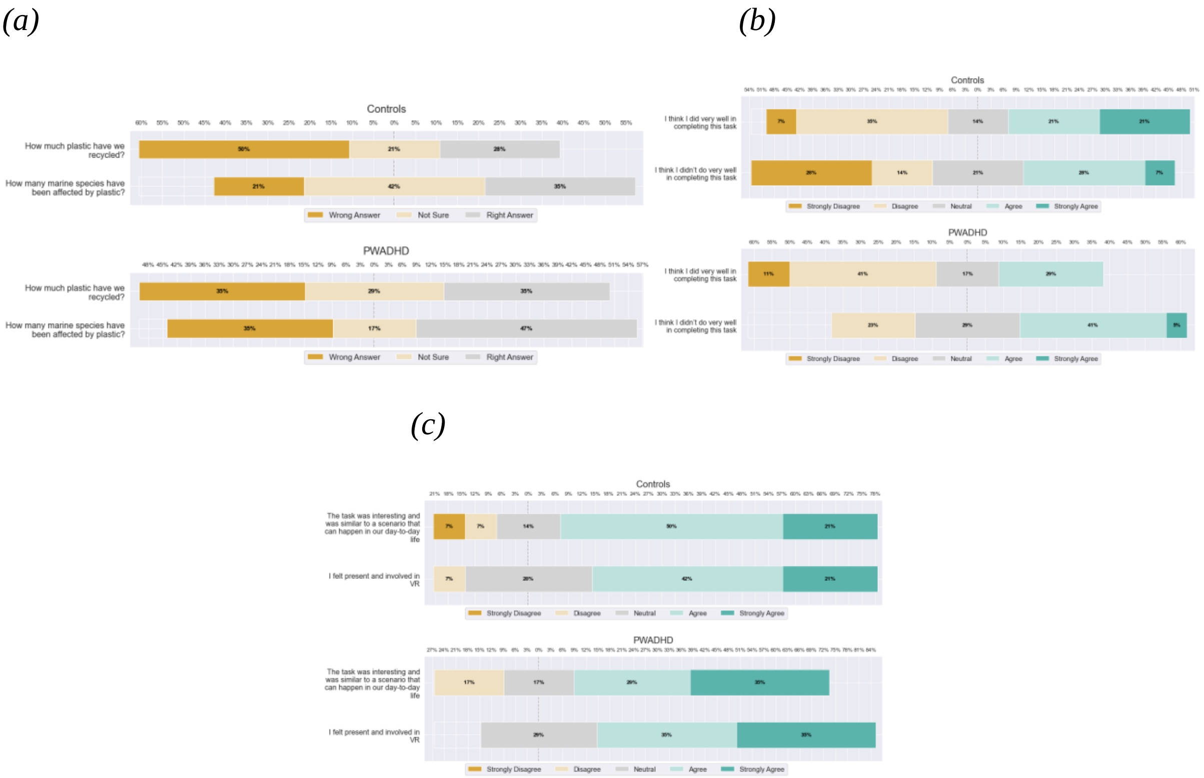
Note. TLV stands for time looked at tv; CR, IR, RT stands for correct responses, incorrect responses and reaction time respectively; LCD, LID stand for looked at correct direction and looked at incorrect direction respectively; MP, PP, TCT and SAT represent map pressed, phone pressed, time to complete the task and scores achieved in the task. Cohen's d represents the effect size: d = 0.2 is small effect; d = 0.5 is medium effect; d = 0.8 is large effect.

Results for questionnaires

Task 1

Figure D5.1

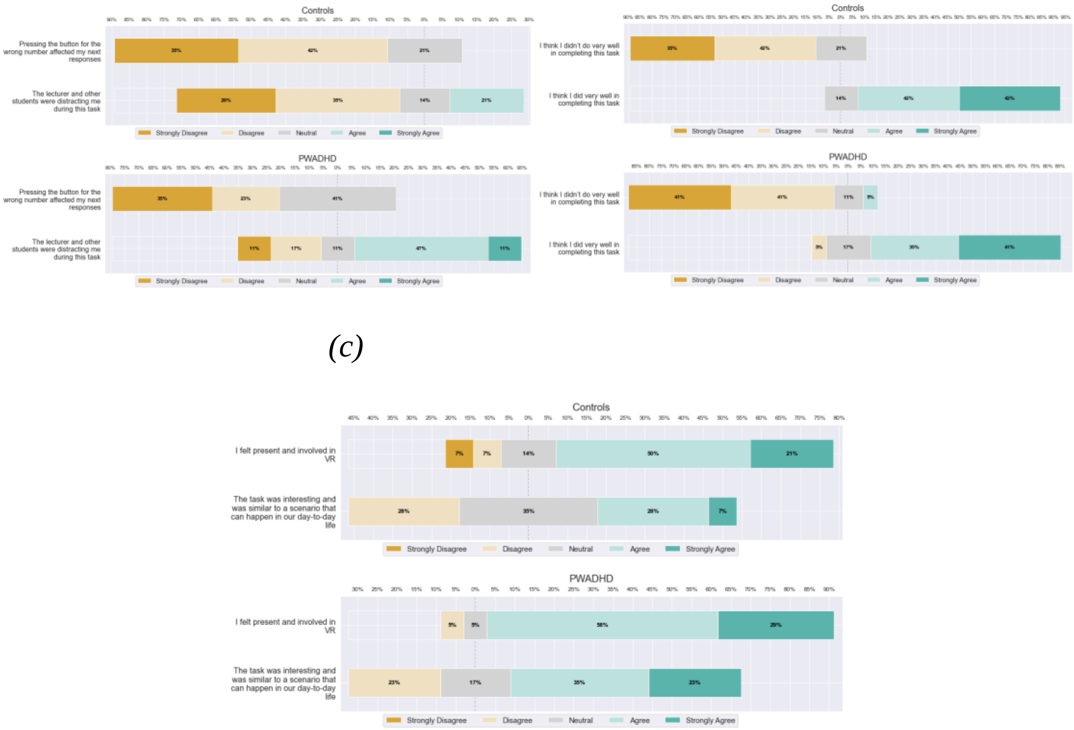
Results from Likert scale questionnaire on two questions asked about the task. Panel a represent answers on the task, panel b shows answers on confidence to complete the task, in panel c are answers for the VR experience. Top row represents answers from controls, bottom row represents answers from PWADHD on each a ,b, c panels. Right answers, not sure and wrong answers are visualised with grey, light orange and orange respectively. Strongly agree is shown with colour blue, agree is in colour light blue, neutral is represented in grey, disagree is shown with colour light orange and strongly disagree is presented in colour orange.



Task 2

Figure D5.2

Likert scale questionnaire results on two questions asked about the task (panel a), two questions on confidence to complete the task (panel b) and two questions on VR experience (panel c). Top row are answers from controls, bottom row shows answers from PWADHD on each panel. Strongly agree is shown with colour blue, agree is in colour light blue, neutral is represented in grey, disagree is shown with colour light orange and strongly disagree is presented in colour orange.



(a)

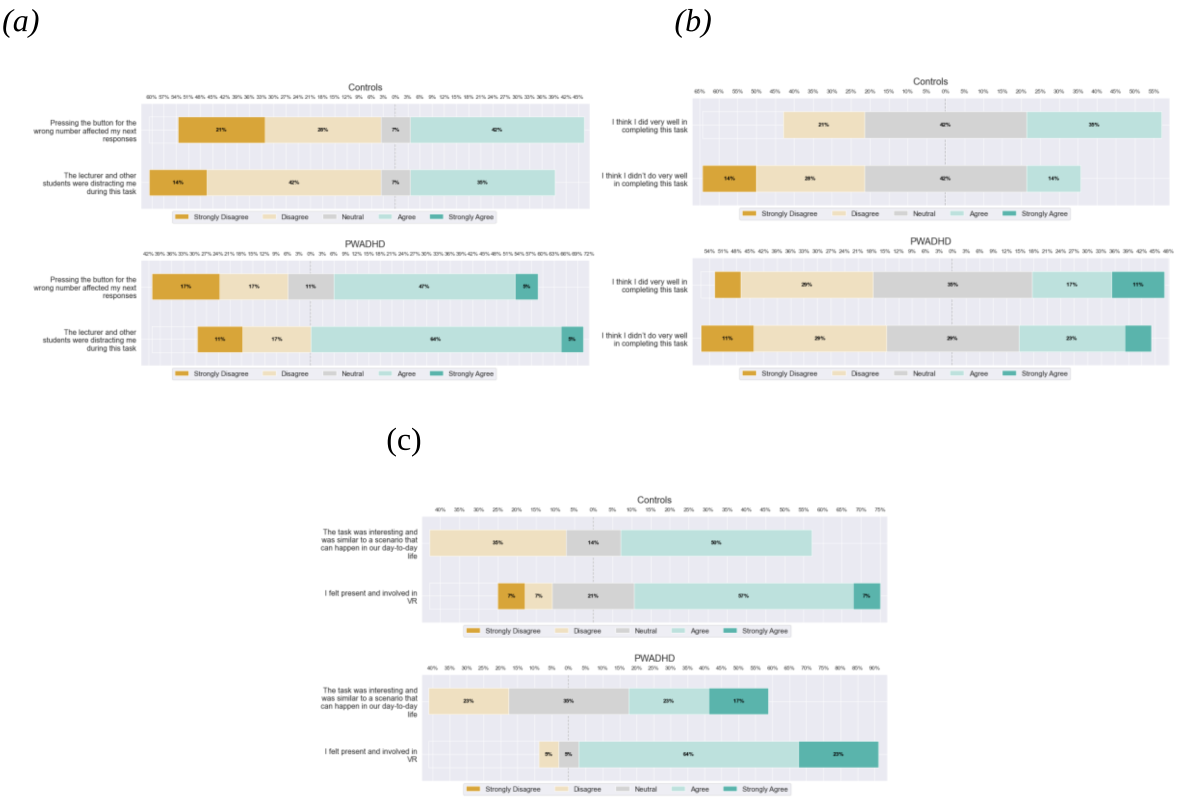
(b)

(c)

Task 3

Figure D5.3

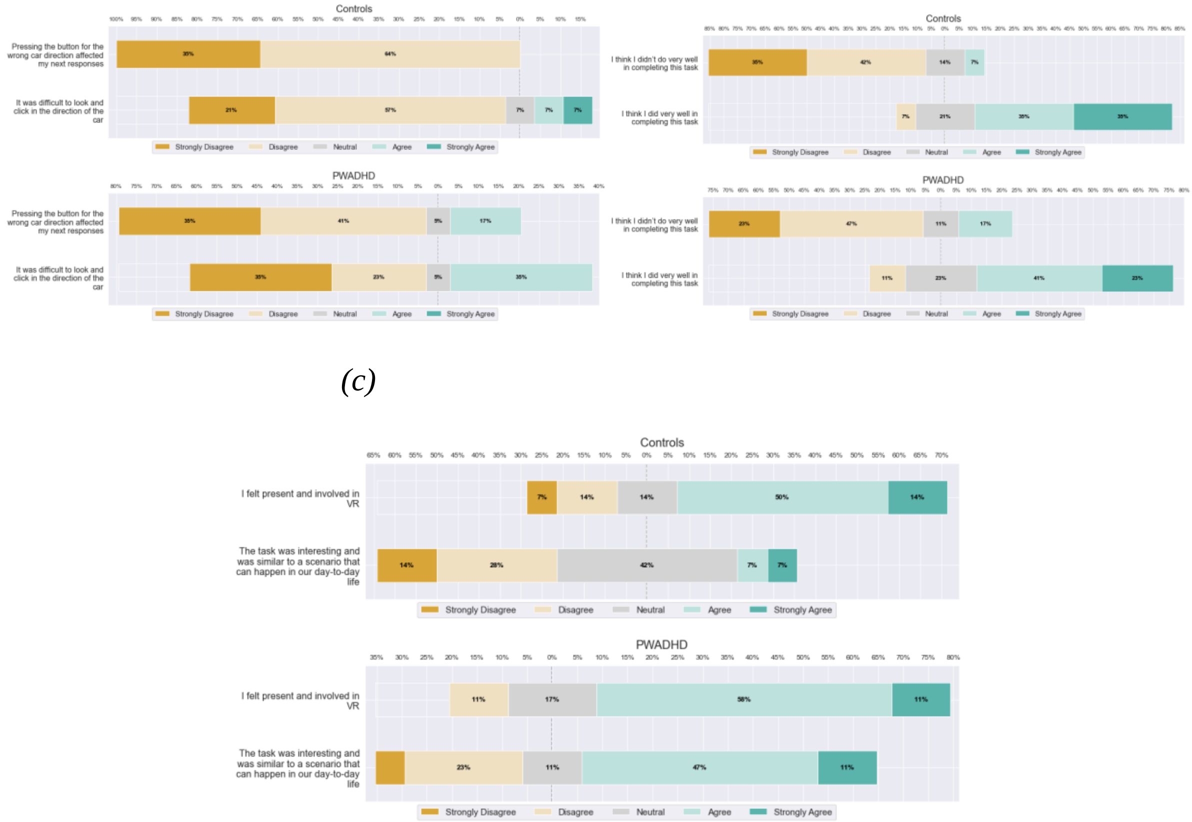
Likert scale questionnaire results on two questions asked about the task (panel a), two questions on confidence to complete the task (panel b) and two questions on VR experience (panel c). Top row are answers from controls, bottom row shows answers from PWADHD on each panel. Strongly agree is shown with colour blue, agree is in colour light blue, neutral is represented in grey, disagree is shown with colour light orange and strongly disagree is presented in colour orange.



Task 4

Figure 5.4

Likert scale questionnaire results on two questions asked about the task (panel a), two questions on confidence to complete the task (panel b) and two questions on VR experience (panel c). Top row are answers from controls, bottom row shows answers from PWADHD on each panel. Strongly agree is shown with colour blue, agree is in colour light blue, neutral is represented in grey, disagree is shown with colour light orange and strongly disagree is presented in colour orange.



(a)

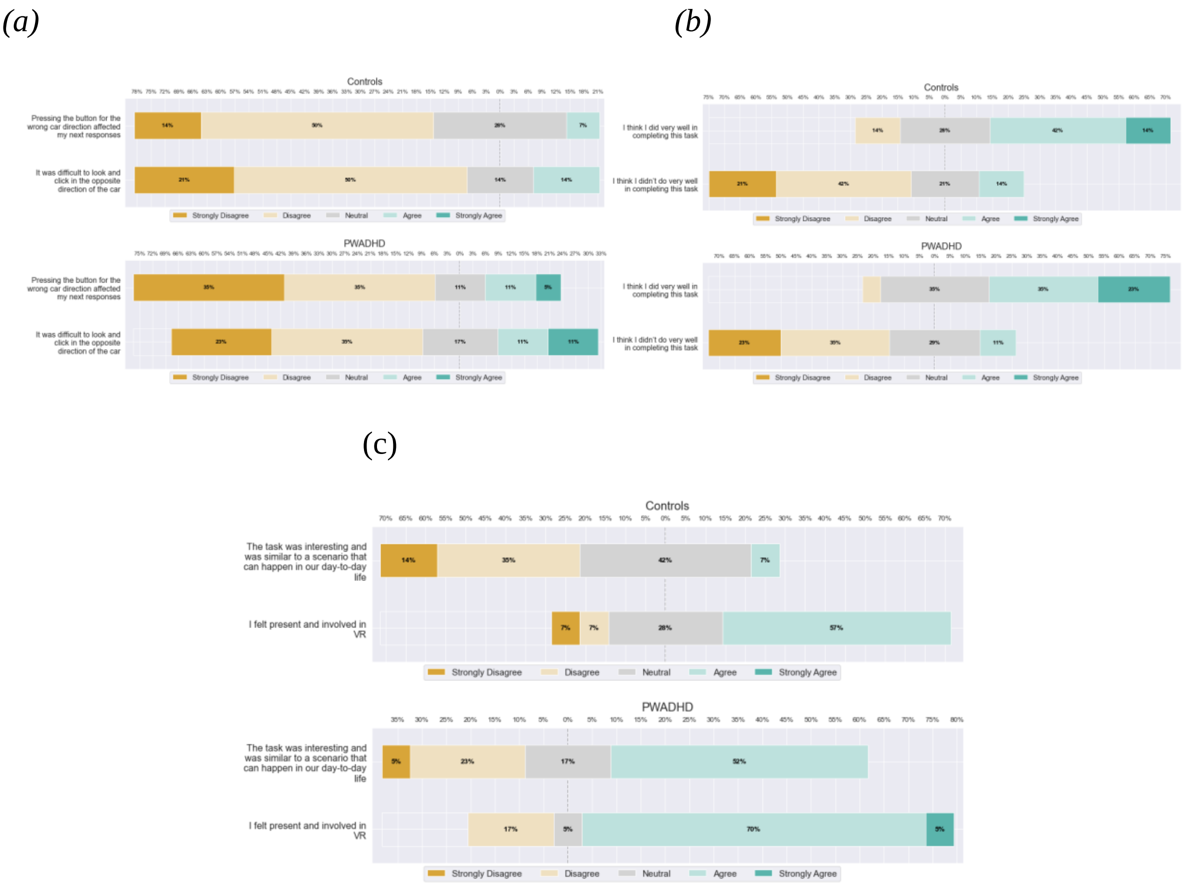
(b)

(c)

Task 5

Figure D5.5

Likert scale questionnaire results on two questions asked about the task (panel a), two questions on confidence to complete the task (panel b) and two questions on VR experience (panel c). Top row are answers from controls, bottom row shows answers from PWADHD on each panel. Strongly agree is shown with colour blue, agree is in colour light blue, neutral is represented in grey, disagree is shown with colour light orange and strongly disagree is presented in colour orange.


(a)

(b)

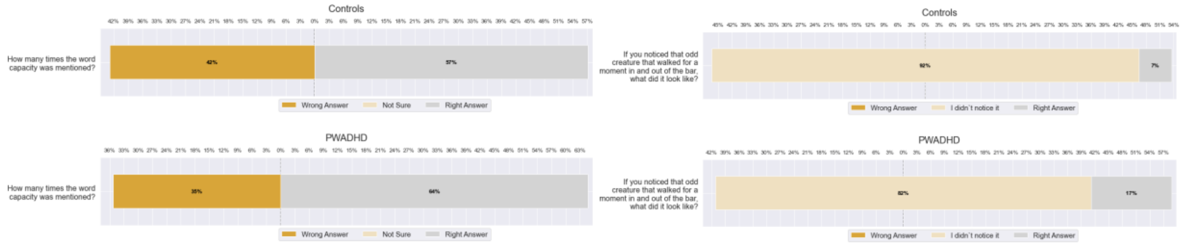
(c)

Task 6

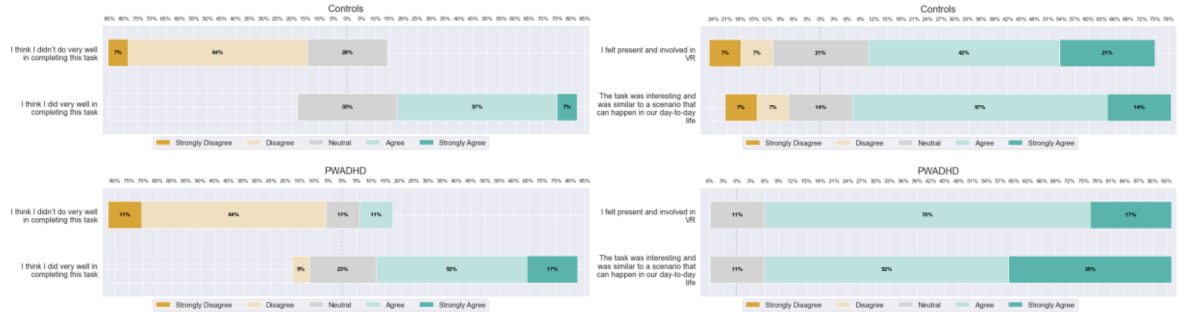
Figure D5.6

Results from Likert scale questionnaire on two questions asked about the task. Panel a represent answers on the task, panel b shows answers on confidence to complete the task, in panel c are answers for the VR experience. Top row represents answers from controls, bottom row represents answers from PWADHD on each a ,b, c panels. Right answers, not sure and wrong answers are visualised with grey, light orange and orange respectively. Strongly agree is shown with colour blue, agree is in colour light blue, neutral is represented in grey, disagree is shown with colour light orange and strongly disagree is presented in colour orange.

(a)



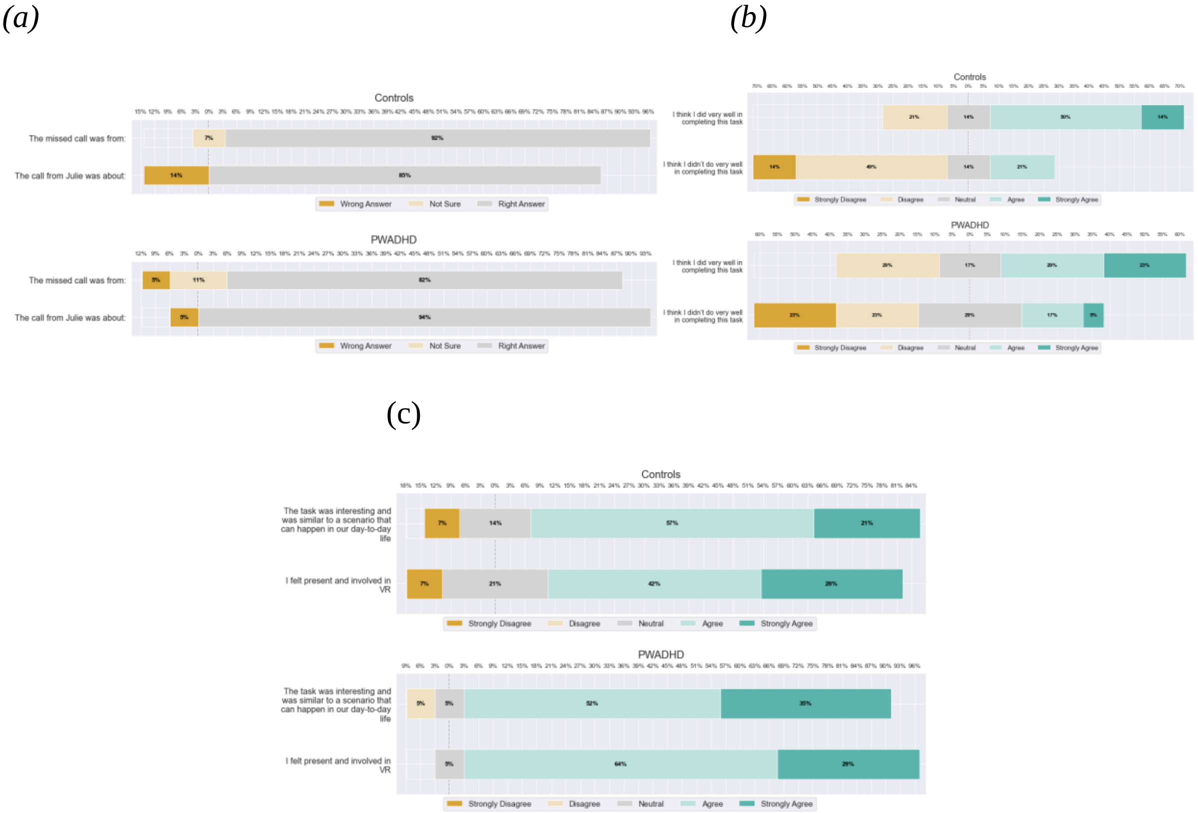
(b) *(c)*



Task 7

Figure D5.7

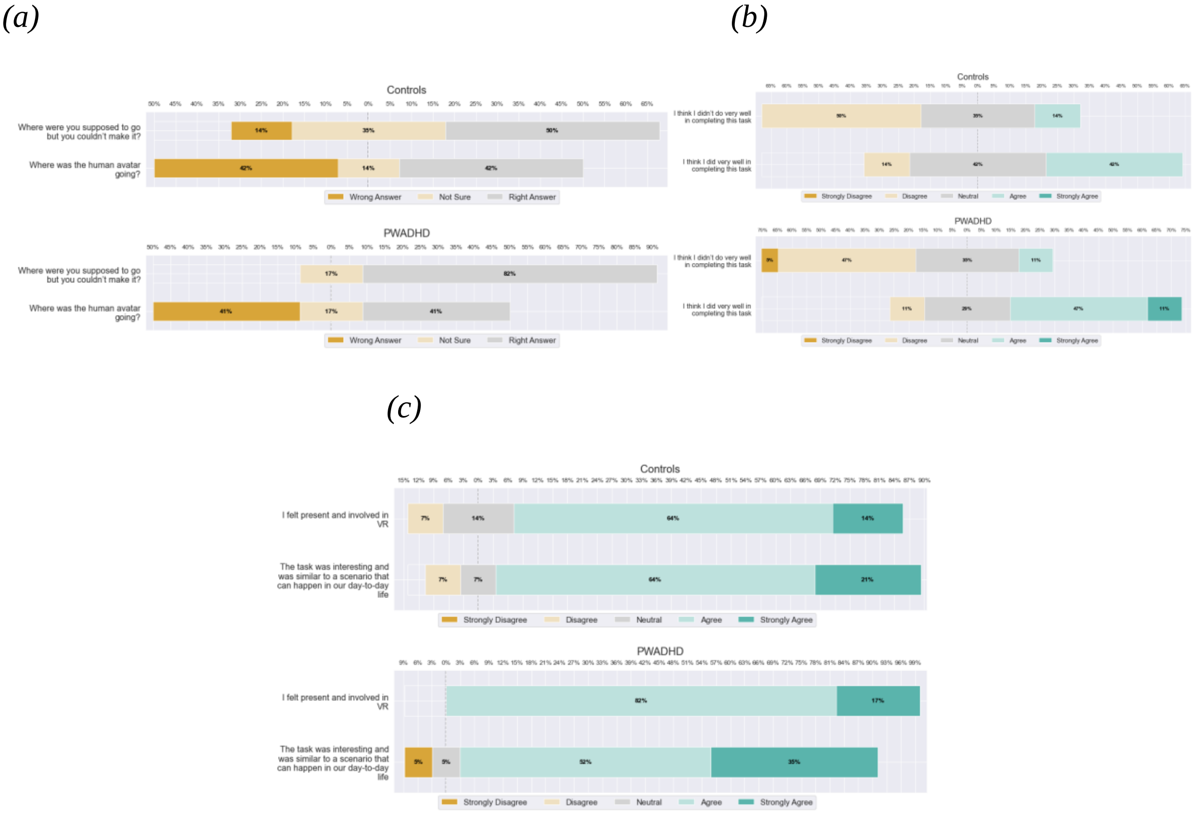
Likert scale questionnaire results on two questions asked about the task (panel a), answers on two questions about confidence in task (panel b) and answers on two questions about VR experience (panel c). Controls shown in top row and PWADHD shown in bottom row in each panel. Strongly agree is shown with colour blue, agree is in colour light blue, neutral is represented in grey, disagree is shown with colour light orange and strongly disagree is presented in colour orange.



Task 8

Figure D5.8

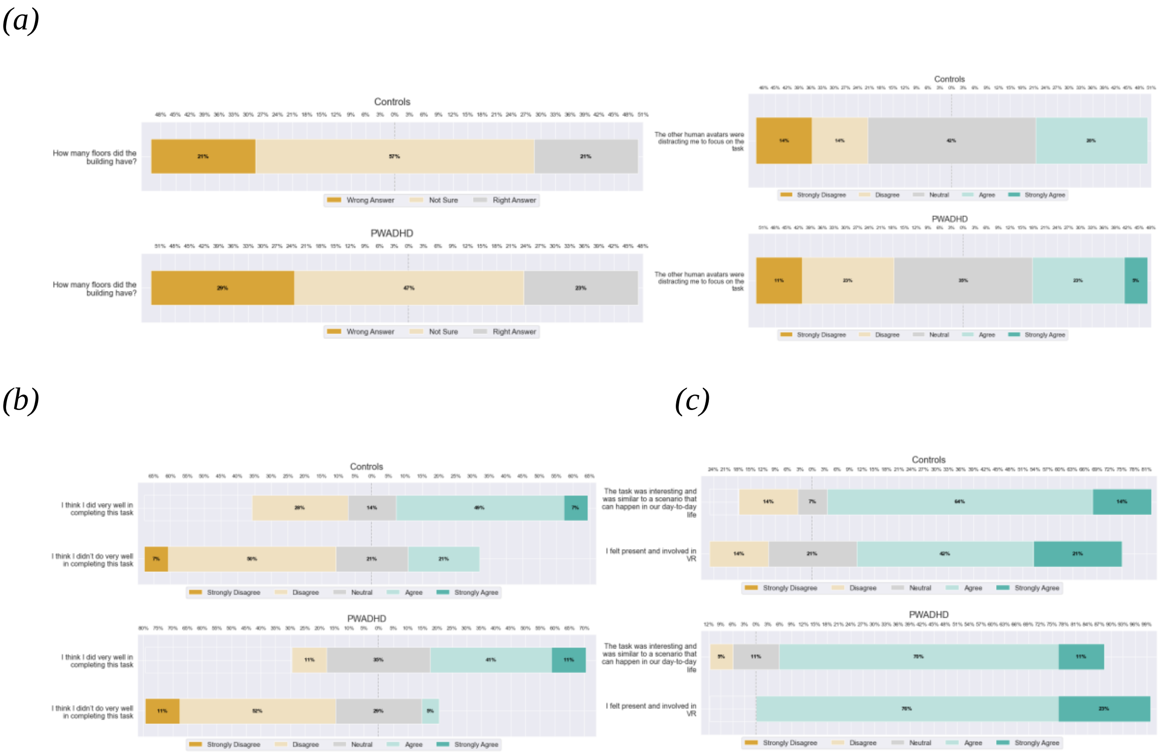
Results from Likert scale questionnaire on two questions asked about the task. Panel a represent answers on the task, panel b shows answers on confidence to complete the task, in panel c are answers for the VR experience. Top row represents answers from controls, bottom row represents answers from PWADHD on each a ,b, c panels. Right answers, not sure and wrong answers are visualised with grey, light orange and orange respectively. Strongly agree is shown with colour blue, agree is in colour light blue, neutral is represented in grey, disagree is shown with colour light orange and strongly disagree is presented in colour orange.



Task 9

Figure D5.9

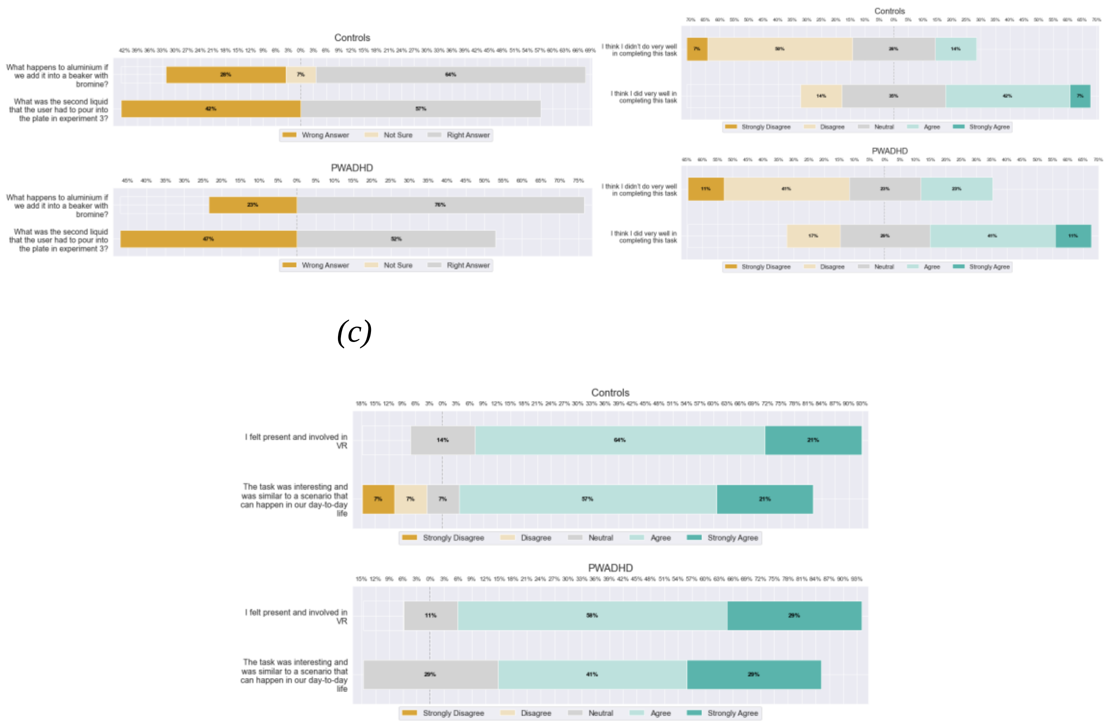
Results from Likert scale questionnaire on two questions asked about the task. Panel a represent answers on the task, panel b shows answers on confidence to complete the task, in panel c are answers for the VR experience. Top row represents answers from controls, bottom row represents answers from PWADHD on each a ,b, c panels. Right answers, not sure and wrong answers are visualised with grey, light orange and orange respectively. Strongly agree is shown with colour blue, agree is in colour light blue, neutral is represented in grey, disagree is shown with colour light orange and strongly disagree is presented in colour orange.



Task 10

Figure D5.10

Results from Likert scale questionnaire on two questions asked about the task. Panel a represent answers on the task, panel b shows answers on confidence to complete the task, in panel c are answers for the VR experience. Top row represents answers from controls, bottom row represents answers from PWADHD on each a ,b, c panels. Right answers, not sure and wrong answers are visualised with grey, light orange and orange respectively. Strongly agree is shown with colour blue, agree is in colour light blue, neutral is represented in grey, disagree is shown with colour light orange and strongly disagree is presented in colour orange.



(a)

(b)

(c)

Appendix E. Chapter 6: Results for experiment 6

Results for eye measures

Table E6.1

Mean and SD for oculomotor and brain activity measures.

		Controls			***PWADHD***			
		M	**SD**	**N**	**M**	**SD**	**N**	***Cohen's d***
Task1	***NOS***	46.11	14.9	9	60.14	17.96	14	0.480
	SMV	134.3	5.499	11	128.75	5.957	14	0.602
	NOF	585.7	128.4	8	371.69	245.98	16	0.518
	FD	145.8	16.47	10	125.581	13.654	15	0.804
	Blinks	30.69	23.36	13	46.83	25.51	12	0.457
	PD	2.10	0.815	14	3.05	0.799	13	0.815
Task2	***NOS***	62.89	14.786	9	47.5	15.716	12	0.609
	SMV	124.73	3.859	14	109.566	12.2976	11	1.271
	NOF	606.8	165.3	10	397.93	200.17	14	0.674
	FD	136.57	12.99	13	122.44	10.57	11	0.836
	Blinks	148.29	43.319	14	94.57	41.430	14	0.861
	PD	2.71	1.1693	13	3.77	1.37	12	0.577
Task3	***NOS***	59.31	24.858	13	35.29	23.375	14	0.661
	SMV	127.80	6.65	13	117.09	10.03	11	0.906
	NOF	603.6	189.009	11	322.25	206.298	12	0.929
	FD	141.77	12.882	13	128.961	12.388	11	0.715
	Blinks	39.15	35.407	13	78.00	45.459	12	0.662
	PD	2.41	0.886	13	3.477	0.9835	10	0.831
Task4	***NOS***	29.00	17.544	11	56.82	33.39	17	0.577
	SMV	130.74	4.68	13	123.83	5.309	15	0.893
	NOF	230.6	142.14	10	510.0	273.9	15	0.711
	FD	123.43	6.881	9	110.5	6.18	16	1.108
	Blinks	24.00	8.396	13	36.87	14.947	15	0.677
	PD	1.784	0.421	13	2.55	0.6981	15	0.849

		Controls			***PWADHD***			
		M	**SD**	**N**	**M**	**SD**	**N**	***Cohen's d***
Task5	***NOS***	22.20	14.498	10	49.56	28.486	16	0.652
	SMV	132.83	6.81	11	126.51	6.272	14	0.607
	NOF	236.18	148.9	11	508.77	252.892	13	0.822
	FD	118.18	8.14	12	109.15	7.766	17	0.693
	Blinks	25.30	9.346	10	43.21	16.409	14	0.773
	PD	1.5	0.325	10	2.44	0.477	14	1.344
Task6	***NOS***	28.80	7.208	10	14.63	11.266	16	0.823
	SMV	128.15	5.39	14	120.97	6.09	17	0.798
	NOF	59.73	62.626	11	160.13	72.56	16	0.876
	FD	115.47	10.623	10	135.9	11.63	16	1.047
	Blinks	39.92	19.584	12	19.69	16.97	13	0.730
	PD	2.67	0.81	14	1.819	0.959	17	0.611
Task7	***NOS***	26.90	11.497	10	42.88	16.998	16	0.608
	SMV	132.7	5.336	10	125.65	6.80	15	0.663
	NOF	530.30	153.024	10	325.73	175.4	15	0.722
	FD	118.25	6.81	10	107.93	5.21	16	1.016
	Blinks	42.90	18.254	10	94.06	42.804	16	0.828
	PD	1.387	0.311	12	2.21	0.62	16	0.995
Task8	***NOS***	22.70	8.832	10	12.25	8.896	16	0.680
	SMV	127.2	11.11	13	105.64	19.17	15	0.878
	NOF	197.0	77.2	11	83.86	76.301	14	0.922
	FD	131.97	9.0	12	115.43	13.38	16	0.874
	Blinks	86.00	34.00	9	31.14	31.52	14	0.974
	PD	2.5	0.937	13	1.61	0.788	16	0.662
Task9	***NOS***	15.50	3.896	12	9.53	5.293	17	0.761
	SMV	115.82	5.39	13	125.81	6.657	16	1.040
	NOF	128.31	41.421	13	76.47	34.05	17	0.869
	FD	120.5	6.50	14	113.18	7.59	17	0.661
	Blinks	10.31	6.626	13	20.94	9.297	17	0.806
	PD	3.2	1.10	12	2.03	1.10	17	0.647

		Controls			***PWADHD***			
		M	**SD**	**N**	**M**	**SD**	**N**	***Cohen's d***
Task10	***NOS***	37.64	15.360	14	21.29	12.39	17	0.762
	SMV	127.67	5.63	13	119.31	5.43	17	0.949
	NOF	422.38	166.21	13	215.13	130.139	16	0.898
	FD	122.80	9.12	14	113.21	6.77	17	0.779
	Blinks	18.08	12.553	13	34.88	16.989	17	0.690
	PD	3.4	1.07	13	1.79	0.872	17	1.049

Note. NOS, SMV, NOF, FD, PD, TBR stands for number of saccades, saccade mean velocity, number of fixations, fixation durations, pupil diameter and theta-beta ratio respectively. Cohen's d represents the effect size: d = 0.2 is small effect; d = 0.5 is medium effect; d = 0.8 is large effect.

Task 1

Results for oculomotor measures

Figure E6.1

Heatmap generated from fixations for controls (top row) and PWADHD (bottom row) in task 1.

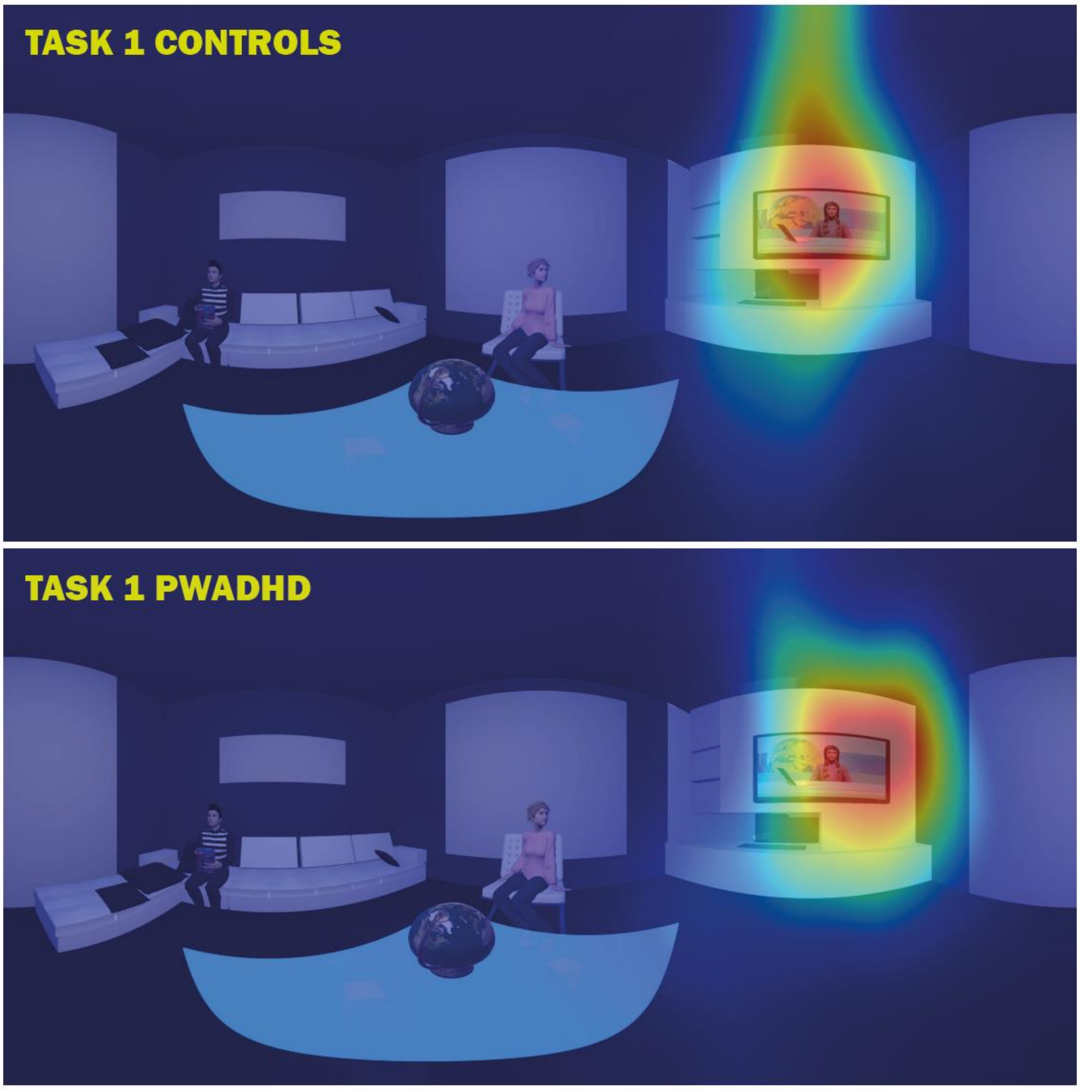


Figure E6.2

Mean pupil distributions for controls and PWADHD in task 1 (controls shown in blue, PWADHD visualised in orange).

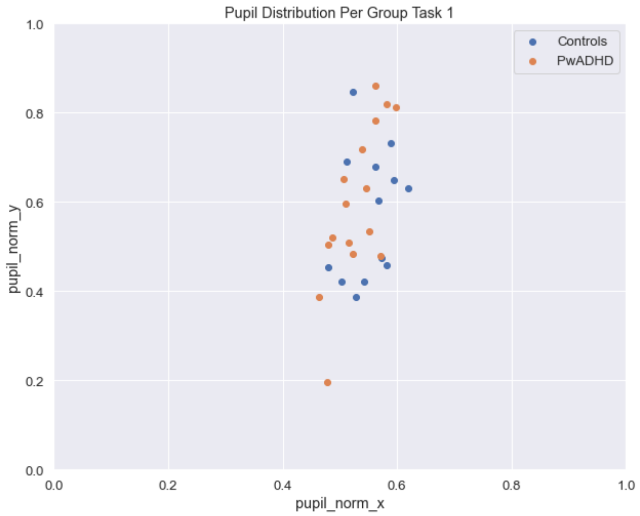


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Figure E6.3

Pupil spatial distributions for controls and PWADHD in task 1 (controls in the left; PWADHD in the right).

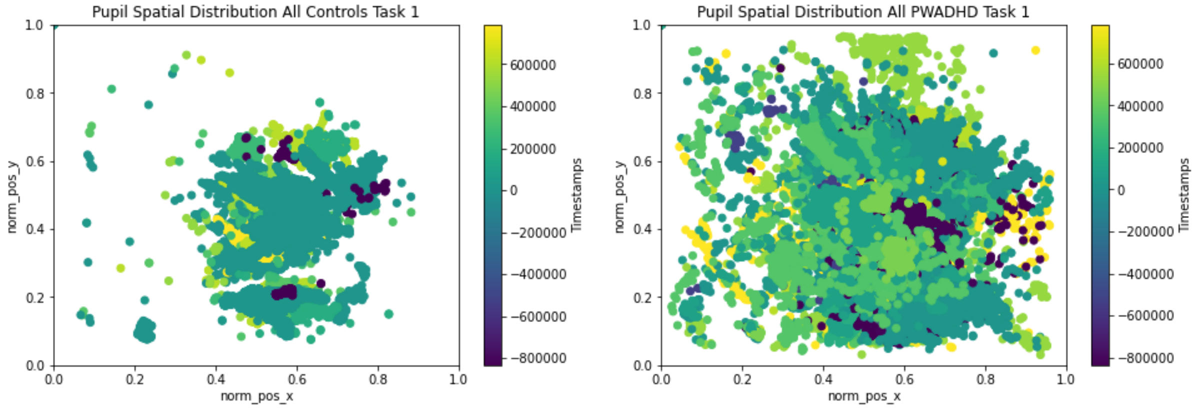


Figure E6.4

Saccades generated from fixations for controls and PWADHD in task 1 (controls in the left; PWADHD in the right).

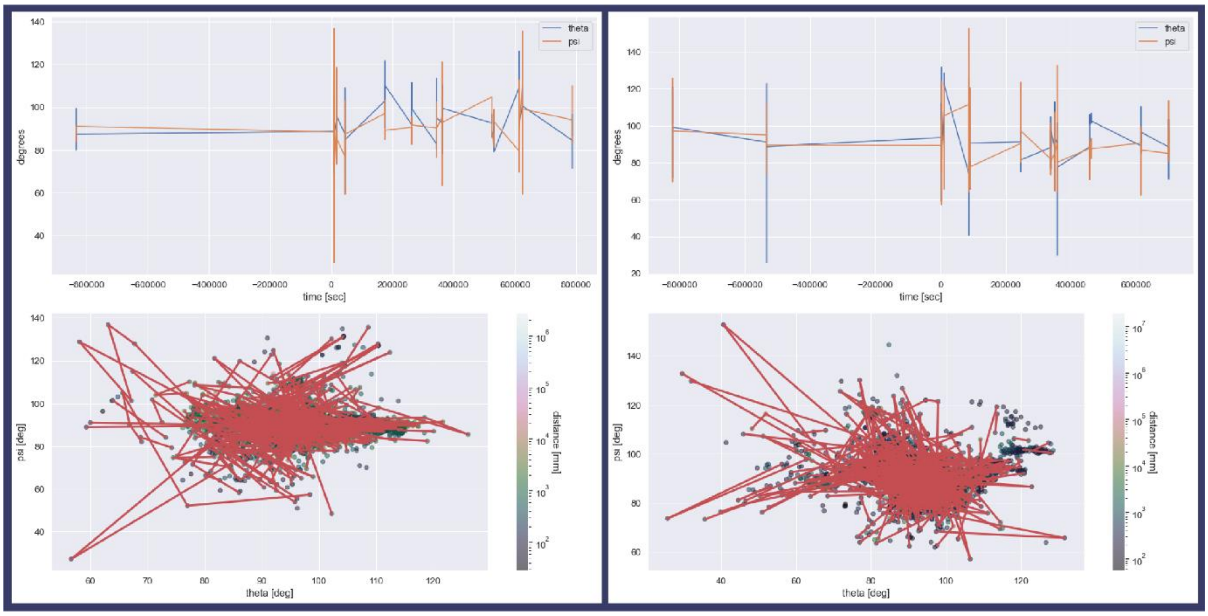
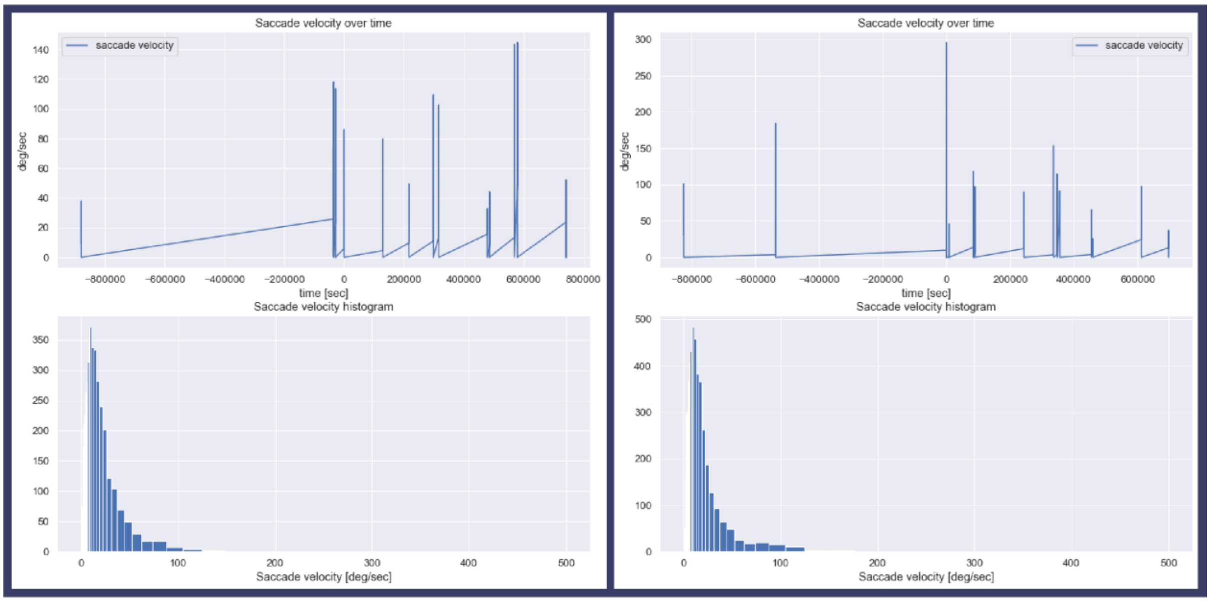


Figure E6.5

Saccade velocities generated from fixations for controls and PWADHD in task 1 (controls in the left; PWADHD in the right).



Task 2

Results for oculomotor measures

Figure E6.6

Task 2 heatmap generated from fixations for controls (top row) and PWADHD (bottom row).

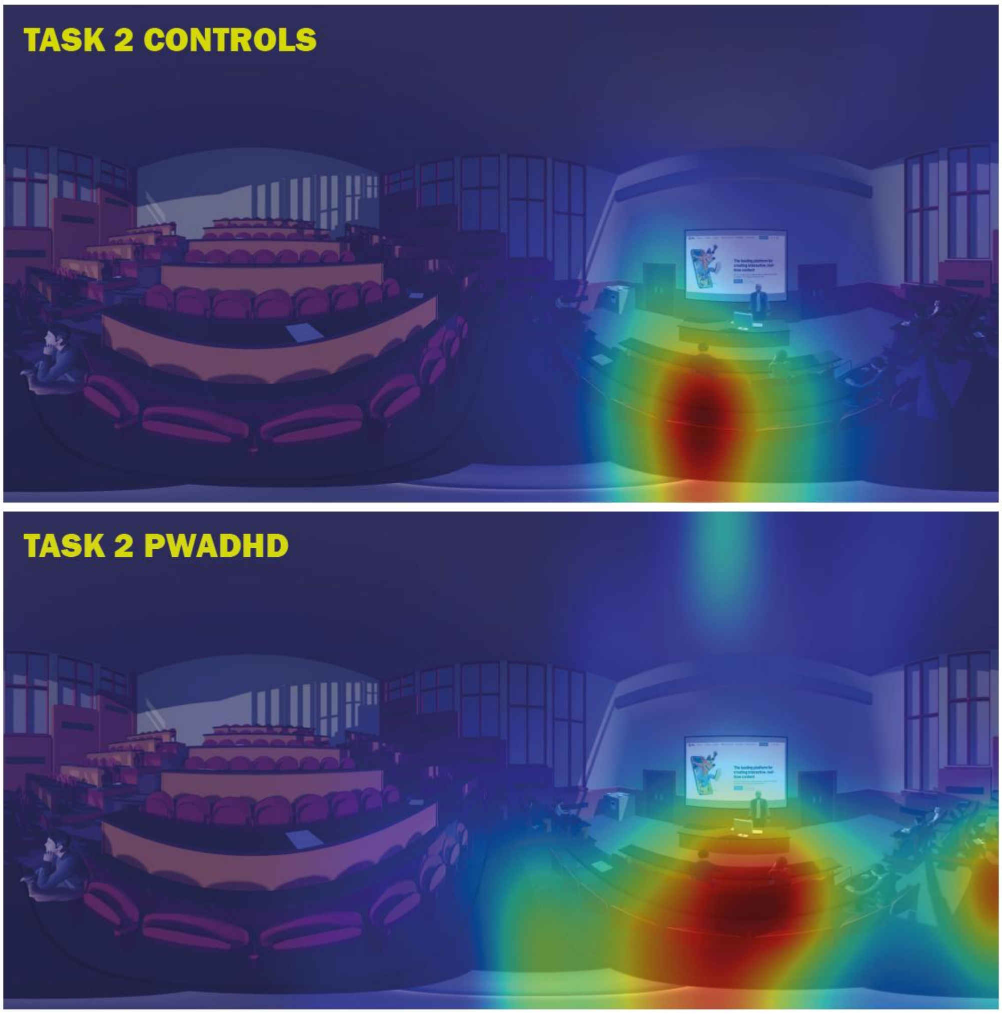


Figure E6.7

Mean pupil distributions for controls and PWADHD in task 2 (controls shown in blue, PWADHD visualised in orange).

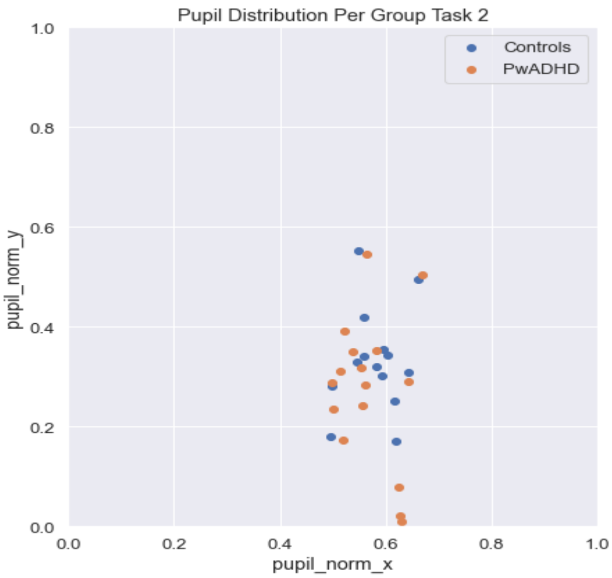


Figure E6.8

Spatial distributions between groups in task 2 (controls in the left; PWADHD in the right).

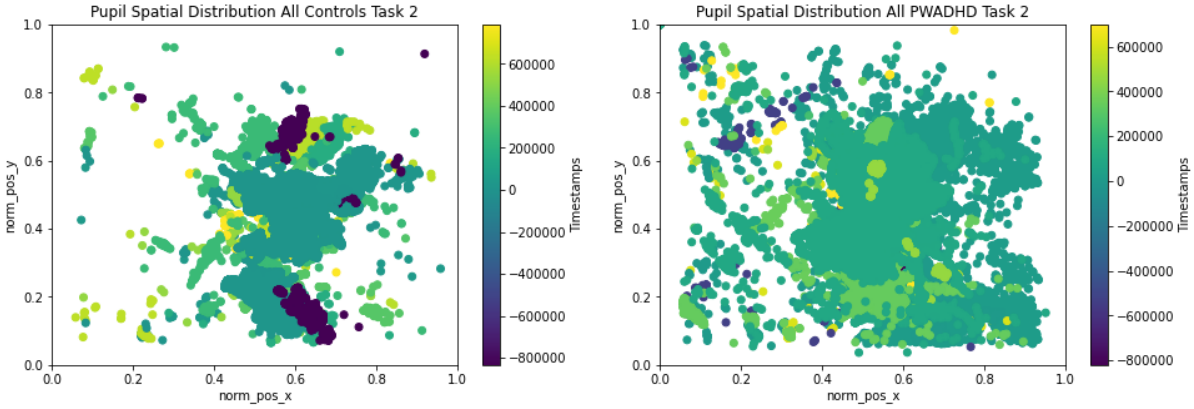


Figure E6.9

Saccades generated for groups in task 2 (controls in the left; PWADHD in the right).

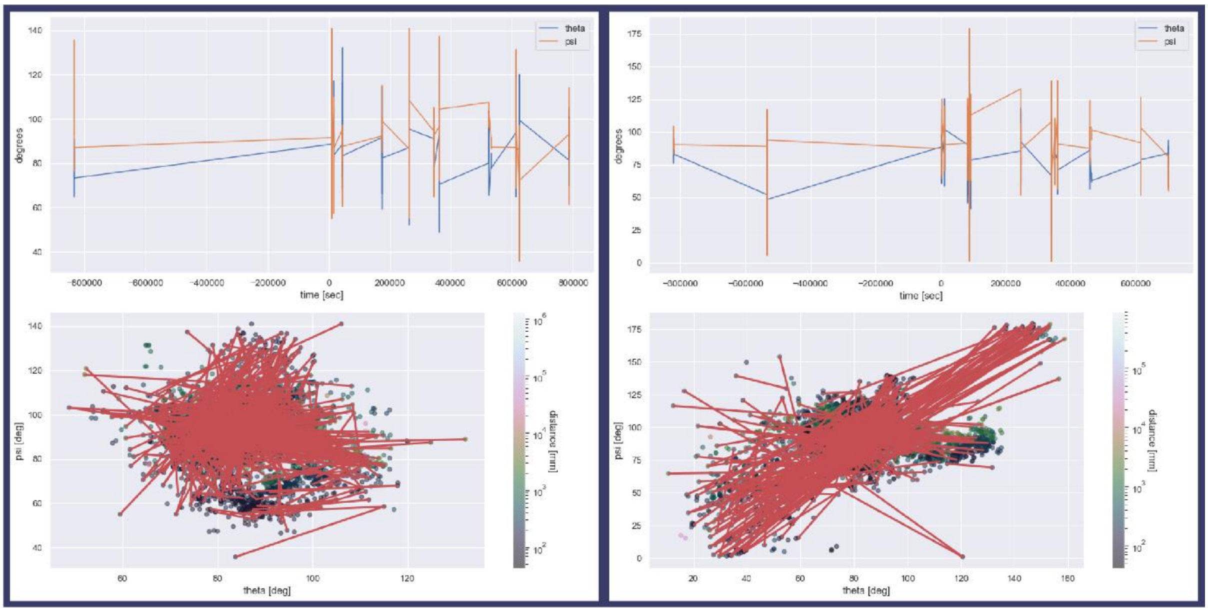
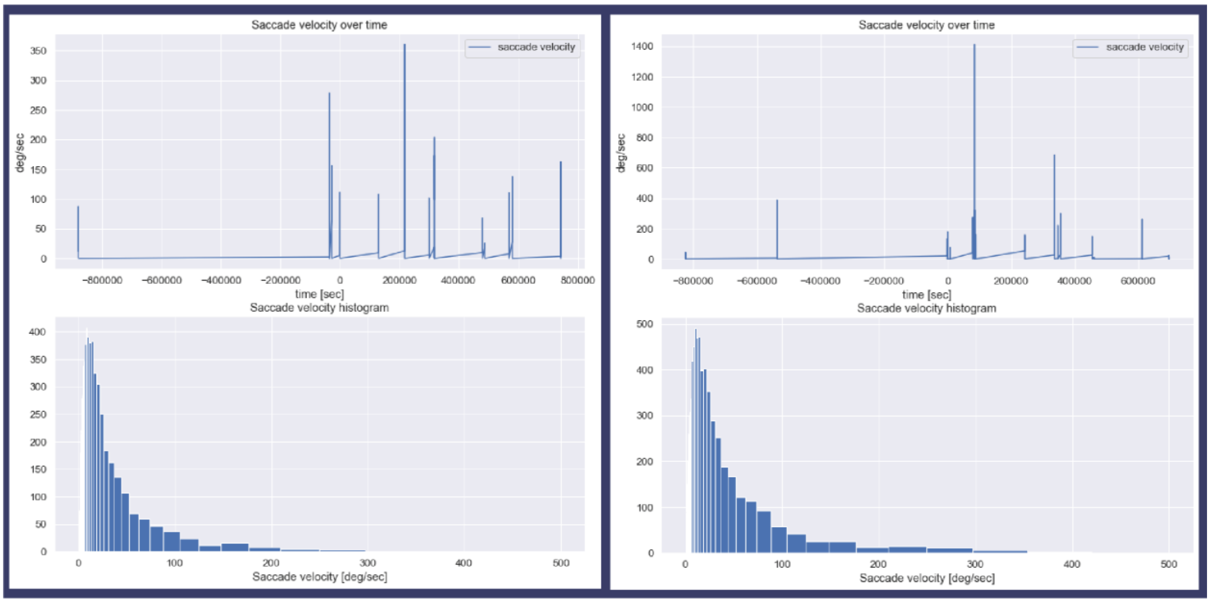


Figure E6.10

SMVs generated from fixations for controls and PWADHD in task 2 (controls in the left; PWADHD in the right).



Task 3

Results for oculomotor measures

Figure E6.11

Task 3 heatmap generated from fixations for controls (top row) and PWADHD (bottom row).

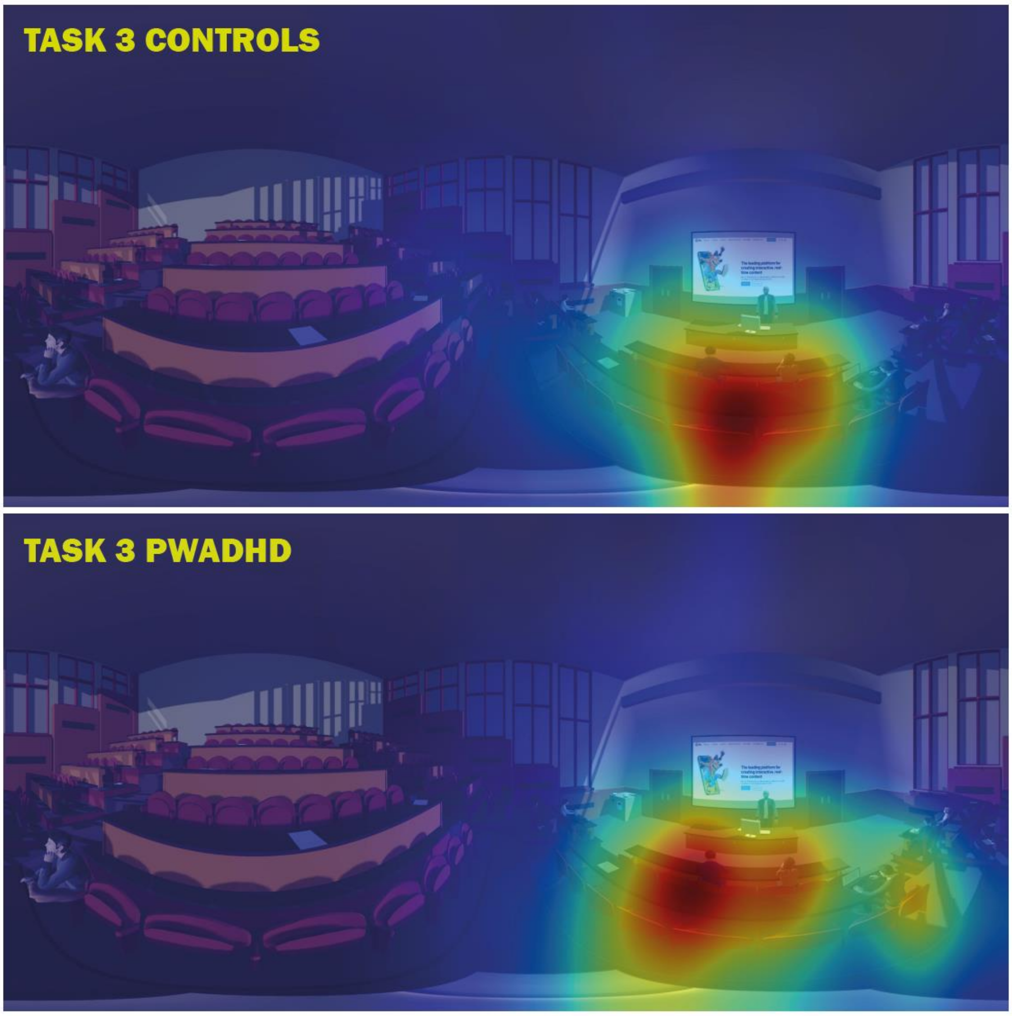


Figure E6.12

Mean pupil distributions for controls and PWADHD in task 3 (controls shown in blue, PWADHD visualised in orange).

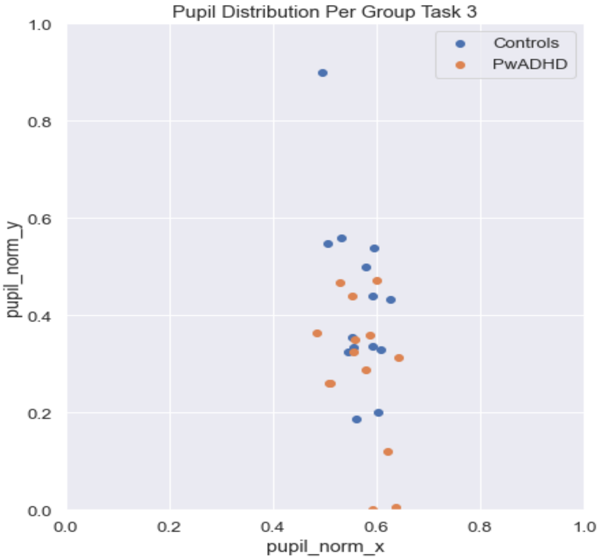


Figure E6.13

Spatial distributions between groups in task 3 (controls in the left; PWADHD in the right).

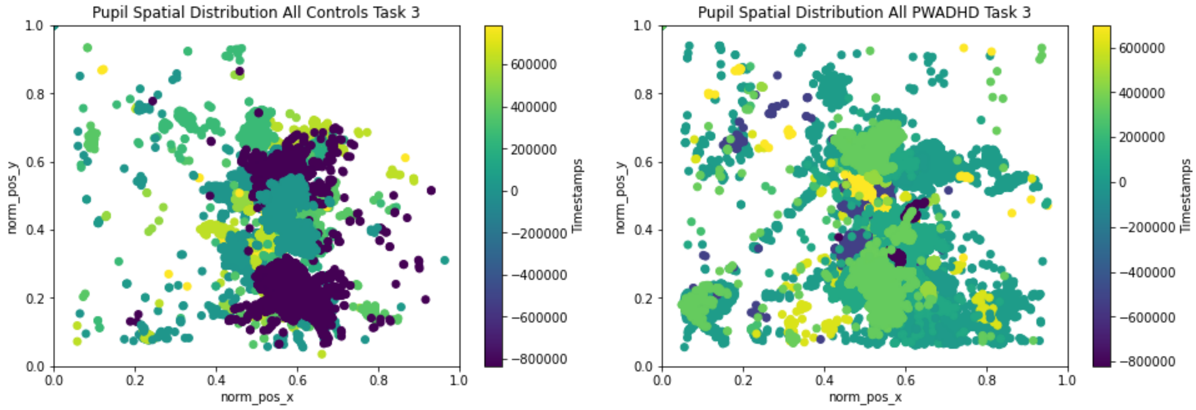


Figure E6.14

Saccades generated for groups in task 3 (controls in the left; PWADHD in the right).

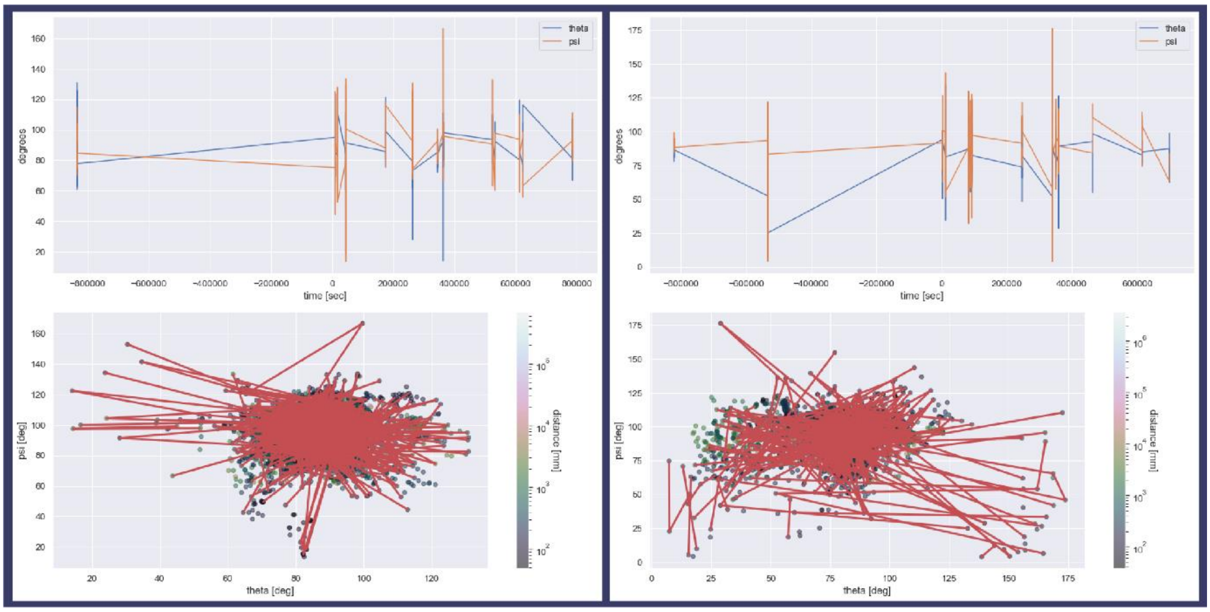
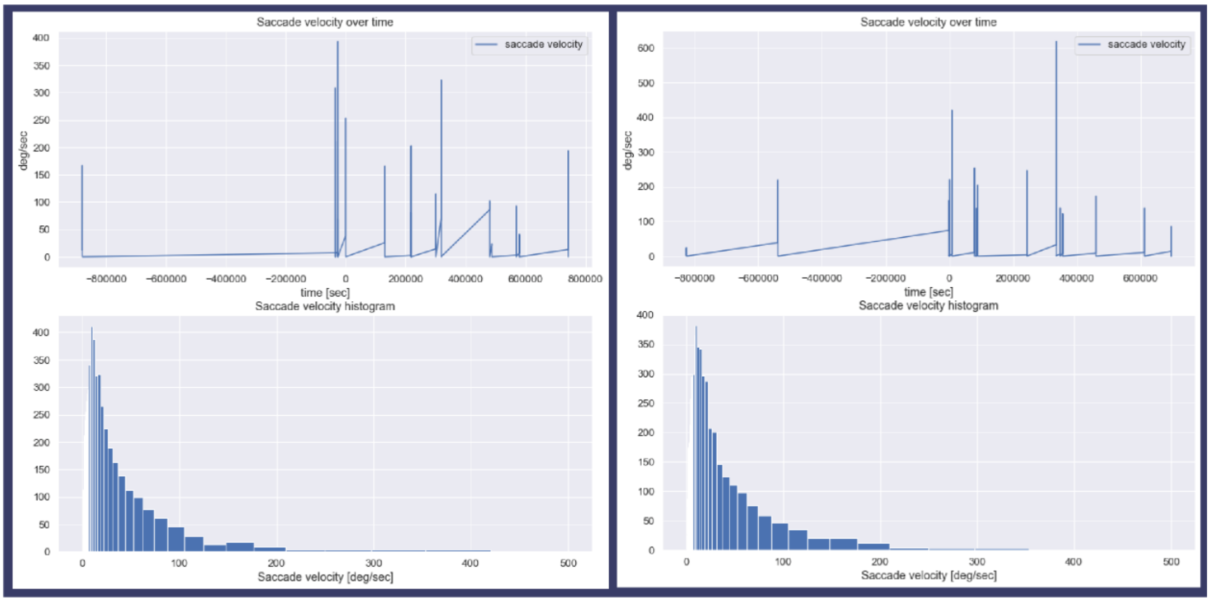


Figure E6.15

SMVs generated from fixations for controls and PWADHD in task 3 (controls in the left; PWADHD in the right).



Task 4

Results for oculomotor measures

Figure E6.16

Task 4 heatmap generated from fixations for controls (top row) and PWADHD (bottom row).

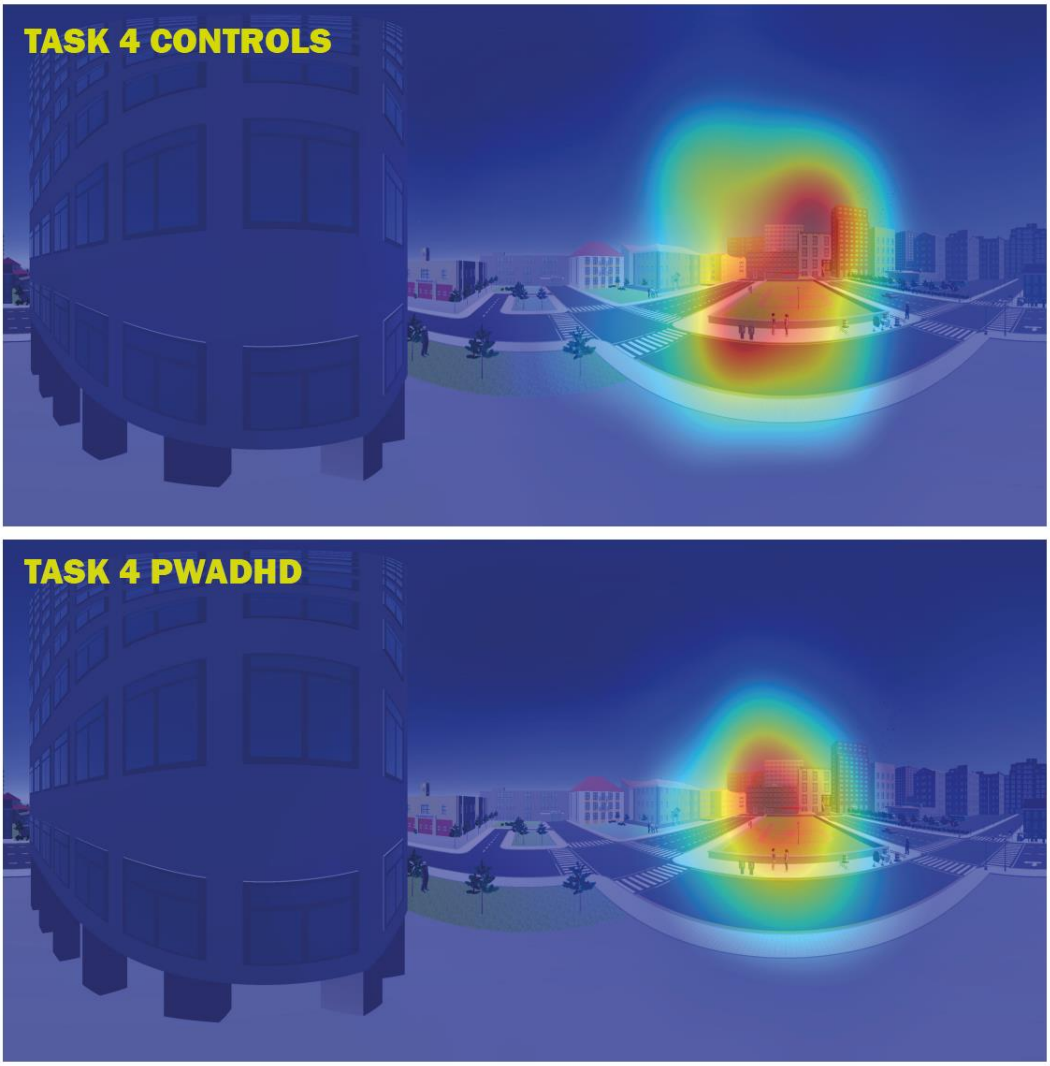


Figure E6.17

Mean pupil distributions for controls and PWADHD in task 4 (controls shown in blue, PWADHD visualised in orange).

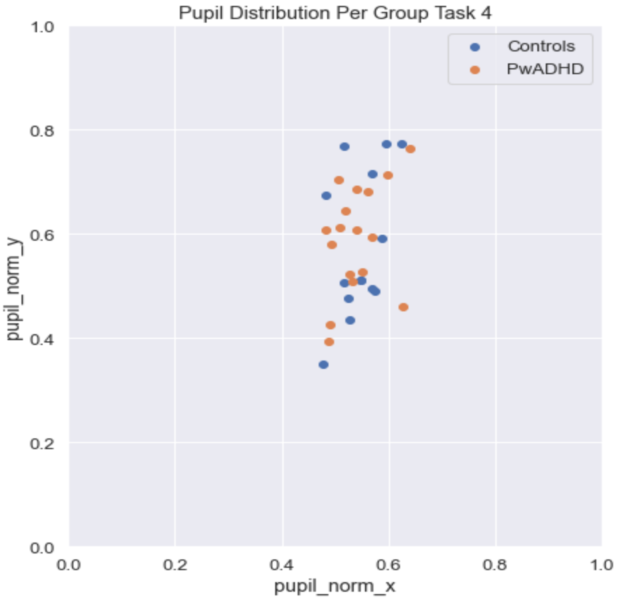


Figure E6.18

Spatial distributions between groups in task 4 (controls in the left; PWADHD in the right).

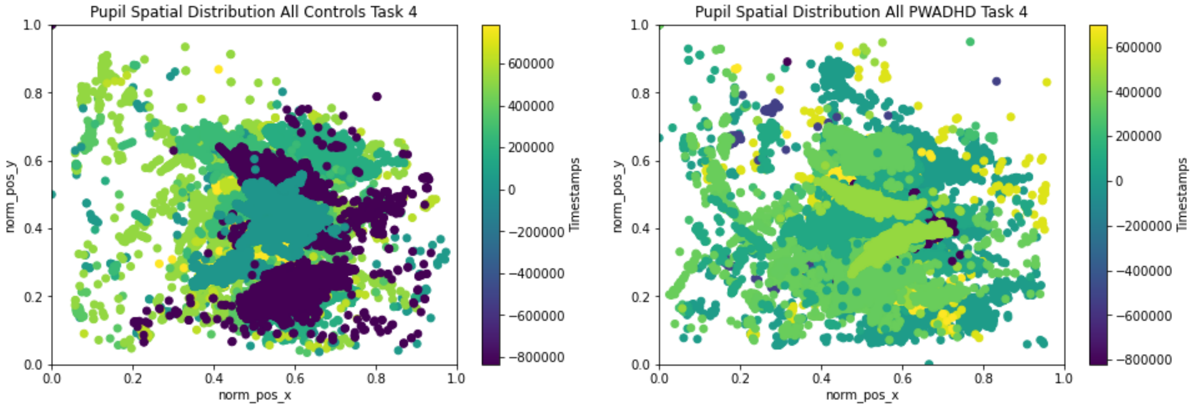


Figure E6.19

Saccades generated for groups in task 4 (controls in the left; PWADHD in the right).

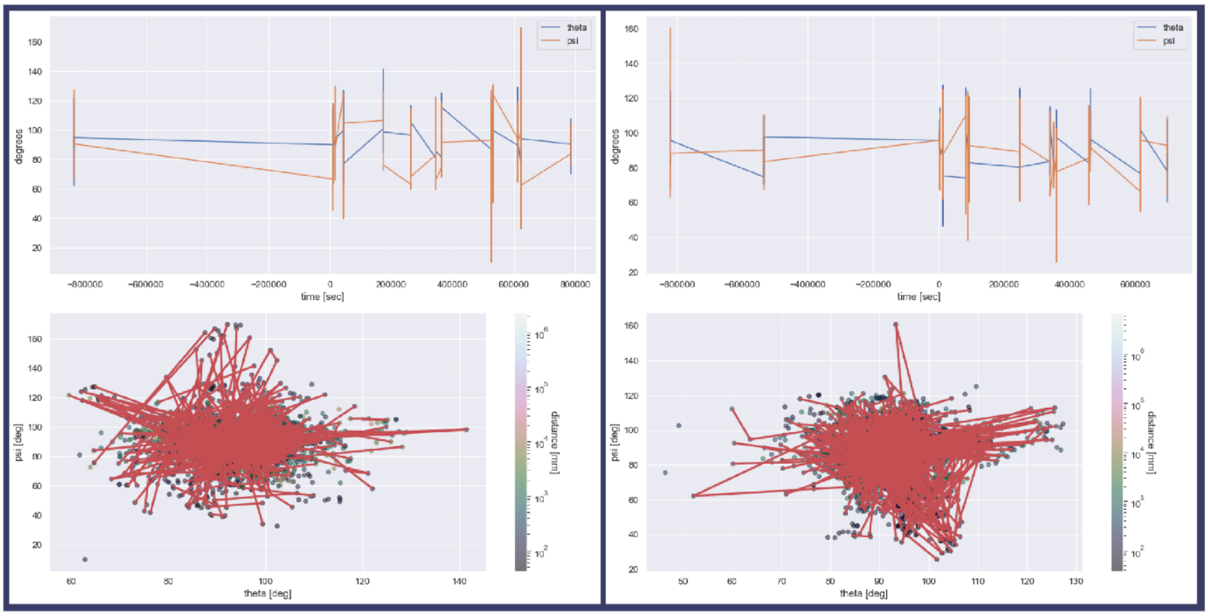
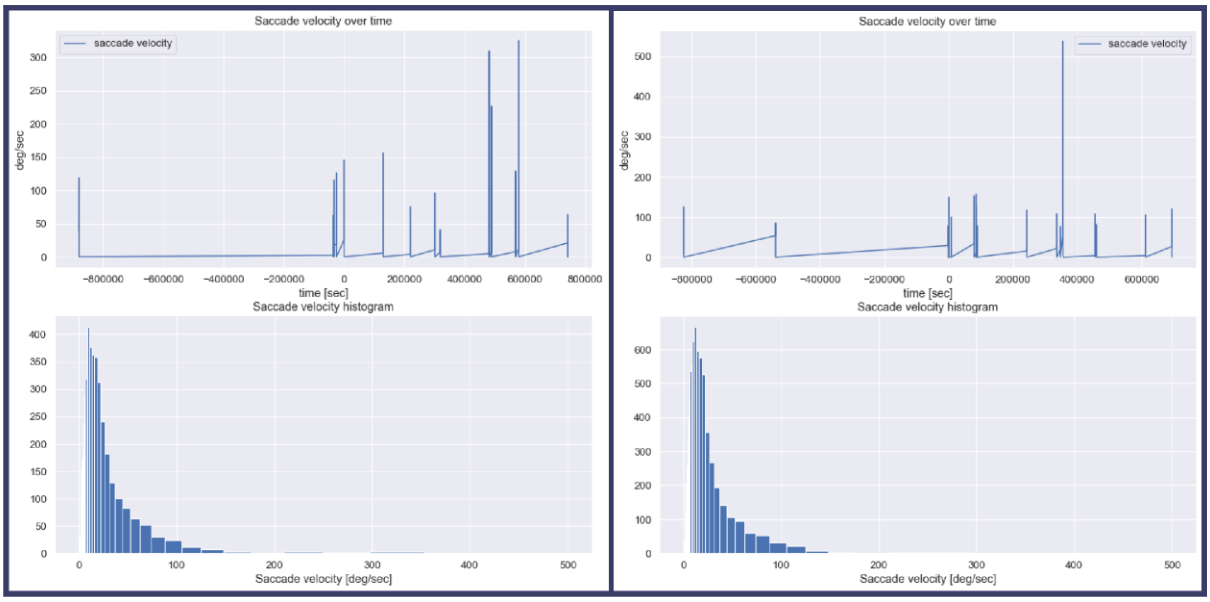


Figure E6.20

SMVs generated from fixations for controls and PWADHD in task 4 (controls in the left; PWADHD in the right).



Task 5

Results for oculomotor measures

Figure E6.21

Task 5 heatmap generated from fixations for controls (top row) and PWADHD (bottom row).

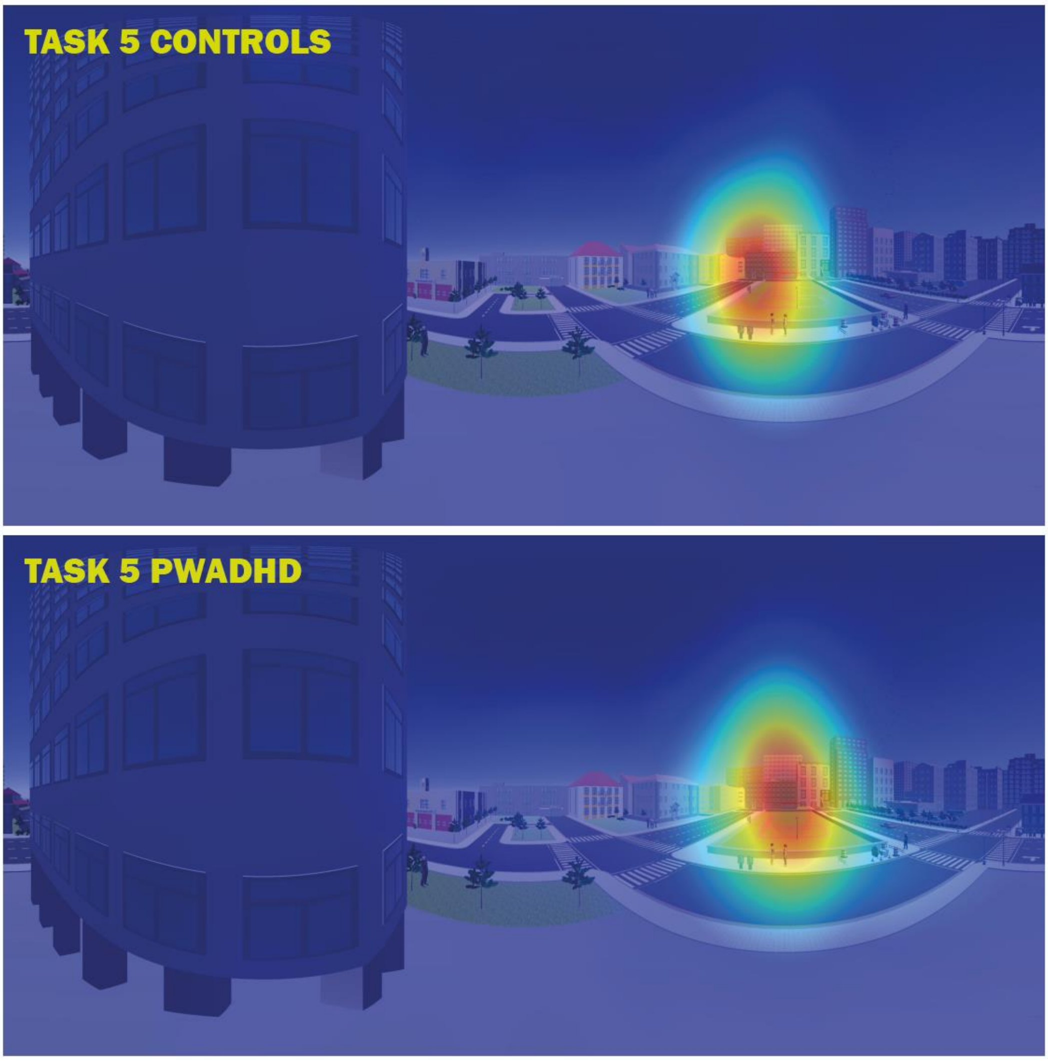


Figure E6.22

Mean pupil distributions for controls and PWADHD in task 5 (controls shown in blue, PWADHD visualised in orange).

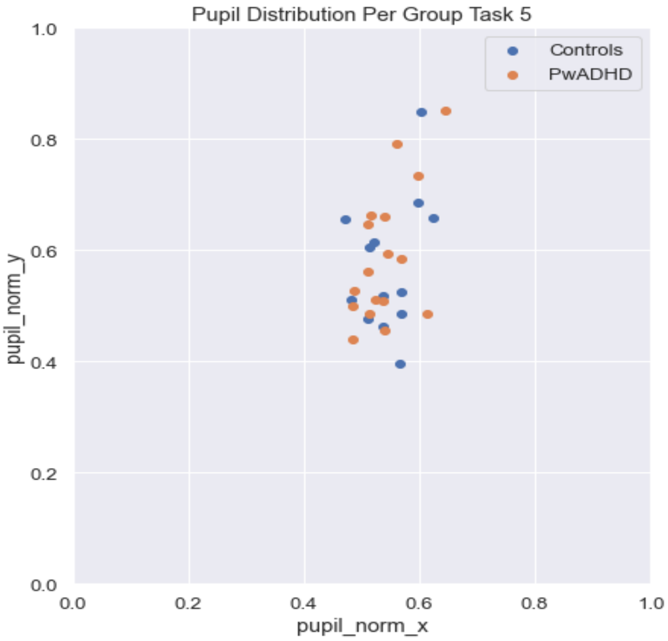


Figure E6.23

Spatial distributions between groups in task 5 (controls in the left; PWADHD in the right).

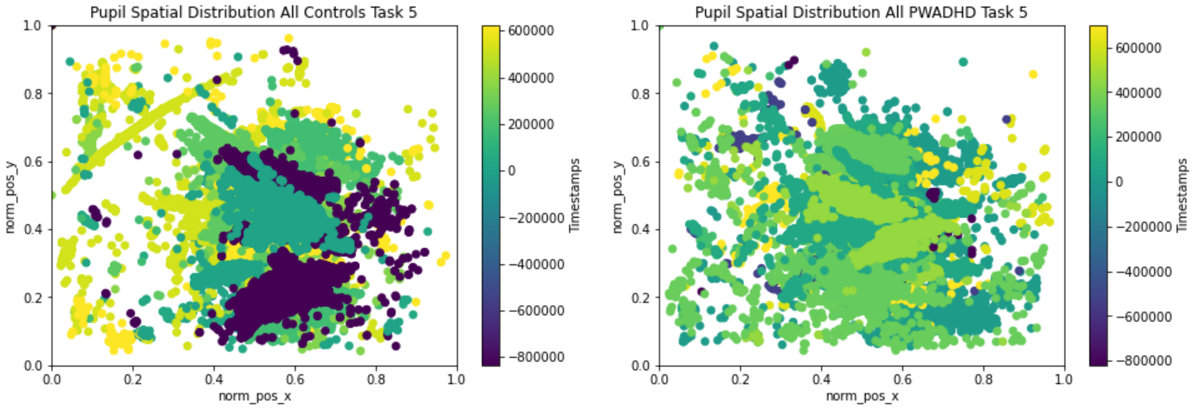


Figure E6.24

Saccades generated for groups in task 5 (controls in the left; PWADHD in the right).

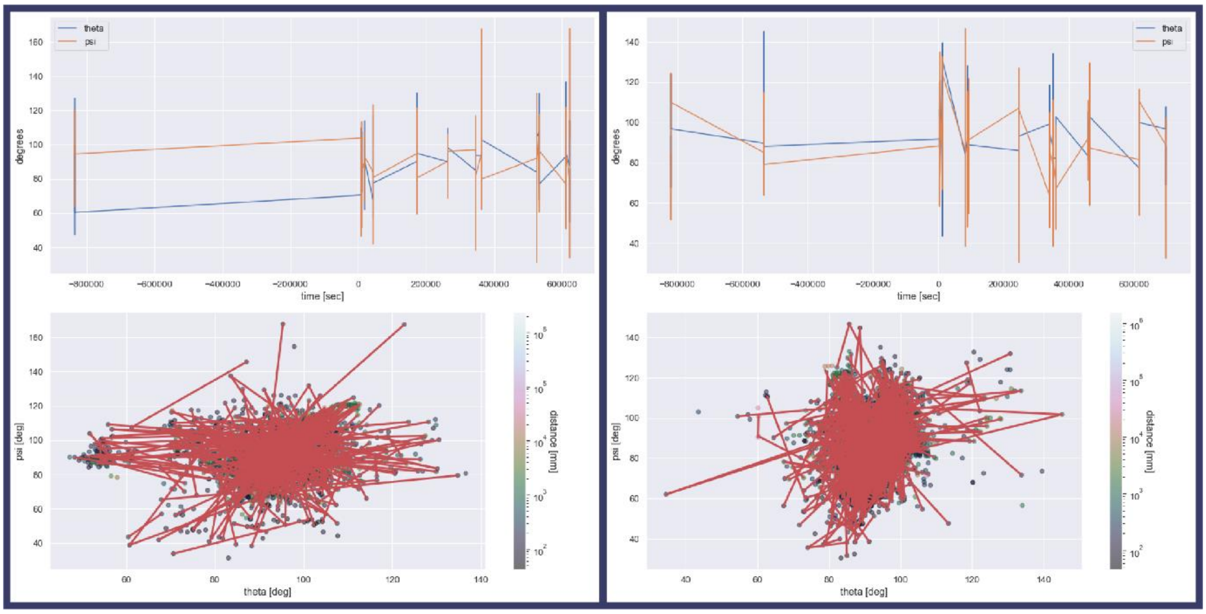
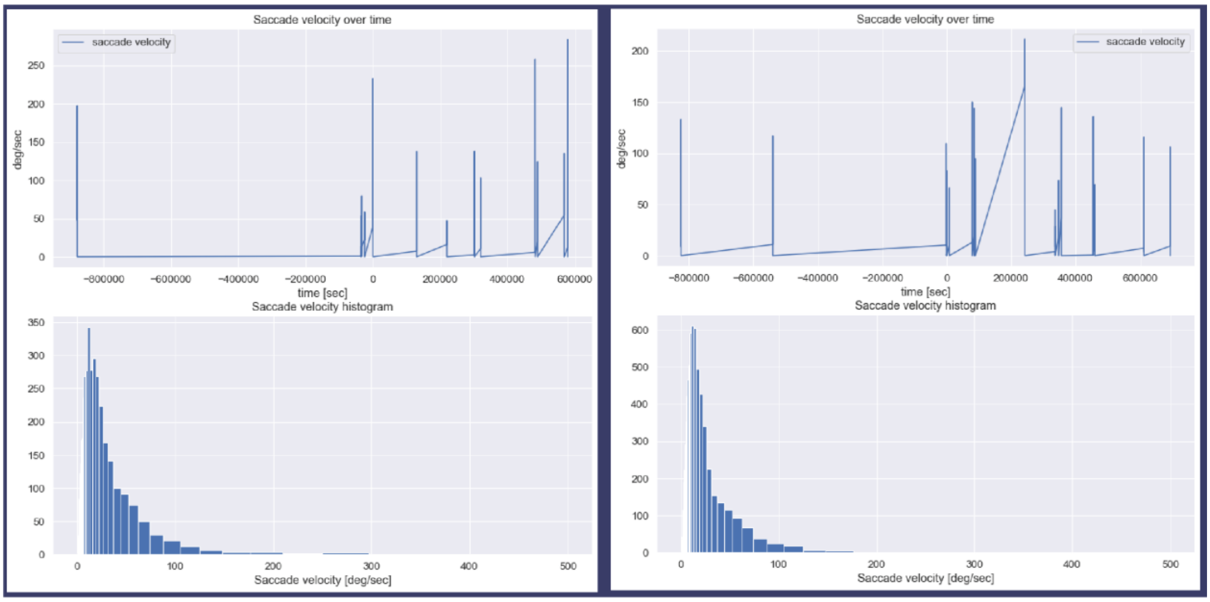


Figure E6.25

SMVs generated from fixations for controls and PWADHD in task 5 (controls in the left; PWADHD in the right).



Task 6

Results for oculomotor measures

Figure E6.26

Task 6 heatmap generated from fixations for controls (top row) and PWADHD (bottom row).

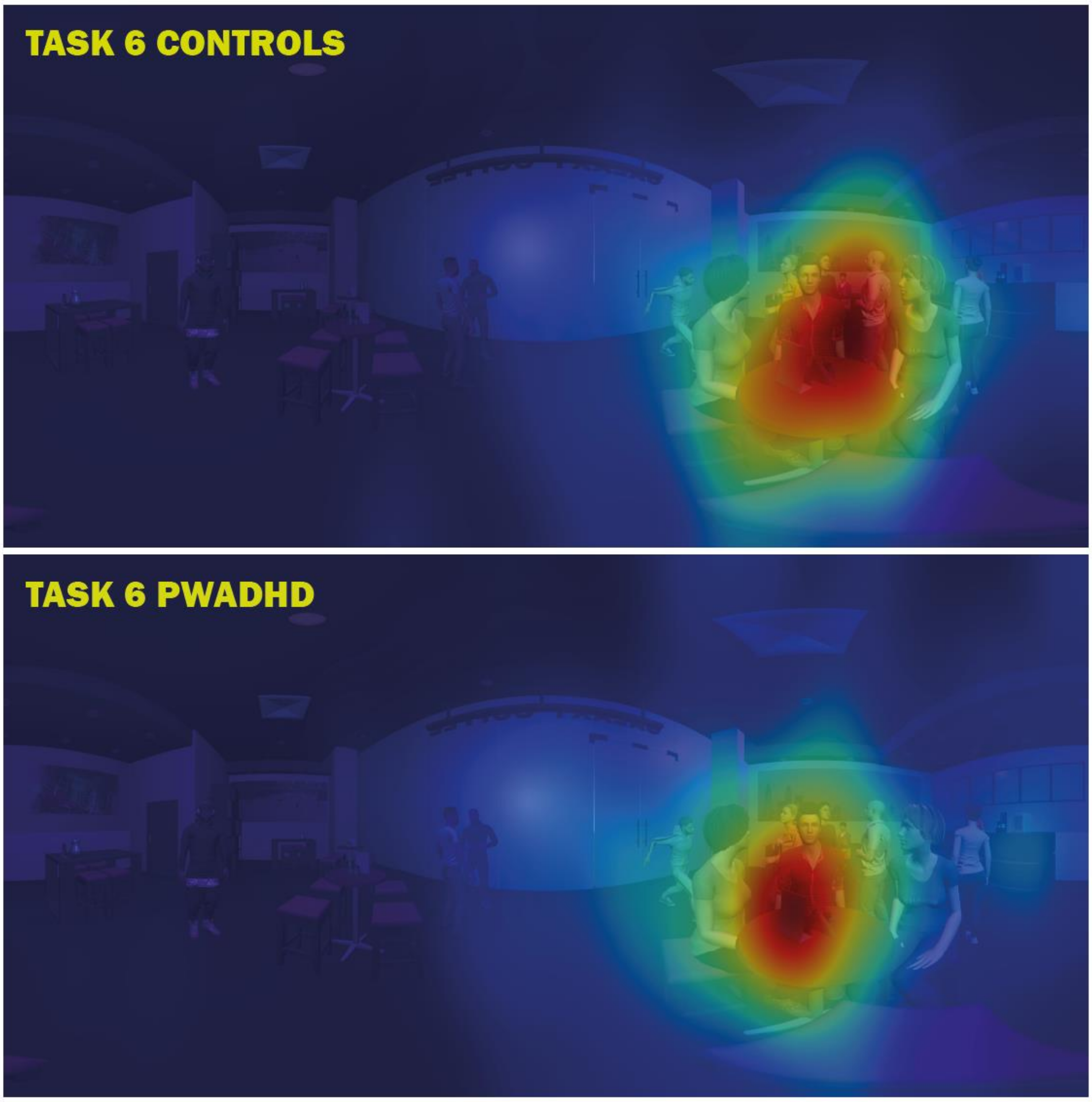


Figure E6.27

Mean pupil distributions for controls and PWADHD in task 6 (controls shown in blue, PWADHD visualised in orange).

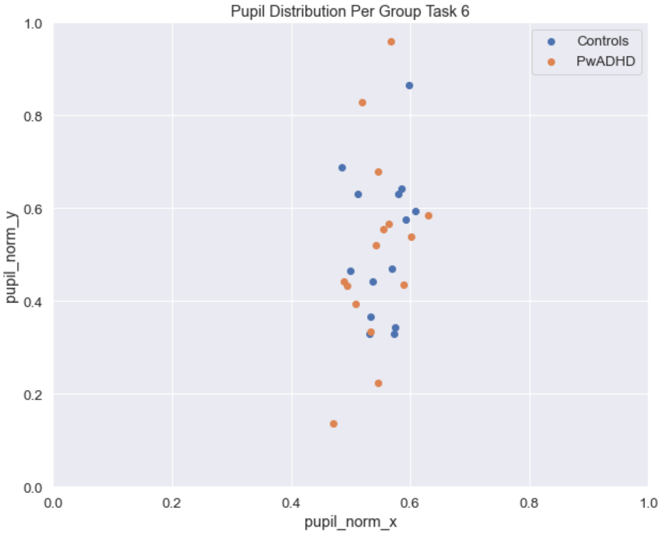


Figure E6.28

Spatial distributions between groups in task 6 (controls in the left; PWADHD in the right).

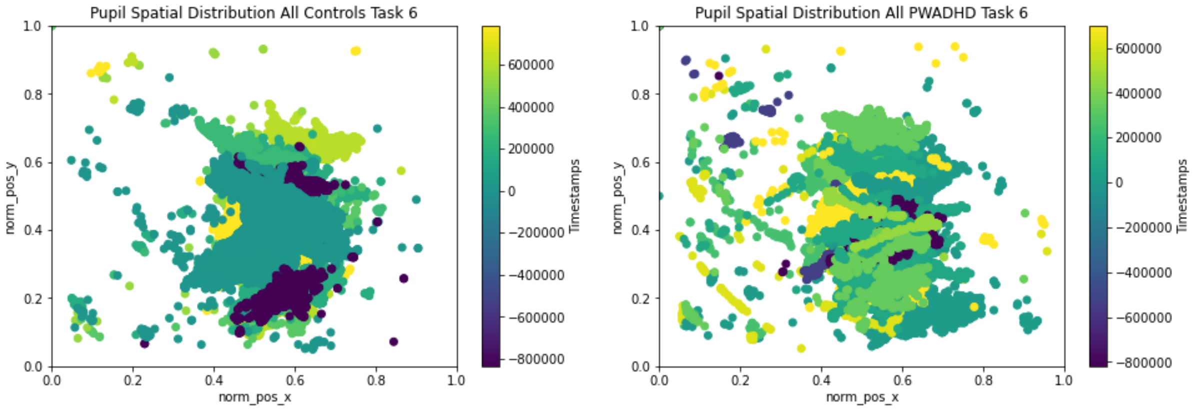


Figure E6.29

Saccades generated for groups in task 6 (controls in the left; PWADHD in the right).

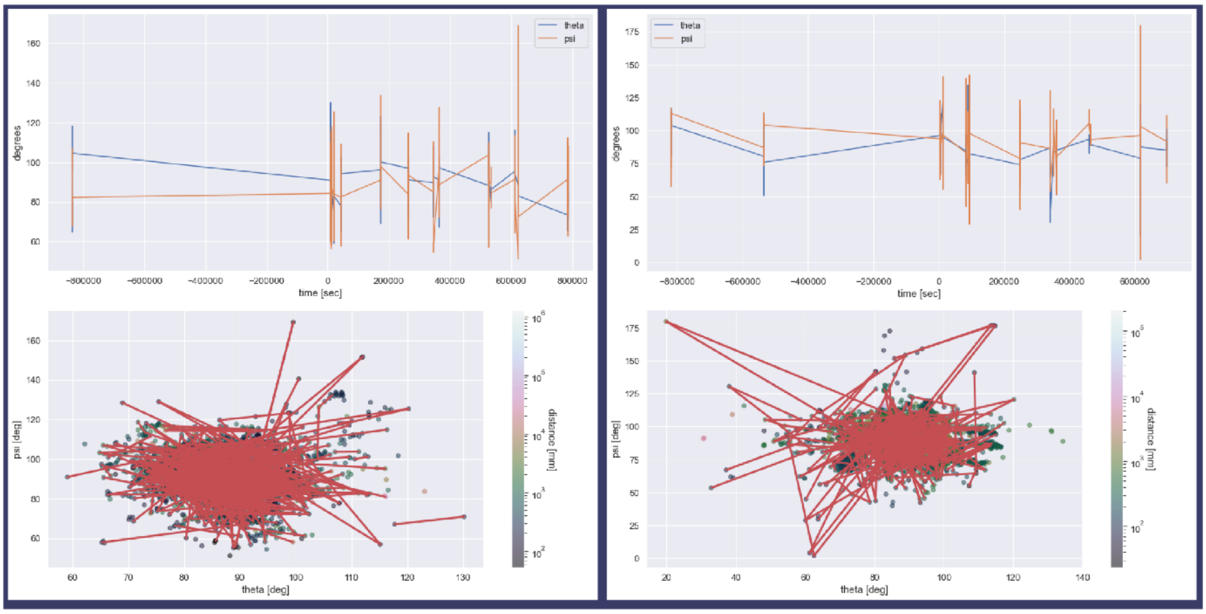
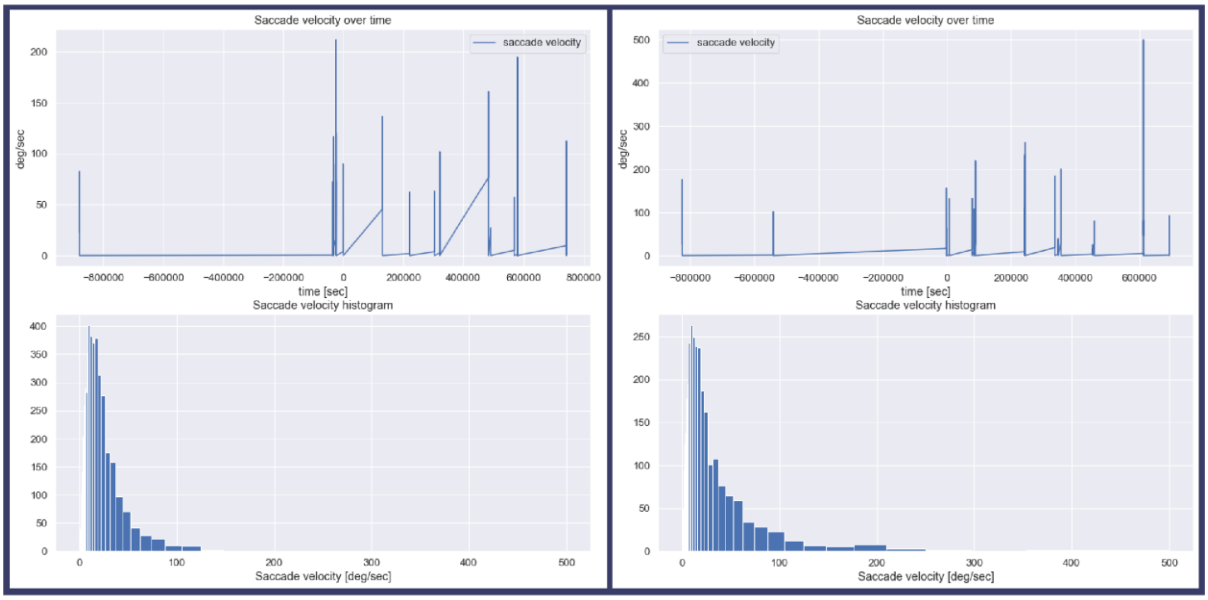


Figure E6.30

SMVs generated from fixations for controls and PWADHD in task 6 (controls in the left; PWADHD in the right).



Task 7

Results for oculomotor measures

Figure E6.31

Task 7 heatmap generated from fixations for controls (top row) and PWADHD (bottom row).

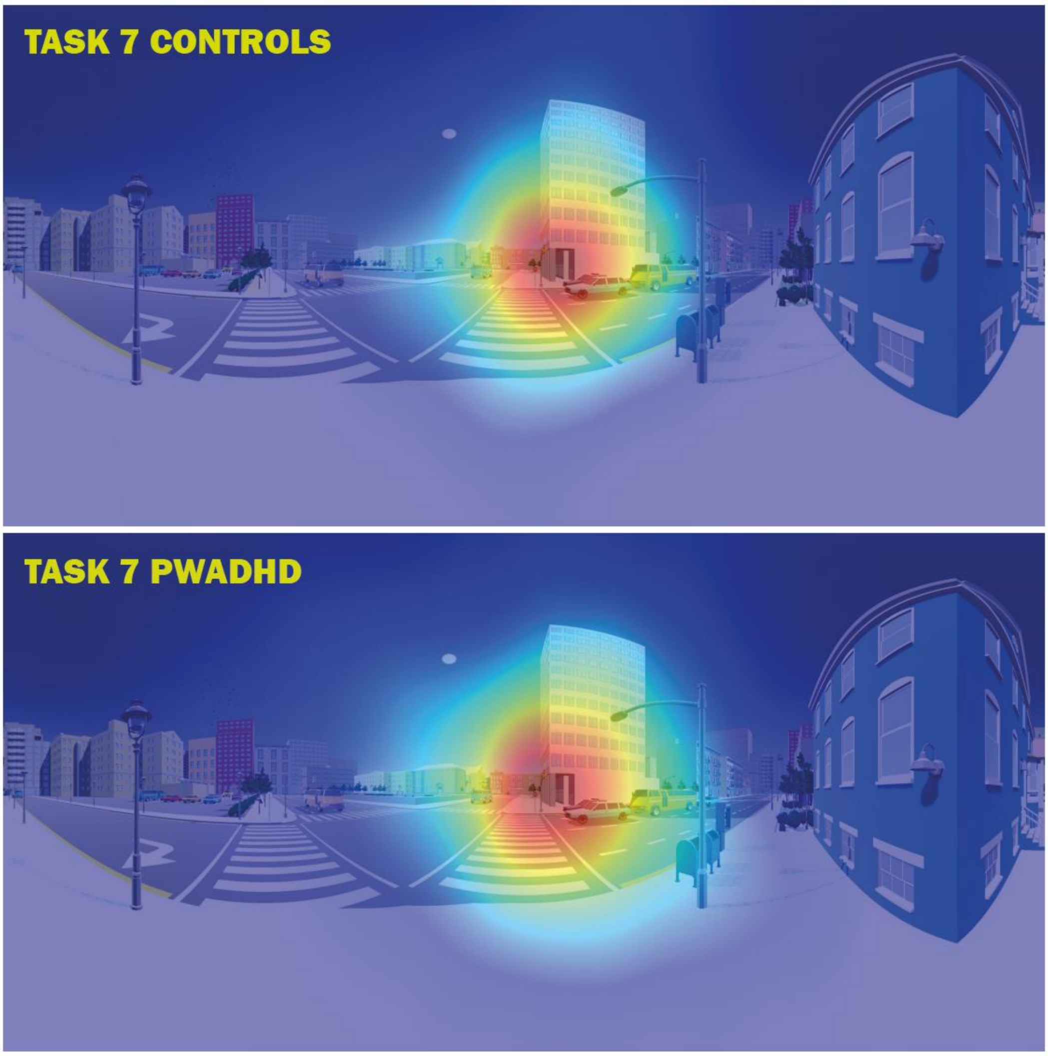


Figure E6.32

Mean pupil distributions for controls and PWADHD in task 7 (controls shown in blue, PWADHD visualised in orange).

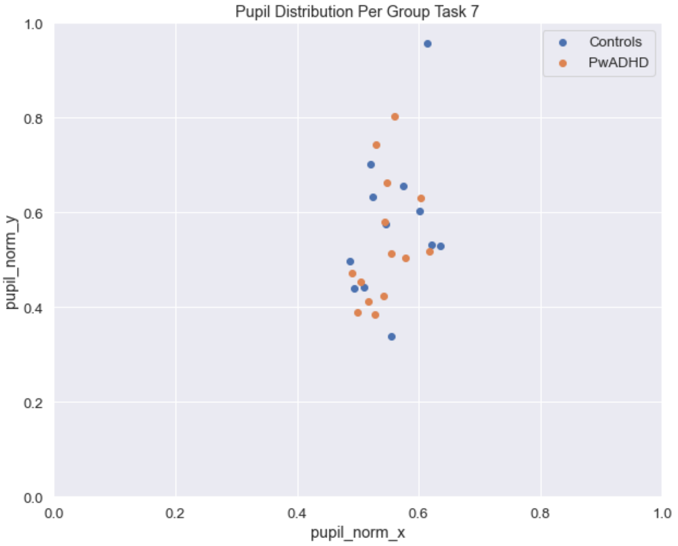


Figure E6.33

Spatial distributions between groups in task 7 (controls in the left; PWADHD in the right).

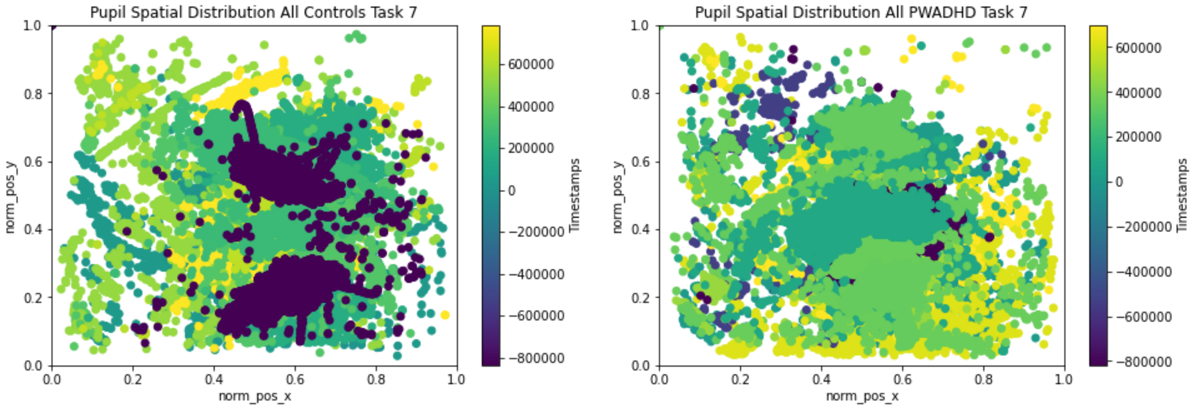


Figure E6.34

Saccades generated for groups in task 7 (controls in the left; PWADHD in the right).

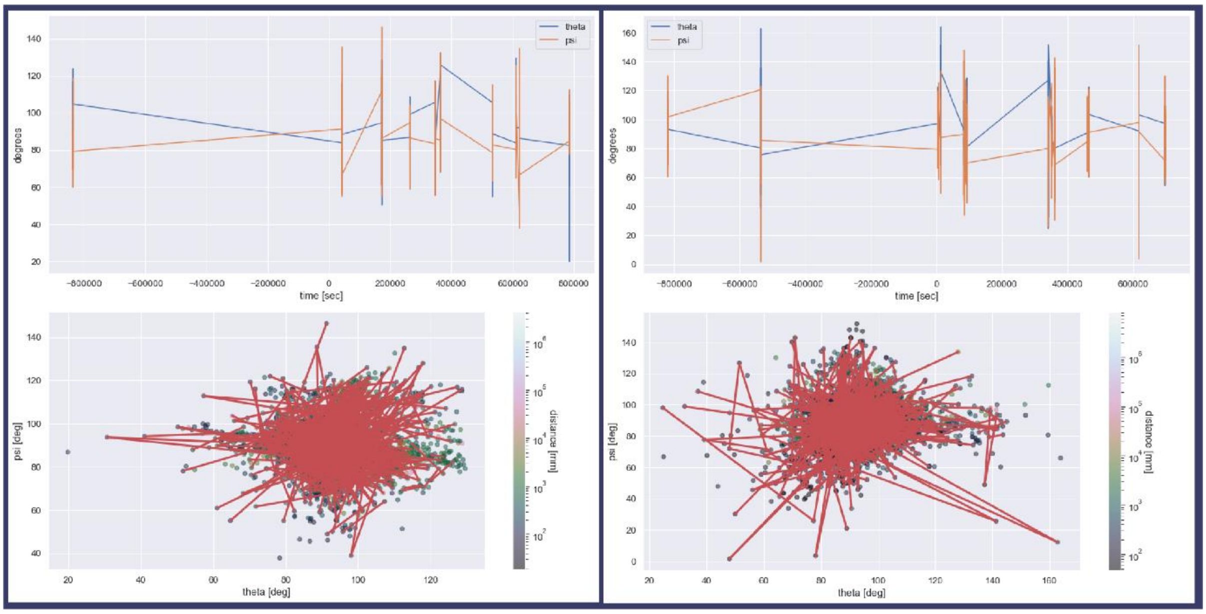
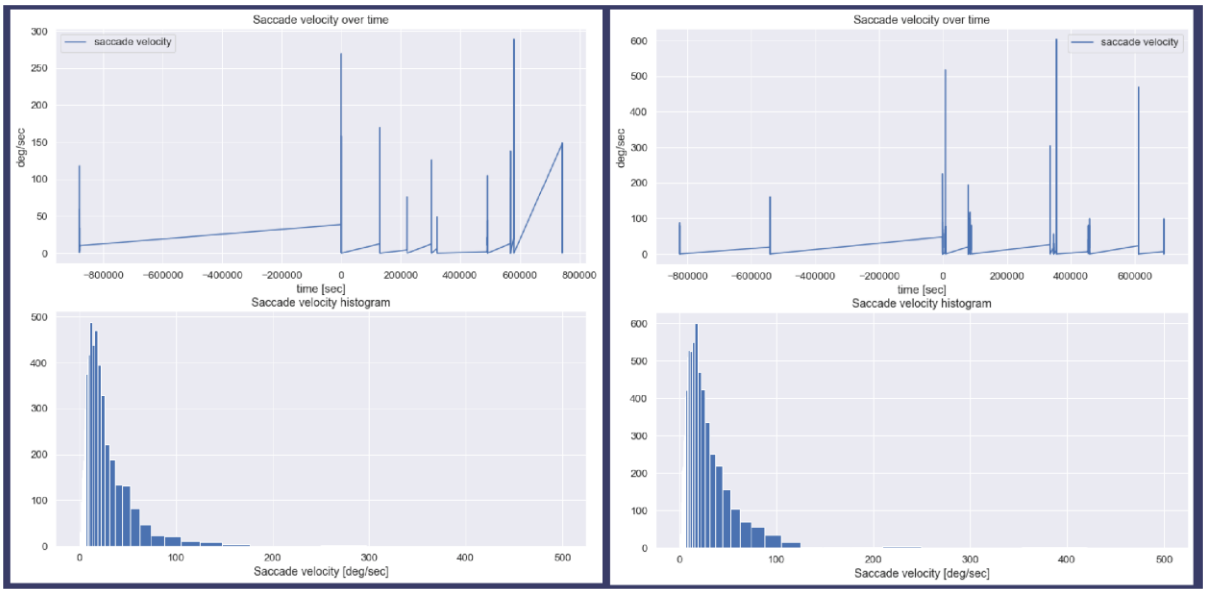


Figure E6.35

SMVs generated from fixations for controls and PWADHD in task 7 (controls in the left; PWADHD in the right).



Task 8

Results for oculomotor measures

Figure E6.36

Task 8 heatmap generated from fixations for controls (top row) and PWADHD (bottom row).

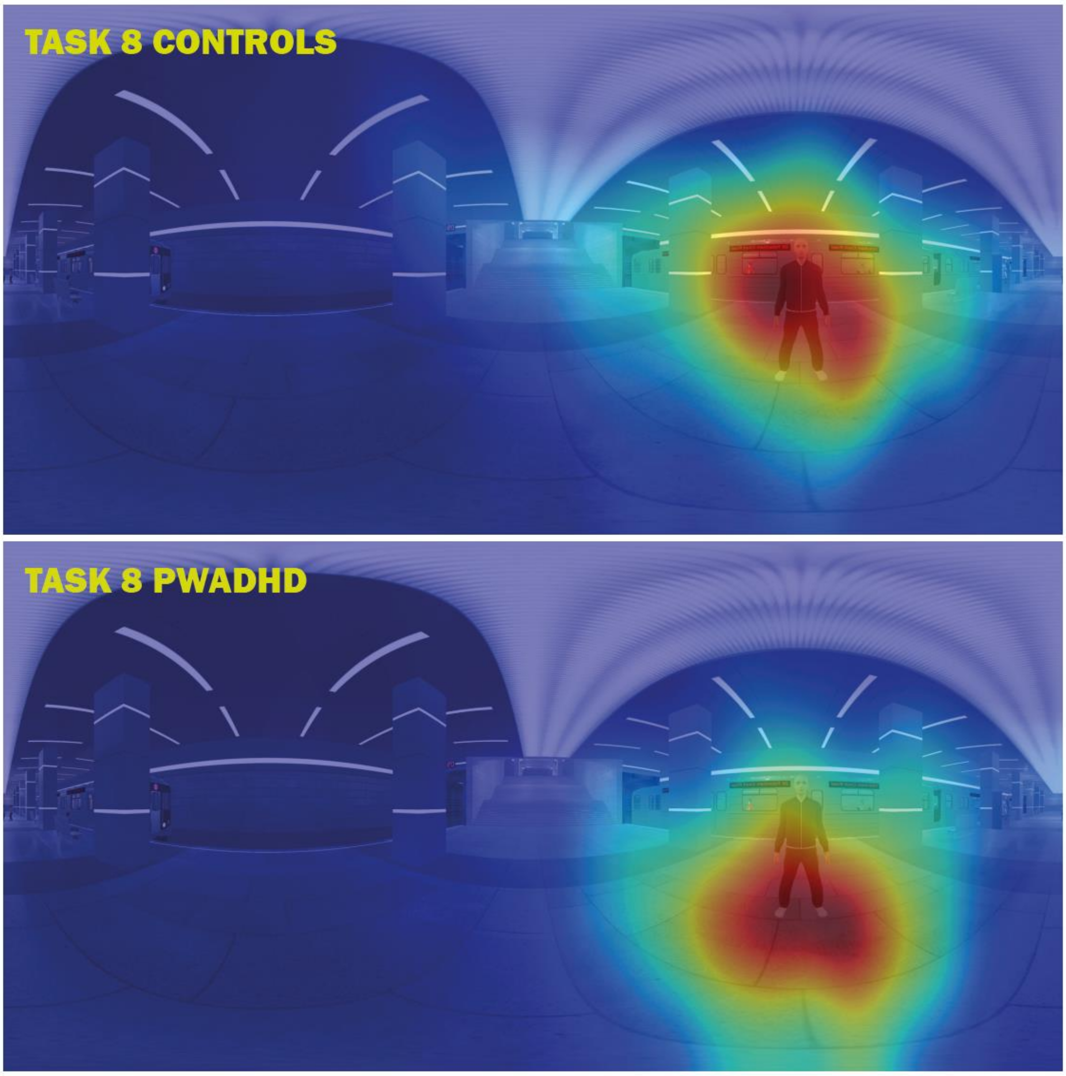


Figure E6.37

Mean pupil distributions for controls and PWADHD in task 8 (controls shown in blue, PWADHD visualised in orange).

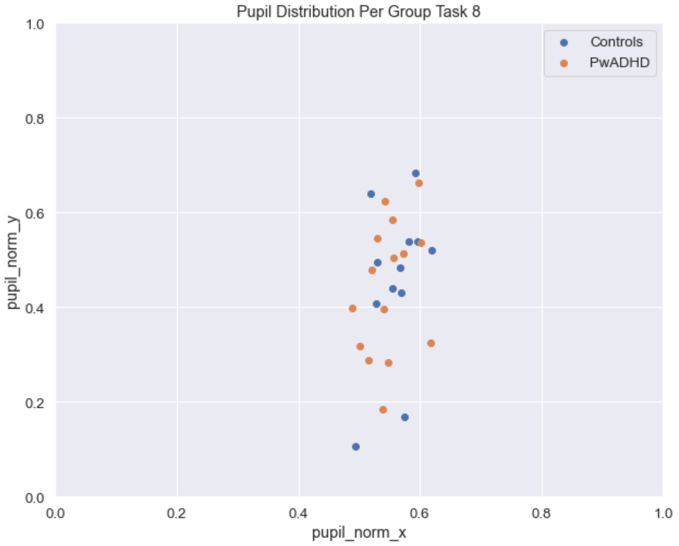


Figure E6.38

Spatial distributions between groups in task 8 (controls in the left; PWADHD in the right).

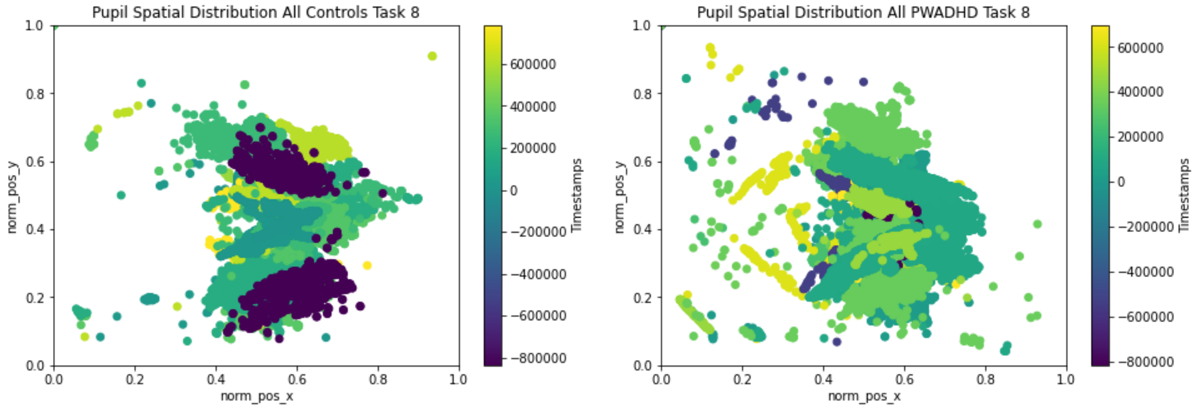


Figure E6.39

Saccades generated for groups in task 8 (controls in the left; PWADHD in the right).

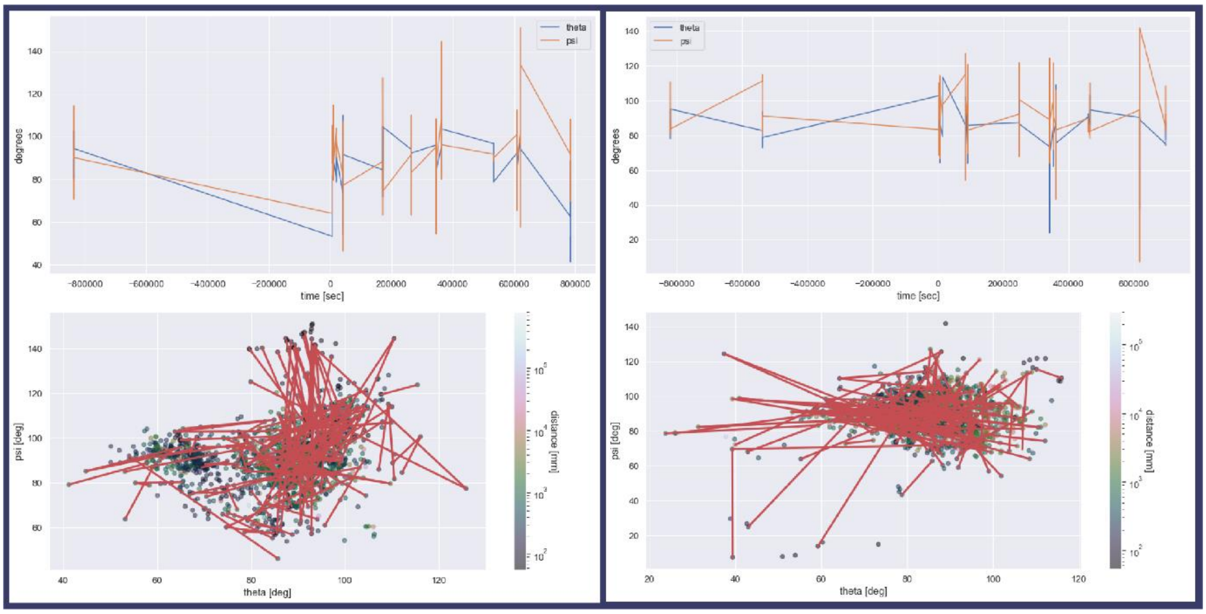
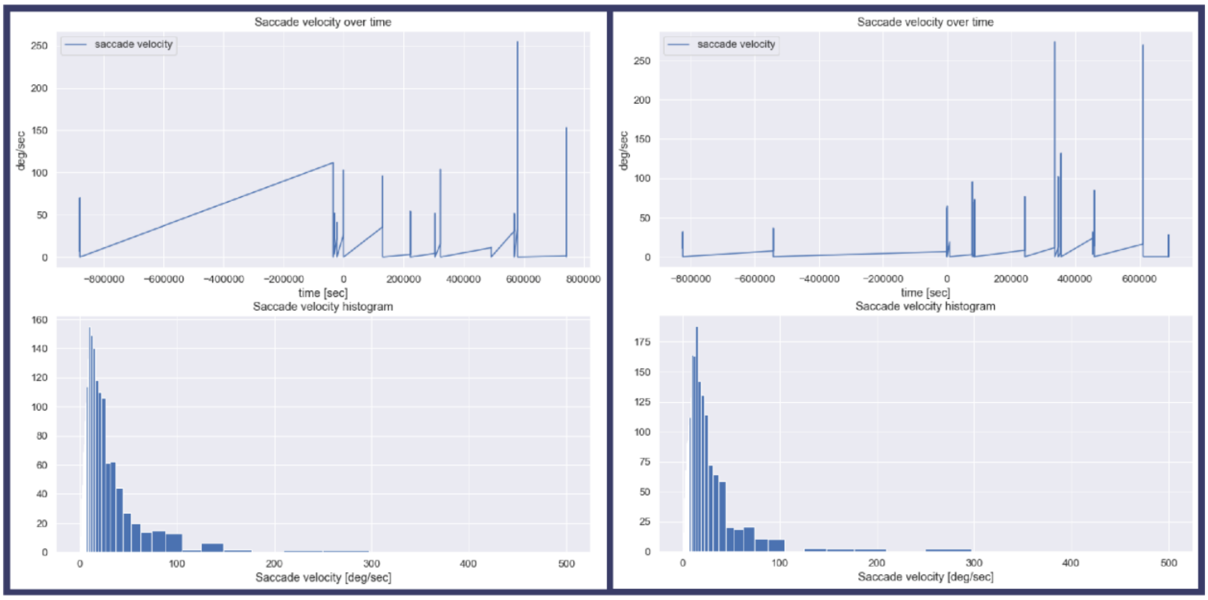


Figure E6.40

SMVs generated from fixations for controls and PWADHD in task 8 (controls in the left; PWADHD in the right).



Task 9

Results for oculomotor measures

Figure E6.41

Task 9 heatmap generated from fixations for controls (top row) and PWADHD (bottom row).

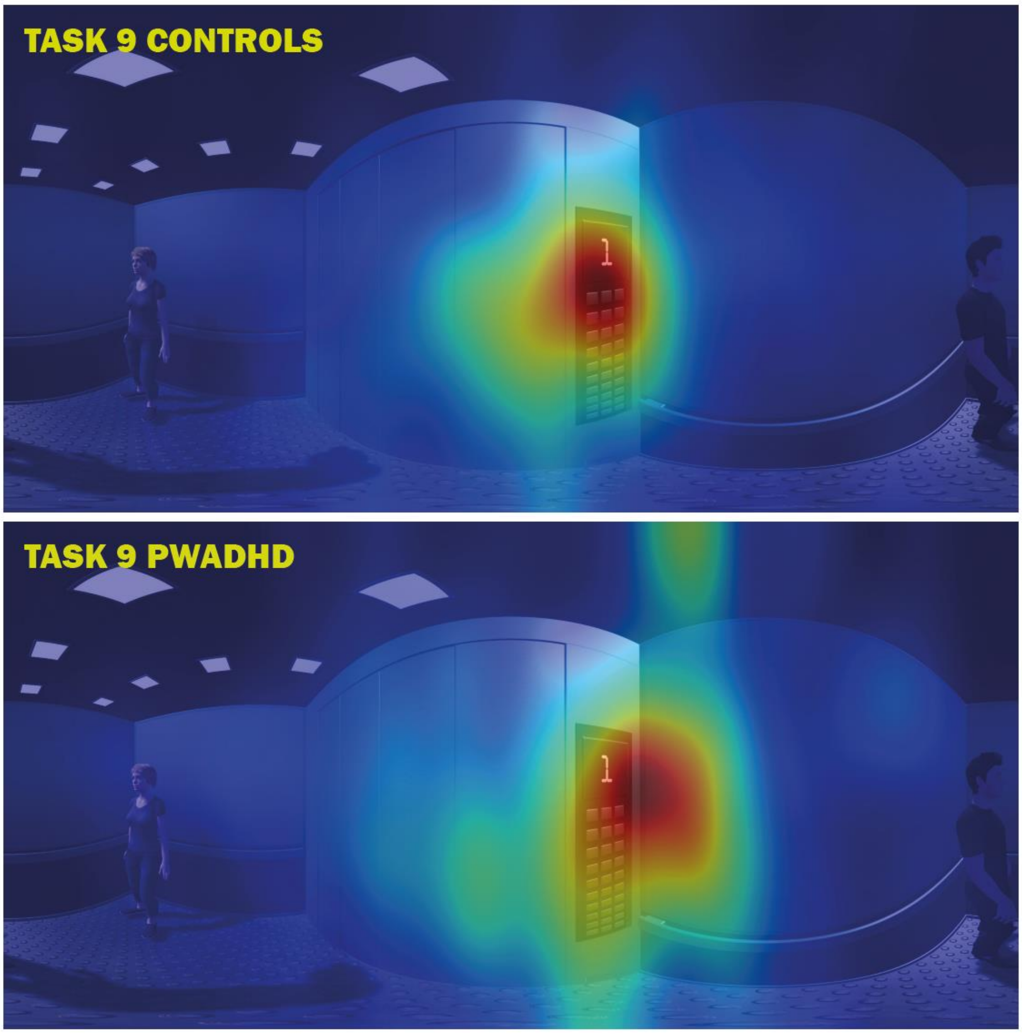


Figure E6.42

Mean pupil distributions for controls and PWADHD in task 9 (controls shown in blue, PWADHD visualised in orange).

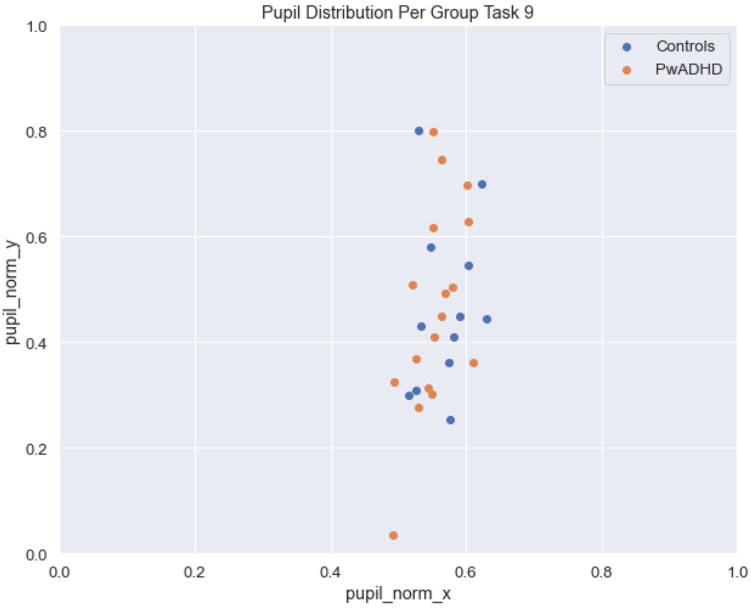


Figure E6.43

Spatial distributions between groups in task 9 (controls in the left; PWADHD in the right).

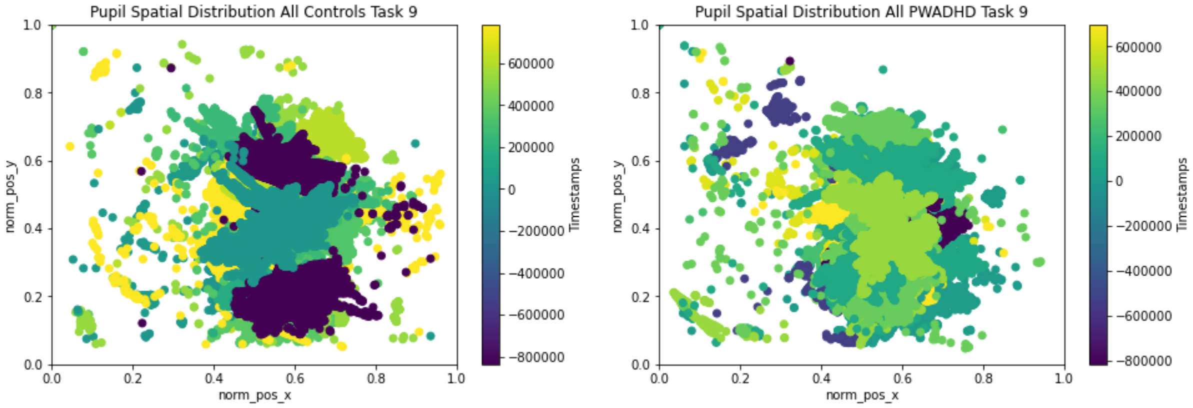


Figure E6.44

Saccades generated for groups in task 9 (controls in the left; PWADHD in the right).

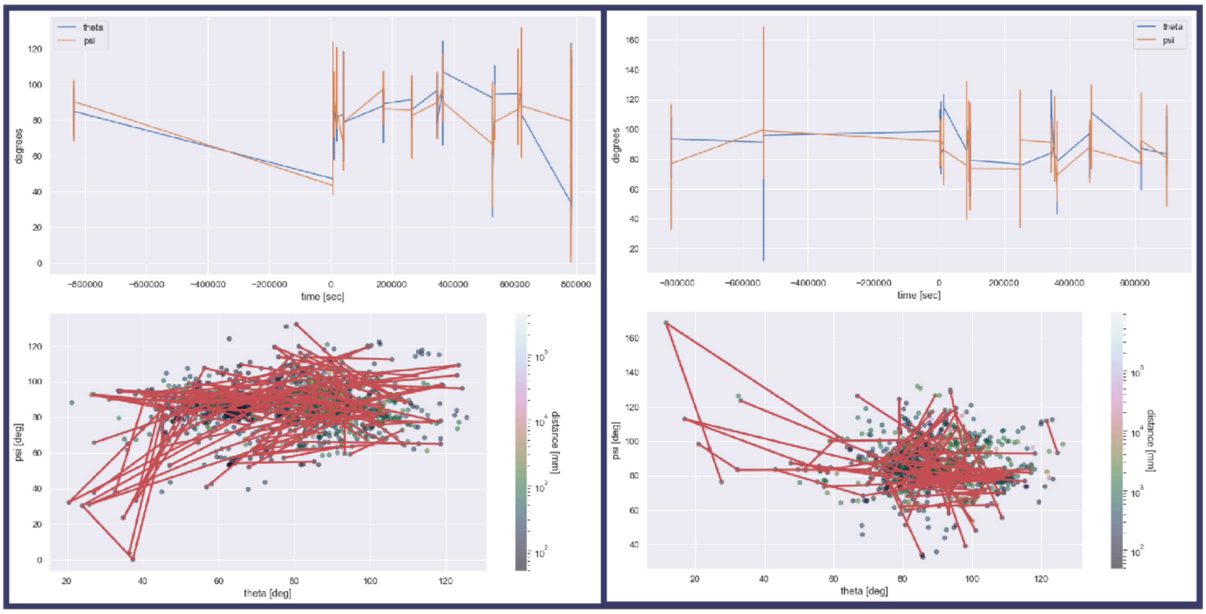
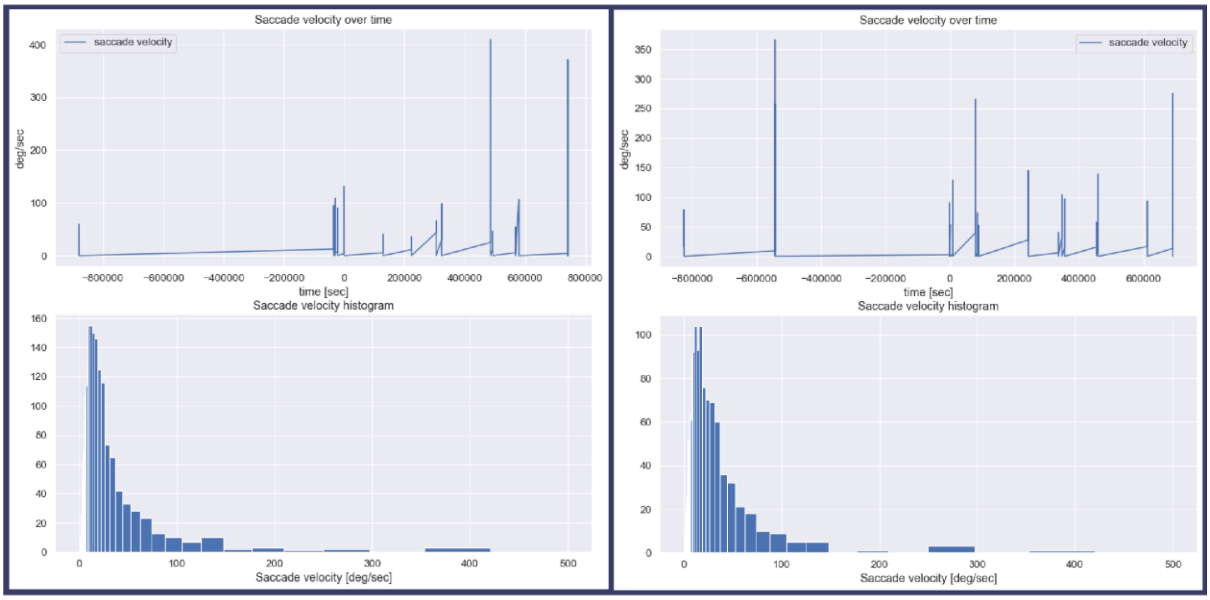


Figure E6.45

SMVs generated from fixations for controls and PWADHD in task 9 (controls in the left; PWADHD in the right).



Task 10

Results for oculomotor measures

Figure E6.46

Task 10 heatmap generated from fixations for controls (top row) and PWADHD (bottom row).

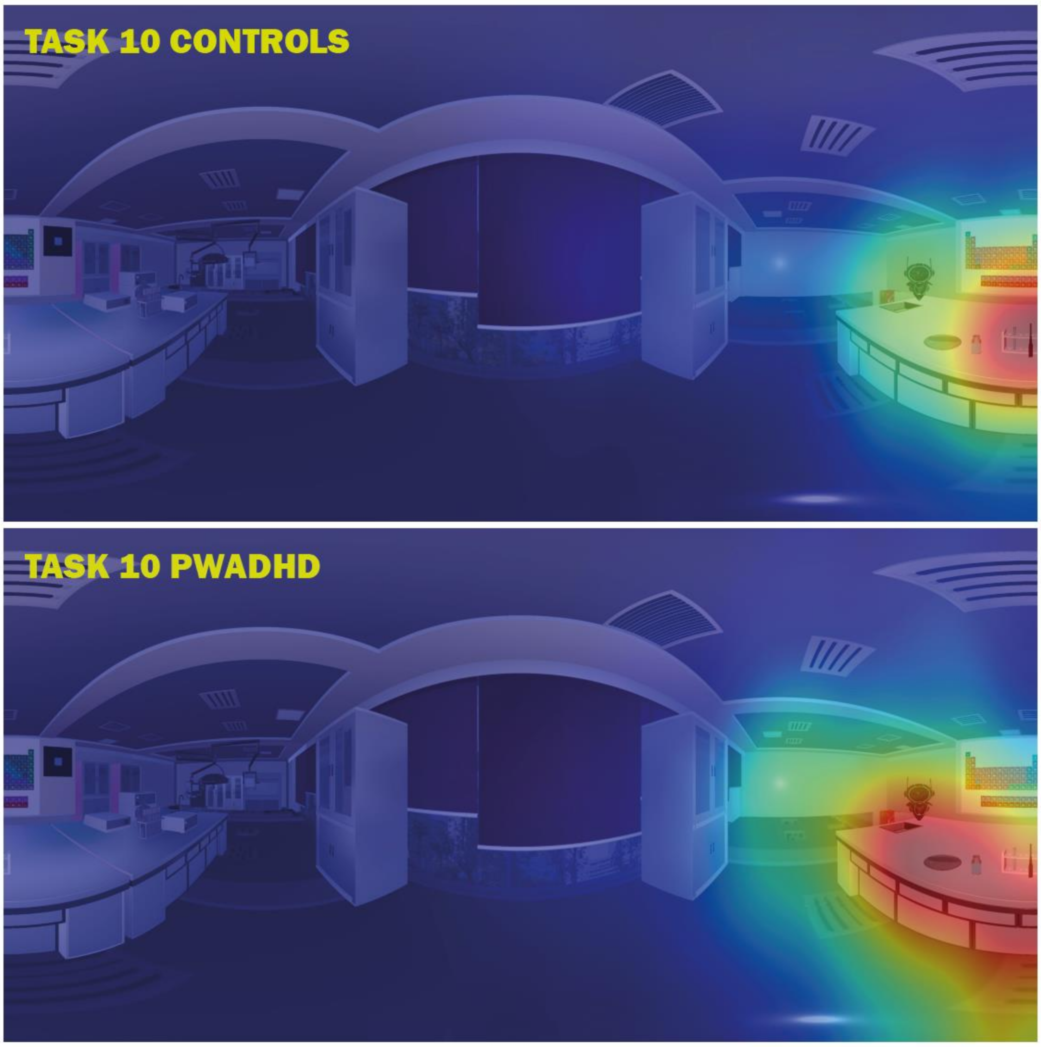


Figure E6.47

Mean pupil distributions for controls and PWADHD in task 10 (controls shown in blue, PWADHD visualised in orange).

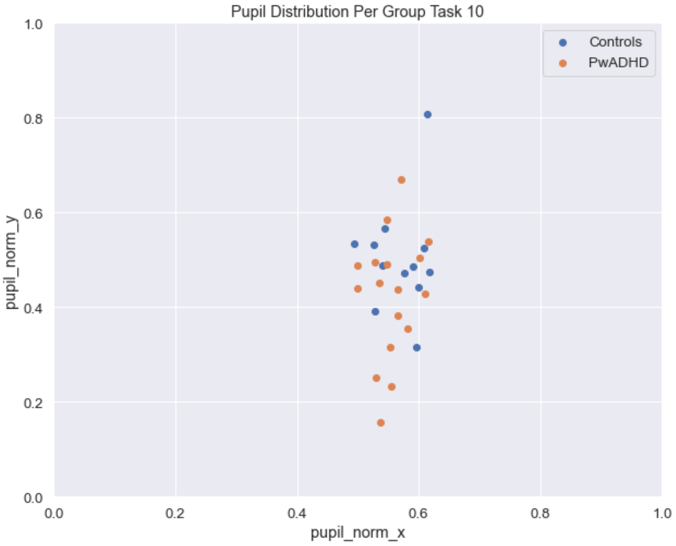


Figure E6.48

Spatial distributions between groups in task 10 (controls in the left; PWADHD in the right).

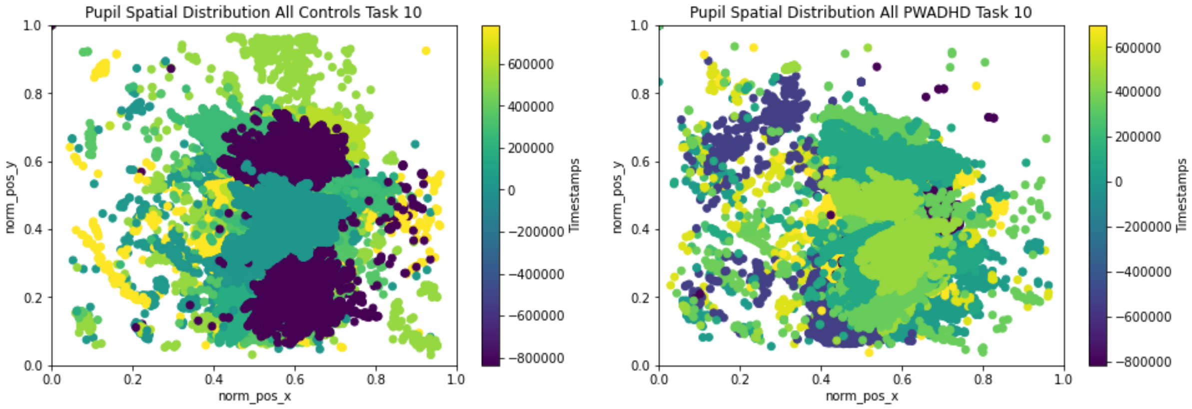


Figure E6.49

Saccades generated for groups in task 10 (controls in the left; PWADHD in the right).

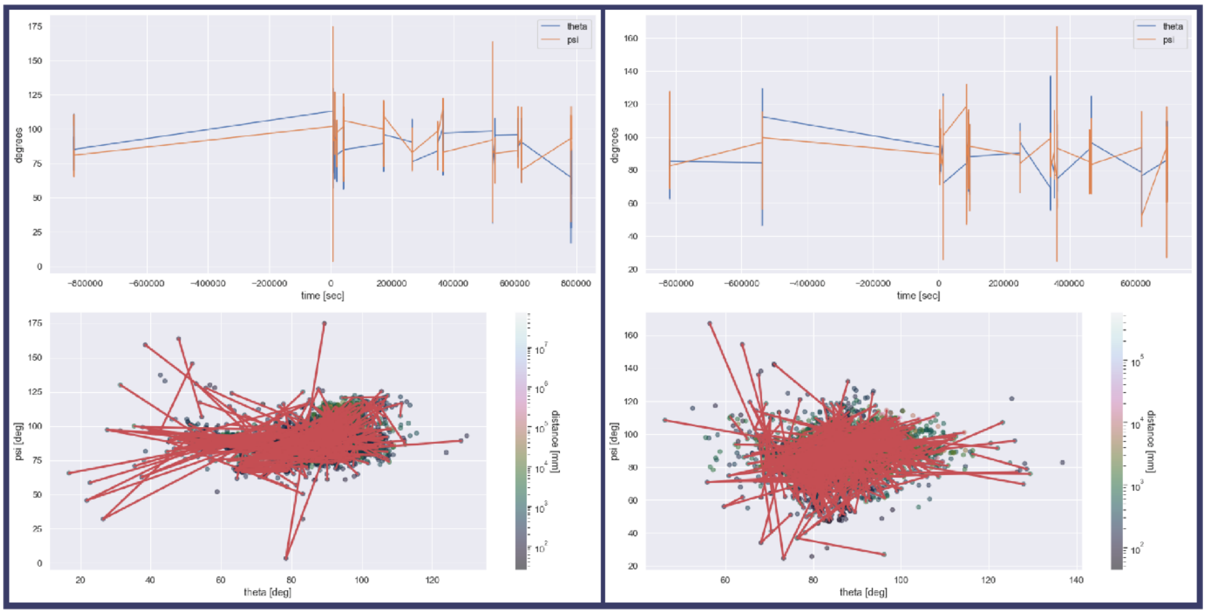
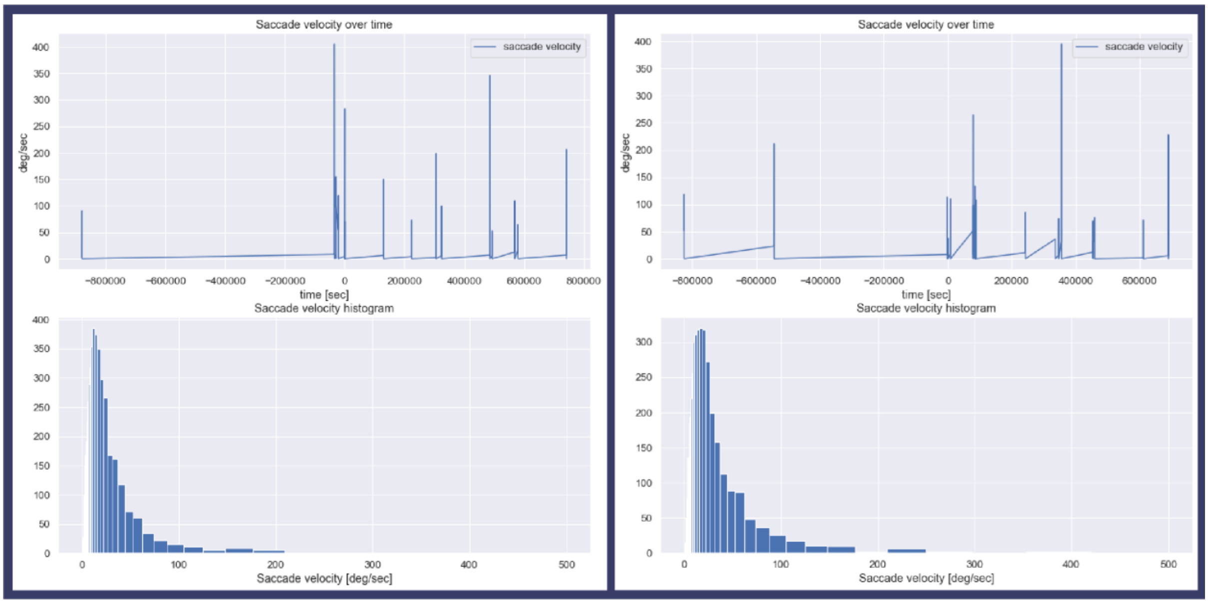


Figure E6.50

SMVs generated from fixations for controls and PWADHD in task 10 (controls in the left; PWADHD in the right).



Appendix F. Chapter 7: Results for experiment 7

Results for EEG measures

Table F7.1

Mean and SD for oculomotor and brain activity measures.

		Controls			***PWADHD***			
		M	**SD**	**N**	**M**	**SD**	**N**	***Cohen's d***
Task1	***Alpha***	0.8658791	0.024004	10	0.8389124	0.013310	9	0.938
	Beta	0.8474335	0.0218821	11	0.8843769	0.0333803	11	0.878
	Theta	0.8071514	0.0296477	14	0.7692902	0.0349002	11	0.853
	TBR	0.9640272	0.0428425	12	0.9201323	0.0396429	17	0.651
	Attention	0.5575681	0.0393628	11	0.4900237	0.0372706	17	1.043
Task2	***Alpha***	0.8641	0.0318	14	0.8056	0.05271	10	1.037
	Beta	0.82863	0.0517	6	0.9042	0.0393	13	0.846
	Theta	0.8231	0.0289	13	0.7773	0.0509	14	0.726
	TBR	0.94471	0.04227	14	0.9003	0.0312	15	0.801
	Attention	0.5850	0.021	12	0.5628	0.01435	14	0.809
Task3	***Alpha***	0.7909	0.042	6	0.8841	0.0375	15	1.103
	Beta	0.841	0.046	9	0.904	0.030	16	0.955
	Theta	0.8425	0.024	12	0.807	0.023	17	0.922
	TBR	0.9581	0.032	12	0.912	0.031	16	0.909
	Attention	0.58	0.021	14	0.543	0.0345	17	0.814
Task4	***Alpha***	0.83159	0.04651	10	0.8819	0.0201	17	0.883
	Beta	0.88271	0.0328	10	0.8332	0.0543	12	0.682
	Theta	0.8354	0.0177	11	0.8135	0.222	12	0.088
	TBR	0.9638	0.0188	12	0.925	0.0322	14	0.931
	Attention	0.587	0.0169	13	0.5633	0.0257	14	0.717
Task5	***Alpha***	0.86	0.018	11	0.8820	0.0187	17	0.702
	Beta	0.852	0.032	13	0.8873	0.0340	17	0.667
	Theta	0.811	0.031	12	0.757	0.0475	15	0.831
	TBR	0.952	0.0281	11	0.904	0.0355	15	0.901
	Attention	0.588	0.013	14	0.57	0.016	17	0.786

		Controls			***PWADHD***			
		M	**SD**	**N**	**M**	**SD**	**N**	***Cohen's d***
Task6	***Alpha***	0.88	0.017	13	0.851	0.0308	17	0.704
	Beta	0.90	0.02	13	0.862	0.028	17	0.956
	Theta	0.84	0.023	14	0.799	0.029	17	0.996
	TBR	0.96	0.025	13	0.931	0.032	17	0.622
	Attention	0.651	0.028	13	0.583	0.0277	15	1.588
Task7	***Alpha***	0.787	0.04	14	0.846	0.03	17	1.089
	Beta	0.761	0.047	14	0.84	0.33	17	0.205
	Theta	0.753	0.036	14	0.801	0.028	17	0.969
	TBR	0.931	0.026	14	0.881	0.048	15	0.854
	Attention	0.535	0.018	13	0.572	0.016	16	1.395
Task8	***Alpha***	0.80	0.035	14	0.86	0.03	17	1.193
	Beta	0.828	0.039	14	0.871	0.031	17	0.794
	Theta	0.81	0.021	12	0.77	0.032	14	0.938
	TBR	0.941	0.025	14	0.881	0.047	15	1.051
	Attention	0.572	0.013	14	0.586	0.012	16	0.734
Task9	***Alpha***	0.787	0.045	14	0.852	0.028	17	1.142
	Beta	0.802	0.039	14	0.866	0.038	17	1.070
	Theta	0.74	0.039	14	0.797	0.0237	17	1.164
	TBR	0.868	0.032	14	0.926	0.026	17	1.293
	Attention	0.557	0.023	13	0.587	0.02	17	0.881
Task10	***Alpha***	0.79	0.04	14	0.845	0.034	17	0.961
	Beta	0.79	0.04	14	0.875	0.04	17	1.366
	Theta	0.745	0.04	14	0.808	0.025	17	1.243
	TBR	0.921	0.033	14	0.857	0.04	16	1.134
	Attention	0.51	0.04	13	0.577	0.031	15	1.229

Note. NOS, SMV, NOF, FD, PD, TBR stands for number of saccades, saccade mean velocity, number of fixations, fixation durations, pupil diameter and theta-beta ratio respectively. Cohen's d represents the effect size: d = 0.2 is small effect; d = 0.5 is medium effect; d = 0.8 is large effect.